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Demand-side strategies enable rapid and deep cuts in buildings and transport emissions to 2050

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Decarbonization of energy-using sectors is essential for tackling climate change. We use an ensemble of global integrated assessment models to assess CO_2 emissions reduction potentials in buildings and transport, accounting for system interactions. We focus on three intervention strategies with distinct emphases: reducing or changing activity, improving technological efficiency and electrifying energy end use. We find that these strategies can reduce emissions by 51–85% in buildings and 37–91% in transport by 2050 relative to a current policies scenario (ranges indicate model variability). Electrification has the largest potential for direct emissions reductions in both sectors. Interactions between the policies and measures that comprise the three strategies have a modest overall effect on mitigation potentials. However, combining different strategies is strongly beneficial from an energy system perspective as lower electricity demand reduces the need for costly supply-side investments and infrastructure.

Demand-side mitigation forms a critical part of strategies to meet the Paris climate goals[1–5], involving both consumer technology choices related to energy efficiency and energy sources, as well as lifestyle changes. Lower energy demand reduces emissions and also allows for greater flexibility in technology choices within supply sectors by lowering the overall energy production and associated investment requirements[2]. Two critical demand-side sectors include buildings (encompassing residential and service-sector buildings) and transport (encompassing aviation, navigation and land transport) that each represented 29% of global final energy consumption in 2019[6] and, respectively, 19% and 7% of direct energy-related greenhouse gas emissions[7]. In the Sixth Assessment (AR6) Working Group (WG) III report the Intergovernmental Panel on Climate Change (IPCC) for the first time included a chapter on demand-side reductions (Ch. 5). It estimates that demand-side options in buildings and land transport could potentially lead to greenhouse gas emissions reductions of 66% and 67% by 2050, respectively[2]. Complementing this, a similar assessment by Creutzig et al. also reports high potentials of 78% and 62% for the same sectors[3].

These figures represent median estimates derived from a review of 'bottom-up' assessments of individual demand-side mitigation options found in existing literature. However, the reliance on bottom-up approaches faces limitations due to potentially inconsistent assumptions regarding the effects of individual measures, varying

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baselines and the challenge of capturing interactions between multiple strategies. System interactions that need to be considered include the complementarity or overlap between options[8] (for example, the electrification of the vehicle fleet limits the potential for emissions reductions through improving combustion engine efficiency), the interactions between energy-supply decarbonization and end-use transformations[9–11] and possible 'rebound effects' (when efficiency measures lead to unintended increase of the demand for energy services that can partly counterbalance the potential of activity-oriented mitigation options)[12,13]. These interactions and system impacts can either improve or reduce the effectiveness of individual strategies and have yet to be assessed in transformation pathways that require adequate modelling tools for doing so.

Whereas recent literature has advanced the understanding of demand-side mitigation, most scenario studies rely on single-model approaches, focusing on long-term global pathways[3,14–17] and national trajectories[18–21] and critical factors such as material efficiency[22,23]. This reliance on single models limits the robustness of findings, as they do not account for the structural uncertainties inherent in these models.

Integrated assessment models (IAMs) are specifically designed to capture interactions among the energy system, economy and environment, making them valuable tools for assessing the potential of demand-side intervention strategies in the buildings and transport sectors. These models not only facilitate the systematic assessment of the impacts of such strategies through scenario analysis but also incorporate the system-wide impacts that arise from their implementation. Integrated modelling frameworks allow to build consolidated trajectories whereas ensuring consistency not only between sectors and intervention strategies but also over time.

Historically, global IAMs have predominantly emphasized supply-side measures in global mitigation scenarios[24,25], which has limited their capacity to address demand-side pathways effectively. This has been complicated by the complexity of consumer groups and behaviour, diverse sectors, services and technologies that depend on local circumstances, climate and socio-economic conditions, infrastructures and technological development. However, in recent years, IAMs have improved their representation of energy-demand sectors, particularly in the buildings and transport sectors. These advancements are driven by rapid technological advancements, such as electric mobility and heat pumps, necessitating ongoing model updates. The improvements encompass various aspects, including alternative electrification pathways in transport[26,27], more diverse building types and expanded options for renovations in buildings[28–30] and improvements in the representation of international transport[31–34]. Moreover, gradual advancements have been made in modelling behavioural transitions within IAMs[35,36].

Our study leverages the modelling improvements of multiple IAMs (COFFEE, IMACLIM-R, IMAGE, MESSAGEix-Buildings, PROMETHEUS, REMIND and WITCH) to analyse the relative importance of key demand-side mitigation strategies, examining specifically the areas of buildings and transport, including personal mobility and freight transport. The main features of each model are provided in Supplementary Information 1. The seven models capture the interactions between measures and system effects to various degrees. Although a complete disentangling of the contributions of these interactions within each model is beyond the scope of this study, our work aims to provide a robust assessment of demand-side measures potentials and interactions across the structural uncertainty of the models included. We analyse interactions between strategies and apply decomposition analysis to evaluate the scenario results, identifying key drivers of emissions reductions and revealing some interaction effects. Our findings highlight the key role of electrification, yet underscore that a combined approach further reduces emissions and alleviates pressure on the energy supply side. Our results also show that there is a considerable spread in the results across models, indicating substantial structural uncertainty about the complex dynamics drive the results.

Analysis of modelled reduction strategies

We identified a comprehensive list of mitigation measures from relevant literature and developed scenarios to analyse their implications for mitigation pathways. To ensure that the scenarios are credible and policy-relevant, while accounting for all key factors, we involved policymakers and demand-side experts. Through a survey, they evaluated the feasibility of the narratives and measures and their potential for emissions reduction (Methods). The various emissions abatement measures are grouped into behavioural changes impacting activity, technical efficiency improvements and electrification of energy end uses. To analyse the impact of these groups and their interactions, we translated them into the following scenarios, each representing distinct intervention strategies (Table 1).

The activity-focused strategy (ACT) involves redesigning service-provisioning systems to either reduce or shift consumption of energy and transport services. In buildings, this strategy includes reduction of average dwelling size, working in shared buildings with flexible use, adjusting thermostat settings to lower (heating) or higher (cooling) set points. In transport, it includes promotion of active modes (walking, biking), public and shared mobility options. Air travel is discouraged, whereas advancements in freight logistics and speed restrictions in maritime transport enable more efficient movement of goods.

The technology-optimizing strategy (TEC) focuses on improvements in the efficiency of existing technologies. Higher levels of energy efficiency are achieved in both new constructions and existing buildings through increased renovation rates, improved thermal insulation and more efficient heating, ventilation and air conditioning (HVAC) systems. Efficiency standards for road vehicles, aircraft and ships are implemented. Environmental certification of airplanes and ships is required for using airports and ports.

The electrification-focused strategy (ELE) focuses on switching to electricity and alternative fuels. Heat pumps and electricity-based heating systems are widely adopted in buildings. Fossil fuels are phased out and new natural gas connections are banned in the global north. Passenger vehicles, light-duty trucks and ports transition to full electrification. Diesel engines are phased out of heavy-duty vehicles, and biofuels and electrofuels are increasingly used in aviation and shipping.

Finally, a combined approach, referred to as all interventions (ALL), integrates all the interventions from ACT, TEC and ELE.

These scenarios build upon the ASI (Avoid-Shift-Improve) framework developed by Creutzig et al.[3], which categorizes demand-side actions into the three components *avoid*, *shift* and *improve*. However, our approach provides a direct and consistent mapping to concrete intervention strategies and their impacts on the energy system and emissions (Methods). For instance, ASI categorizes installing heat pumps as a 'shift' intervention, whereas adopting electric cars as 'improve'. In our framework, both interventions are part of the electrification strategy, as they do not change the quantity or quality of energy service provided and have very similar energy system implications.

As a starting point for the analysis, a 'middle-of-the-road' socio-economic pathway (SSP2) is used together with current national policies implementation (NPi)[37,38]. This includes the most important policies per country adopted by national parliaments (Supplementary Information 3). The scenarios use different gross domestic product (GDP) and population projections for each country to capture inter-regional heterogeneity. Subsequently, the additional policies and measures affecting demand-side sectors are explicitly modelled in scenarios. Although many measures are likely to impact industrial emissions, this impact is outside the scope of this study. To explore the interactions with more stringent climate ambitions, we also consider scenarios aligned with 1.5 °C global warming, implemented through a carbon tax that limits the cumulative CO_2 budget to 400 Gt (peak) and 650 Gt (by 2100) in the period 2020–2100. An overview of these scenarios is provided in Table 2.

Table 1 | Overview of the demand-side strategies and references supporting the underlying assumptions with further details and motivation for the assumptions provided in Methods

Scenario	Description and assumptions	Supporting references
Activity reduction and shifts (ACT)	Buildings Policies limiting floorspace in new constructions, along with flexible use of buildings and shared building spaces (such as co-housing and working), reduce per capita floorspace in both the residential and commercial sectors. Shifts in household preferences and policies that limit new construction of single-family houses increase the share of multi-family houses. Stimulated by information campaigns and restrictive policies, the set-point temperatures in buildings shift to 20 °C for heating and 25 °C for cooling.	16,70–73
	Transport Measures such as congestion charges and growing prevalence of remote working reduce demand for driving private vehicles within cities, and more bike lanes and pedestrian zones increase the adoption of active modes (bicycles, e-scooters and walking), whereas improvements in public transport infrastructure, last-mile services and free/lower public transport fares increase the adoption of public transport. Also car-sharing/pooling is actively promoted. In the aviation sector, passenger transport is reduced by fuel taxes (by abolishing tax exemptions), movement taxes such as a frequent flyer levy and development of increased virtual connectivity. Also freight transport is affected by fuel taxes and movement taxes. Policies encourage development of local manufacturing and storage, and improved road freight logistics reduce road freight activity. Worldwide speed restrictions are introduced in maritime transport (slow steaming shipping) and short-haul air travel is phased out by 2030.	14,32,73–79
Technological improvements (TEC)	Buildings Building codes and standards, energy performance certification and subsidies are implemented to reduce energy intensity by improving insulation levels and enhancing overall energy efficiency per surface area. This results in more efficient heating, ventilation and air conditioning. Additionally, the current retrofit rate doubles to 2% per year in the global north.	16,30,73,80,82
	Transport Efficiency standards result in efficiency improvements across all new passenger vehicles, trucks, airplanes and ships. In addition, environmental certification for using airports and ports further drives efficiency improvements across the entire aviation and shipping fleets.	83,84
Electrification and fuel shift (ELE)	Buildings Fuel mandates accelerate electrification and heating fuel switching, with heat pumps in all new buildings by 2030. By 2050, we assume that 70% of space and water heating is electricity based. Building regulations and neighbourhood-based approaches also stimulate deployment of on-site, and building-integrated renewables and renewable energy (photovoltaics and thermal solar) meet 50% of the demand for cooling and heating in the global north by 2050. New natural gas connections for heating are banned in the global north by 2030, and non-clean heating fuels are phased out by 2050.	71,73,85
	Transport Fuel/technology mandates ensure full electrification of passenger vehicles and light-duty trucks by 2040, using battery or fuel cell electric vehicles. In the fleet of heavy-duty vehicles, diesel engines are phased out by 2040. By 2030, ports are fully electrified, reducing ships' reliance on auxiliary engines, and vessels meet zero-emissions berth standards by 2040. Fuel standards/mandates, infrastructure development and removing blending restrictions increase the use of alternative fuels (biofuels/electrofuels) in international transport. After 2050, electric short-haul planes become available.	73,76,86–91

Table 2 | Overview of the scenarios with the implementation of the scenarios detailed in Methods

Additional policies affecting demand-side sectors	Climate ambitions	
	Current national policies (NPi)	***1.5 °C scenario***
None (REF)	NPi-REF	1.5C-REF
Activity-focused (ACT)	NPi-ACT	1.5C-ACT
Technology-optimizing (TEC)	NPi-TEC	1.5C-TEC
Electrification-focused (ELE)	NPi-ELE	1.5C-ELE
All interventions (ALL)	NPi-ALL	1.5C-ALL

Mitigation potential and interactions

In the default current policy scenario (REF), direct CO_2 emissions from buildings increase by −1% to 36% in 2030 and −8% to 31% in 2050 compared with 2015 levels, whereas direct emissions from transport increase by 5% to 32% in 2030 and −10% to 49% in 2050 (Fig. 1). This increase is mainly caused by increasing final energy demand after 2015. However, not all models also indicate a correspondingly strong increase in emissions; in fact, some models even project a decrease due to a more pronounced shift to less carbon-intense fuels. The wide variation in projections across the models is closely related to how efficiency and changes in service demand (for example, elasticities or relationships with economic activity) are modelled. In some models, increasing activities result in increasing emissions, whereas in others, activity growth is partially offset by efficiency improvements. Nonetheless, in both sectors, final energy demand continues its upward trend in the majority of models.

The intervention strategies mitigate the increase in energy demand and reduce the growth in direct emissions in both buildings and transport—in a similar way across models. Emissions reductions from current levels are robust across models for both ELE and ALL, particularly in buildings, but with more inter-model variation for the activity-focused and technology-optimizing strategies. Emissions reduction potentials in 2030, with respect to the reference scenario (REF), are 3–16% (ACT), 3–19% (TEC) and 10–31% (ELE) of direct buildings emissions and 4–15% (ACT), 2–10% (TEC) and 3–17% (ELE) of direct transport emissions (Fig. 2). The potentials become more substantial in 2050 and reach 6–23% (ACT), 11–33% (TEC) and 45–77% (ELE) for buildings and 17–28% (ACT), 2–67% (TEC) and 22–86% (ELE) for transport.

We also estimated the impact of all measures combined as a product of the impact of each individual strategy, shown as the no-interaction estimate in Fig. 1. This approach assumes that the measures interact independently. Comparison with ALL shows that interaction between measures from different strategies actually play a role, although their impact on the overall mitigation potential is limited. In the buildings sector, the models project an effective potential in 2050 that is lower than the no-interaction estimate. However, considering

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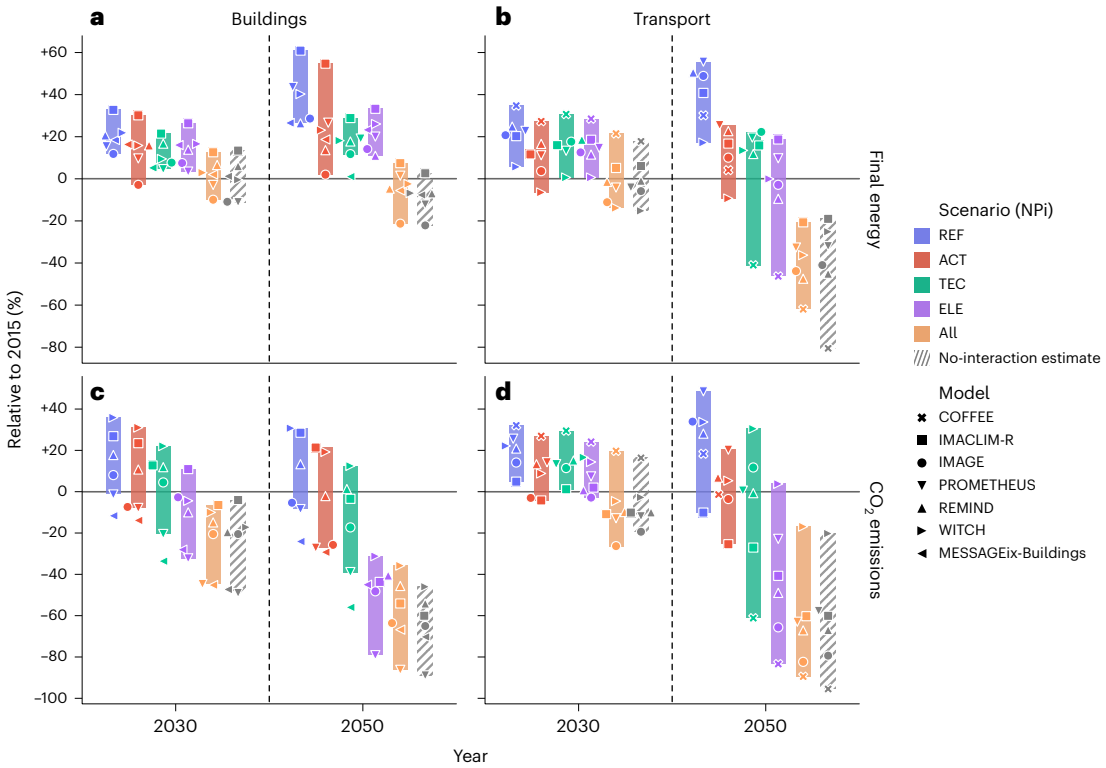

Fig. 1 | Change in global final energy use and direct CO_2 emissions from fuel combustion in the buildings and transport sectors. a,**b**, Final energy use in buildings (**a**) and transport (**b**). **c**,**d**, CO_2 emissions from buildings (**c**) and transport (**d**). Results are presented relative to 2015 levels to reduce model differences resulting from calibration against different historical datasets. All scenarios have current NPi. Markers indicate individual model results and bars depict the model ranges. The grey hatches and markers represent the no-interaction estimates, which approximate the combined impact of each individual strategy relative to NPi-REF by multiplying their respective effects. MESSAGEix-Buildings results are shown, but for cross-sectoral consistency are not factored into the averages and ranges (Methods). Projections for activity patterns in the reference scenario (floorspace, passenger-kilometres and freight tonne-kilometres) are provided in Supplementary Information 5. Subsectoral projections for the residential, commercial, passenger and freight sectors are available in Supplementary Information 8.

only the interactions represented in the models, the accumulation of the various measures still remains largely effective. In the transport sector, remarkably, four models simulated an effective potential slightly greater than the no-interaction estimate (IMAGE, IMACLIM-R, PROMETHEUS, REMIND).

Examples of counteracting interactions include the diminished impact of improved insulation on emissions reductions when inefficient boilers are replaced with electric heat pumps. Likewise, lowering set-point temperatures reduces the potential emissions savings that could otherwise be achieved through enhanced insulation or the adoption of heat pumps. In transport, the additional impact of efficiency standards is limited as the vehicle fleet becomes predominantly electric, given the much higher efficiency of electric motors. Conversely, certain measures can amplify the effectiveness of others, which is evident in the transport results for some models. For instance, as electrification policies increase the market share of electric vehicles (EVs), declining costs from learning effects enhance their competitiveness. At the same time, car-sharing services also reduce the effective cost of higher-priced EVs, and together these factors can accelerate the transition.

Under a 1.5 °C climate ambition, the implementation of demand-side measures generally results in emissions reductions greater than those in 1.5C-REF, with WITCH being an exception and some models showing only marginal differences. The COFFEE results show a short-term rebound effect in oil consumption for TEC, ELE and ALL. With perfect foresight, COFFEE anticipates a decrease in long-term fossil fuel demand, leading to price reductions and an increase in short-term fossil fuel consumption.

Interestingly, there is no consensus among the models about the most effective strategy under 1.5 °C climate ambition. This could be attributed to variations in models' responses to carbon tax, leading to utilization of different mitigation options. Conventional mitigation scenarios such as 1.5C-REF include measures that are assumed to be cost effective, thereby leaving part of the demand-side mitigation potential unexploited. Such scenarios are often implemented through a (globally uniform) carbon tax, whereas demand-side measures—such as accelerating technology adoption and modal shifting—can be cost insensitive.

The integration of all intervention strategies (ALL) can reverse the trend of rising emissions in buildings and transport. Without additional climate policies, the buildings sector could reduce CO_2 emissions, on average across models, by 63% (51–85%) and the transport sector by 70% (37–91%) in 2050. The combination of strategies achieves sectoral emissions reductions compatible with a 1.5 °C pathway (Fig. 2).

Interestingly, these findings are comparable to—but independent from—reported potentials in the IPCC's AR6 WG III report that use bottom-up studies to estimate emissions reduction potentials in 2050 relative to the IEA WEO (International Energy Agency's World Energy Outlook) stated-policy scenario of 66% (40–91%) for buildings and 67% (44–88%) for land transport[2]. Ranges are not explicitly mentioned in the report, but we derived them by multiplying the lowest and highest reported potentials for the considered mitigation options, consistent with the computation of median estimates. However, in contrast to this study, the IPCC figures relate to total emissions including indirect emissions from electricity generation. Whereas IAMs can quantify these indirect emissions, assessing them within the context

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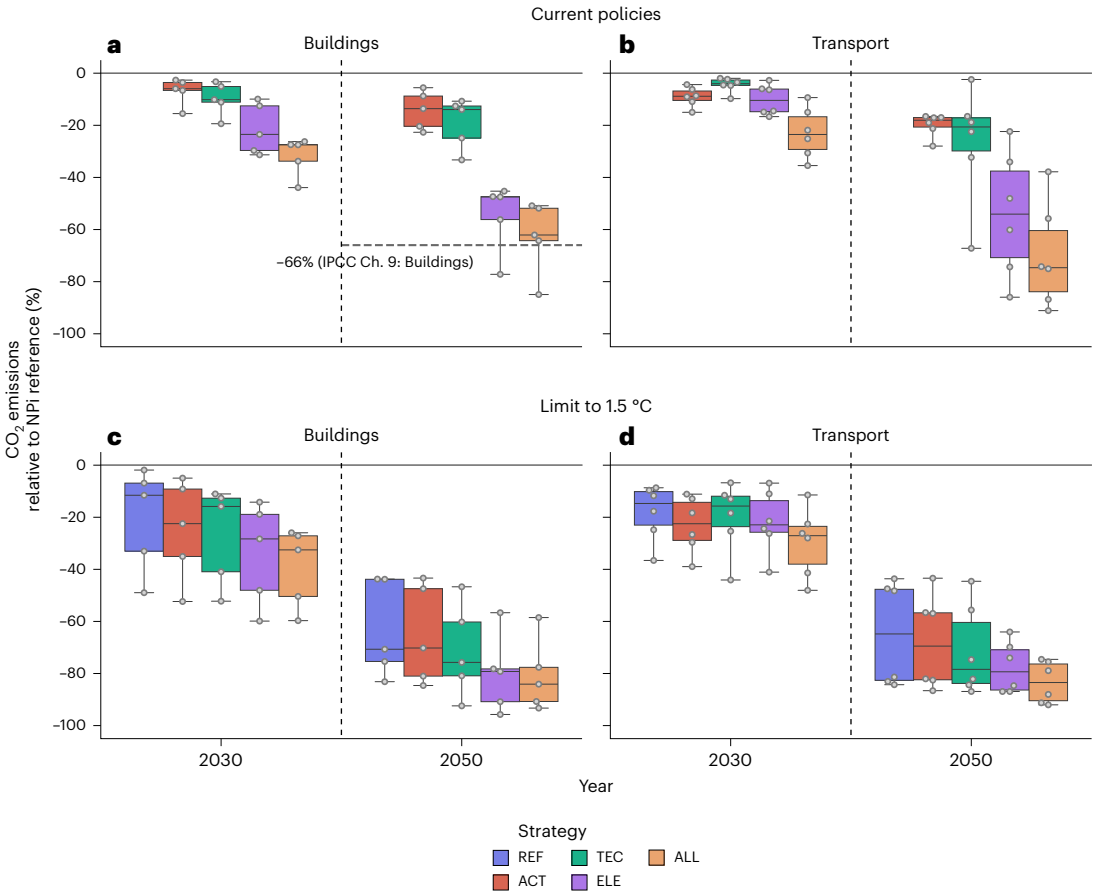

Fig. 2 | Deviation in global direct CO_2 emissions for buildings and transport for different intervention strategies relative to the NPi reference scenario. **a**,**b**, Emissions in scenarios with current NPi from buildings (**a**) and transport (**b**). **c**,**d**, Emissions in the 1.5 °C climate ambition scenarios from buildings (**c**) and transport (**d**). Boxes represent the interquartile range, with the centre line indicating the median and whiskers extending to the minimum and maximum values. The individual data points are shown as dots, with the boxplots based on data from five models for buildings and six models for transport. A dashed line provides a comparison with estimated mitigation potentials from Ch. 9 (Buildings) of the IPCC's AR6 WG III report. A comparable analysis for transport is not available.

of demand-side potentials poses challenges because this relies on the degree of decarbonization in the upstream electricity generation sector that varies vastly across scenarios and models (Supplementary Information 10). When indirect emissions are considered, our study shows considerably lower emissions reduction potentials, particularly in buildings. This difference may stem from the representation of rooftop solar systems, which are generally not explicitly accounted for within IAMs, along with the limited representation of the commercial sector. Also, nuanced disparities arise from differing scopes. Whereas our study covers reduced international transport, improved logistics and fuel shifts for aviation and shipping, the IPCC synthesis includes additional measures for shipping (for example, weather routing) and buildings (for example, shorter showers, smarter energy use and nature-based solutions).

The wide range of projections shown in Figs. 1 and 2 arise from inherent uncertainties in model dynamics and parameterizations that underscore the importance of multi-model studies. Further uncertainties lie in underlying socio-economic projections. For example, higher economic or population growth is likely to lead to increased energy use and emissions[39–41] (although in developed countries, this link is less evident[42]). Other socio-economic factors, such as urbanization and household size, affect energy demand[43–46]. Higher energy demand could ultimately limit the potential of the ELE scenario, if the energy supply fails to meet the additional demand for cleaner fuels. Conversely, lower growth could alleviate pressure on the supply of cleaner fuels. Moreover, energy intensity is usually lower in richer countries[47], and higher economic growth could thus result in lower baseline energy intensities. This, in turn, would reduce the effectiveness of additional policy measures in the ELE and TEC scenarios. Lastly, the effectiveness of the ACT scenario depends on the adoption of new behaviours, and this process is inherently tied to various socio-economic factors.

Reducing pressure on the electricity system

Electrification is widely recognized as a crucial strategy for emissions reduction[48]. According to most IAMs in this study, ELE yields greater emissions reductions by 2050 compared to the other strategies under current policies (Fig. 2 and Supplementary Information 6). With the exception of MESSAGEix-Buildings and WITCH, the models project over 15% more emissions reductions with ELE than with the other strategies. Only MESSAGEix-Buildings demonstrates larger emissions reductions in TEC, primarily due to the installation of heat pumps, which are most effective when combined with improved insulation. In the WITCH model, emissions reductions in land transport are more pronounced in ELE, consistent with the other models, but bunker emissions remain considerable (Supplementary Fig. 15), probably due to the low technological granularity of alternative shipping technologies[49].

Electrification also poses substantial challenges, particularly regarding the surge in electricity demand (Fig. 3). By 2050, global electricity demand increases by 8–16 EJ per year for buildings and 4–25 EJ per year for transport in NPi-ELE compared to NPi-REF. The larger potential increase in transport reflects its currently low electricity share. Although growth rates from 2015 to 2050 are broadly

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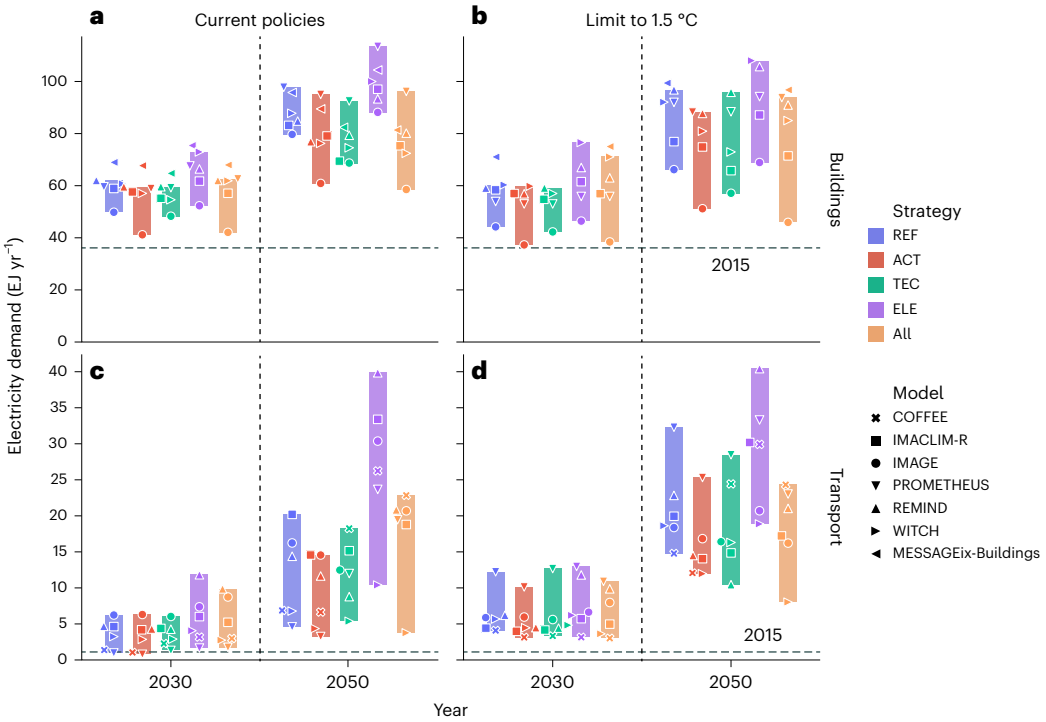

Fig. 3 | Global electricity demand from buildings and transport under two climate ambitions. a,**b**, Buildings electricity demand for scenarios with current national policies implemented (**a**) and for the 1.5 °C climate ambition scenarios (**b**). **c**,**d**, Transport electricity demand for scenarios with current national policies implemented (**c**) and in the 1.5 °C climate ambition scenarios (**d**). Markers indicate individual model results and bars depict the model ranges. A dashed line shows the 2015 levels. Non-electric energy demand is shown and discussed in Supplementary Information 11.

consistent with those observed in previous decades (Supplementary Information 9), suggesting infrastructural challenges can be addressed, more detailed models such as power dispatch models should be used to further explore this. In addition to requiring resilient energy infrastructures, enhanced storage capacities and increased flexibility of the power system, increasing electricity demand may shift emissions from the demand side to the supply side. This is mostly relevant for a weak climate policy regime (NPi), whereas under 1.5 °C policies, electricity supply is projected to be already largely decarbonized by 2040. Moreover, under 1.5 °C climate ambition, some models show lower electricity demand growth due to increased availability of alternative fuels such as modern biomass and/or electrofuels.

In current climate policy scenarios (NPi), emissions reductions in the ELE and ALL scenarios by 2050 are less pronounced when accounting for indirect emissions based on average emissions intensities (Fig. 4). Particularly for buildings, indirect emissions remain high in the near term due to limited supply-side decarbonization and the sector's heavy reliance on electricity. In contrast, the transport sector has a considerably larger share of fossil fuel use, which offers greater potential for emissions reductions through electrification, as there is more opportunity to replace fossil fuels with cleaner alternatives. This is also reflected in the greater final energy reductions for transport than for buildings, as shown in Fig. 1.

In light of increasing electricity demand, it is critical to expand the capacity of the energy supply sector while simultaneously decarbonizing it, as previous research has already suggested[50–52]. Our scenarios show that integrating electrification with other demand-side strategies (ALL) can facilitate necessary transitions, potentially decreasing global electricity demand by 10 to 39 EJ per year, even under a 1.5 °C climate target. Depending on the model and climate policy, this reduction represents 8 to 33% of the electricity demand for transport and buildings. Furthermore, the combined approach leads to over 15% more direct emissions reduction compared to ELE alone in the ALL scenario. This demonstrates that a comprehensive strategy combining electrification with energy efficiency and activity-focused measures substantially reduces the need for supply-side investments in low-carbon generation technologies, large-scale electricity storage and electricity infrastructure and grids.

Decomposing emissions reductions

To understand the key factors that drive emissions reductions, we applied decomposition analysis to passenger transport and residential buildings emissions in 2050. We compared REF and ALL across five models (IMACLIM-R, IMAGE, REMIND, MESSAGEix-Buildings, WITCH) (Fig. 5). Efficiency gains stand out as important contributors to emissions reductions for all models. Improved efficiencies are partly a result of policies that promote higher energy efficiencies (TEC), such as efficiency standards and building codes, but electrification (ELE) also plays a key role and results in similar or even higher improvements: e-mobility is much more efficient than internal combustion engines in vehicles, and so too are heat pumps in comparison to boilers (Supplementary Information 7 provides a decomposition of the individual strategies). In addition, shared services further support efficiency gains (ACT).

It is important to note that the contributing elements in the decomposition are interdependent. For instance, a decrease in car travel will reduce more emissions in scenarios and models in which cars have lower fuel efficiency.

The contribution of electrification, defined as the ratio of electricity to final energy demand, varies across models. Whereas some models show decreasing emissions from electrification (WITCH, REMIND and IMACLIM-R in passenger transport), others show an increase (IMAGE, MESSAGEix-Buildings and IMACLIM-R in buildings). This discrepancy is due to different decarbonization rates of the power supply under current policies and highlights that additional mitigation potential could be achieved by expanding on renewable energy (Fig. 3). Likewise, models also vary in the contribution of carbon intensity reductions.

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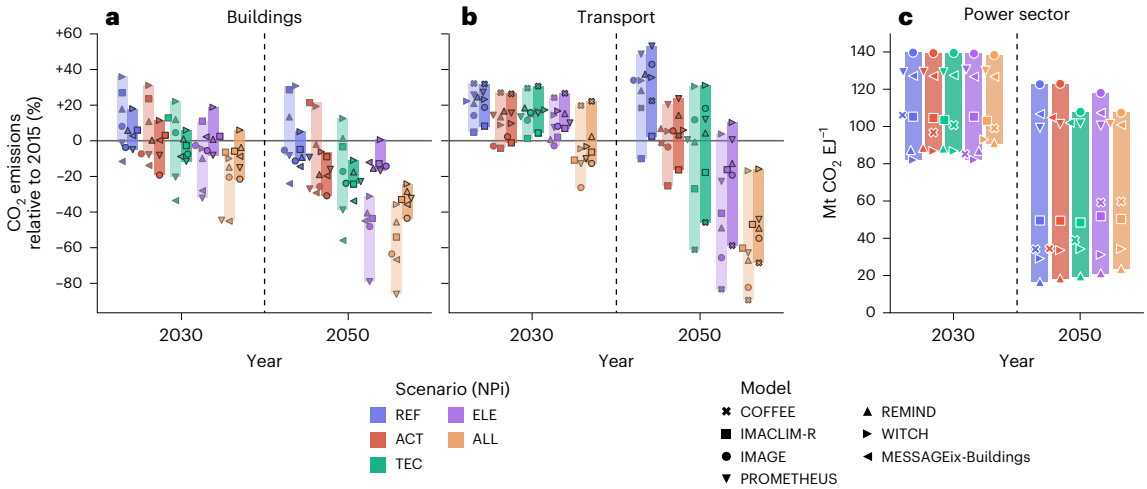

Fig. 4 | Global CO_2 emissions from buildings, transport and the power sector relative to 2015 levels under current NPi. a,**b**, Changes in global CO_2 emissions in the buildings (**a**) and transport (**b**) sectors including emissions from electricity, heat and hydrogen generation. The darker shaded ranges represent the total emissions, combining both direct and indirect sources, with the latter calculated using model-average emissions intensities. In contrast, the lighter shaded ranges represent only direct emissions, matching the results shown in the lower panels of Fig. 1. Markers indicate individual model results and bars depict the model ranges. **c**, Global CO_2 emissions from the power sector. The same figure for scenarios with 1.5 °C climate ambition is available in Supplementary Information 10.

Changes in service demands, such as reduced travel and mode shifts lead to emissions reductions across all models. Previous research indicated that IAMs tend to underestimate the potential for mode shifting when not explicitly prescribed[53] due to the complexities of simulating context-dependent mode choices[54]. Our analysis shows that while mode shifts can be effective and useful to lower energy demand, their contribution to emissions reductions might be limited. Scenario implications for the buildings sector are further explored in ref. 55.

Regional effects

Differences observed in the scenario results are largely attributed to regional variations in the reference scenario, as depicted in Fig. 6 for nine regions. For the reference scenario, all models project an increasing energy demand per capita for all regions except the OECD (Organisation for Economic Co-operation and Development: European Union, United States and Other OECD) for both sectors (buildings and transport) and the Africa and Middle East, other Asian countries and former Soviet Union countries for buildings. Figure 6 also shows that part of the model spread at the global level can be explained by the regional disparities, especially in the buildings sector or in transports for India. However, a broad consensus can be found across models for the most advanced economies of the OECD for transport.

Regional disparities are driven by opposing dynamics in service demand and energy efficiency. As lower- and middle-income countries get wealthier, they increasingly demand more energy services for appliances, heating and cooling to support their improved living standards. At the same time, the use of traditional fuels, which are still commonly used for cooking in certain areas (predominantly in Africa), decreases substantially until 2050. Energy demand reductions also occur in OECD countries, where use of natural gas for space heating is steadily decreasing due to improved insulation levels under current policies. In transport, per capita energy demand reduces in some regions, despite rising demand for mobility, due to increased use of electric vehicles with much higher efficiency[56] than internal combustion engine vehicles. In contrast to the global results, some models signal that emissions from buildings could be higher in ACT and TEC (Supplementary Fig. 22), probably due to rebound effects. This is particularly noticeable in India, other Asian and Africa and Middle East. An increase is also observed in transport emissions by COFFEE and WITCH for the United States (ACT) and European Union (TEC), respectively. Carefully adapted rebound mitigation policies, for example, through carbon pricing or providing consumption information, could in such cases further increase the effectiveness of demand-side measures[57,58].

The combination of all interventions allows for a relative decrease in energy demand in 2050 for all regions and within the transport sector an absolute decrease compared to 2015 levels in all models, with exceptions for India (all models), Other Asia (IMACLIM-R) and China (IMAGE). The strongest disparities of demand-side strategies for developing countries compared to more advanced economies reflect the strong correlation between energy demand and economic development[59], which is likely to be a challenge for an early adoption of demand-side policies in the upcoming years. On the other hand, some interventions, such as reducing the floor space per capita, increasing the energy efficiency in buildings and using low-carbon transport modes, strongly depend on the way emerging cities will be shaped. Through intelligent planning and design, such cities can lead the way in advancing sustainable transformations[60].

Discussion and conclusions

We used seven IAMs to analyse the potential of demand-side mitigation strategies. The reduction potentials of direct CO_2 emissions identified in our study align with trends found in the synthesis of bottom-up studies in the demand chapter of the IPCC's AR6 WG III report and further highlight uncertainty and system-wide effects. Unlike the IPCC's estimations, our analysis builds upon a consistent set of harmonized scenario assumptions and includes interactions between measures and sectors, such as the reduced impact of lowering set-point temperatures in conjunction with enhanced insulation. Our analysis reveals that interactions among different measures do play a role, yet their effect on overall mitigation potential is relatively small. Additionally, we explicitly assessed the importance of decarbonizing electricity generation to disentangle it from demand-side mitigation potentials.

By using an ensemble of models, and presenting a decomposition of the effects across models, we explored inherent uncertainty and diversity of results and the underlying dynamics. The wide variation in projected mitigation potentials across models (51–85% for buildings and 37–91% for transport) reveals the high level of

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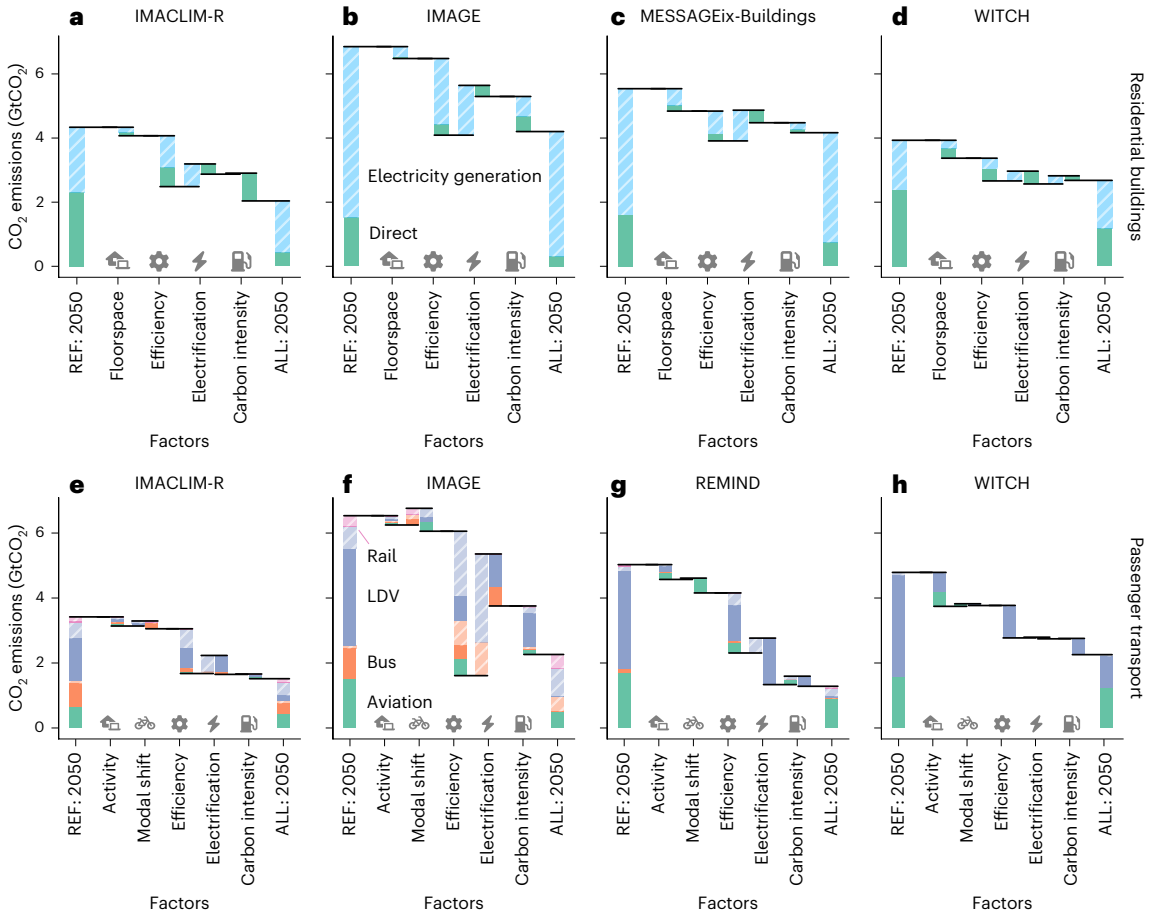

Fig. 5 | Decomposition of global CO_2 emissions for the current policy scenarios in 2050 from the residential sector and passenger transport. **a**–**d**, Decomposition for residential buildings in IMACLIM-R (**a**), IMAGE (**b**), MESSAGEix-Buildings (**c**) and WITCH (**d**). **e**–**h**, Decomposition for passenger transport in IMACLIM-R (**e**), IMAGE (**f**), REMIND (**g**) and WITCH (**h**). Figures include emissions from electricity generation (hatched). Changes in emissions are attributed to the factors activity/floorspace, modal shifts (transport only), efficiency, electrification and carbon intensity. Carbon intensity is the average amount of CO_2 emissions per unit energy of fuel combusted or, for emissions from electricity generation, the average emissions intensity of electricity generation. For passenger transport, four modal categories are considered: aviation, bus, light-duty-vehicle (LDV) and rail. Floorspace use serves as a proxy for activity changes in buildings because most models lack the capability to generate detailed output for service demand. This implies that all activity changes not directly related to floorspace use, such as thermostat adjustments, are classified as efficiency improvements. Methods provide definitions of all factors. Note that REMIND and MESSAGEix-Buildings are exclusively included for passenger transport and buildings, respectively, due to a lack of the required level of granularity.

uncertainty that arises from the complexity of modelling future energy-demand development.

The impact of the selected set of demand-side interventions is high: on average, across the models, 65% reduction of direct CO_2 emissions in buildings and nearly 70% in transport by 2050, compared to a current policies scenario. Activity-focused measures result in reductions by 2050 of 6–23% for buildings and 17–28% for transport, technology-optimizing measures to 11–33% and 2–67%, respectively, and electrification-focused measures to 45–77% and 22–86%. However, the success of these strategies hinges critically on the emergence of social innovations and implementation of policies to overcome crucial barriers.

By disaggregating demand-side strategies, our analysis provides clearer insights into the distinct contributions of different policies. Whereas the importance of electrification and fuel shifts in reducing demand-side CO_2 emissions is well recognized, our results demonstrate that across most models, an electrification-focused strategy yields the greatest reductions in direct CO_2 emissions from buildings and transport by 2050, even lowering emissions below 2015 levels. However, this approach also more than doubles global electricity demand by 2050 compared to 2015. Focusing on increased electrification alone only reduces emissions if this is supplemented by a sustained effort to decarbonize electricity supply. Shifts in activity patterns can also contribute to emissions reduction but have a greater potential in high-income regions, as meeting basic energy services is a higher priority in lower- and middle-income regions.

Integrated approaches combining different strategies not only lead to the greatest reduction in emissions but also help alleviate stresses on the upstream energy supply sector that may arise from individual demand-side strategies, such as an increase in electricity demand, storage and grids due to electrification. Furthermore, decomposition analysis shows that efficiency improvements, and to a lesser extent activity shifts, can contribute to further emissions reductions.

Following the advancements in IAMs, there are several opportunities for improving the assessment of demand-side scenarios. First, lifestyle changes should be better integrated into scenarios[61–66]. Reducing or shifting energy services demand requires widespread changes in social norms to induce more sustainable lifestyles, as discussed and modelled in Supplementary Information 13. These can only partially be achieved by policies and strongly depend on available organizations and infrastructures[67,68]. Second, further developments should enhance the linkage between demand sectors and industrial and

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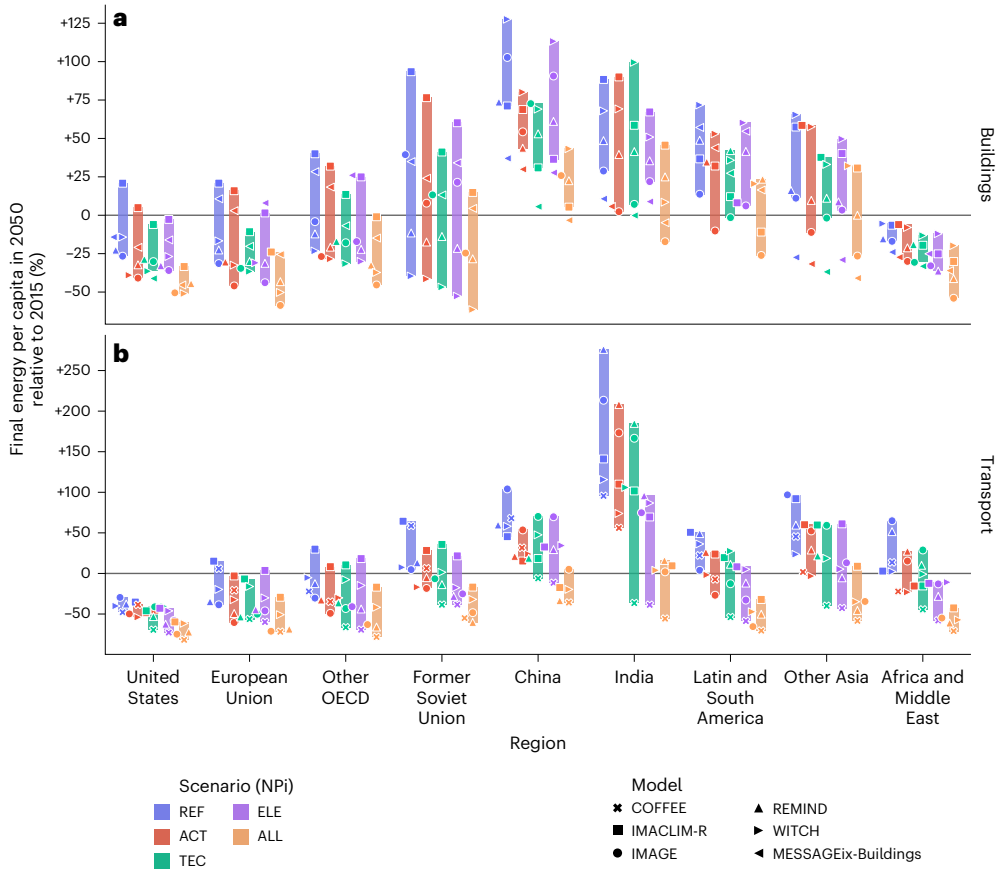

Fig. 6 | Change in final energy per capita in 2050 relative to 2015 under current NPi for nine regions. a, Buildings final energy use. **b**, Transport final energy use. Results are shown for the United States, the European Union, other OECD countries, countries from the Reforming Economies of the Former Soviet Union, China, India, Latin and South American countries, other Asian countries and countries of Africa and the Middle East. Markers indicate individual model results and bars depict the model ranges.

material demands[22]. Strengthening this connection would enable a more complete evaluation of emissions across the supply chain. Third, IAMs do not adequately consider local infrastructural challenges, particularly those related to the power grid. Additional assessments using more detailed models, such as power dispatch models, can help to identify risks, such as increased likelihood of blackouts[69], that could impede consumer adoption.

The success of policies depends on their broader support in society. Measures aimed at behavioural and lifestyle changes, but also interventions such as taxing air travel and restricting low-cost carbon-intensive technologies that directly influence affordability might face resistance. Our study, which assumes that policies are fully effective, does not account for the potential resistance and partial implementation that could affect the outcomes. Therefore, future research should also delve into the impact of these measures on macroeconomics, ensuring that policies are not only effective but also sustainable in their broader socio-economic context.

Methods

Identification of key measures

In the initial phase of this study, an extensive list of demand-side measures was identified, based on relevant literature and Ch. 5 of IPCC's AR6 WG III report[2] (references in Table 1). To improve the credibility and policy relevance of the scenarios, and to ensure that no factors were overlooked, we collected input from experts in relevant areas related to climate change mitigation. This involved conducting an online stakeholder survey in 2021. Experts were asked by means of a questionnaire to evaluate the feasibility and effectiveness of different ways to reduce emissions in the domains of buildings, mobility and international transport (Supplementary Table 7). Details about the stakeholder survey are provided in Supplementary Information 2, and the responses are summarized in Supplementary Tables 7 and 8. This was used as input for designing the three intervention strategy scenarios. The full process of designing, simulating and analysing the scenarios is summarized in Supplementary Fig. 1.

Defining policy scenarios and model assumptions

On the basis of the literature evaluations and feedback from the stakeholder survey, we compiled a comprehensive list of measures that were considered to have substantial impact on reducing demand-side emissions, while also being regarded feasible. We classified these measures into three different intervention strategies, based on a slightly adapted version of the ASI (Avoid–Shift–Improve) framework[3]. Categorizing policy measures in the ASI framework can be ambiguous in some cases. For example, stimulating adoption of heat pumps both *improves* the building technical systems and induces a *shift* from higher-carbon fuels to electrification for space heating. Because we aimed to explore which type of policy interventions are most effective, we needed a cleaner separation between the mitigation options and we use a more distinct separation between the demand-side measures. Table 1 summarizes the key assumptions for the three intervention strategies.

This section presents a detailed description of the modelling protocol used to assess the scenarios. We elaborate on the specific measures for each sector that the scenarios consider, as summarized earlier in Table 1. We explain the quantification of the measures and

outline the literature and scenarios that form the basis of the underlying assumptions.

Activity reduction and activity shifts. Policies that limit floorspace in new building constructions, along with flexible use of buildings and shared spaces (such as co-housing and co-working), reduce per capita floorspace in both the residential and commercial sectors. By 2050, we assume a regional cap of 40 m^2 per capita for residential floorspace, based on the assumptions in the LED (low energy demand) and SSP1 scenarios from Fishman et al.[70] and Mastrucci et al.[16]. For commercial floorspace we assume a regional cap of 25 m^2 per capita by 2050[71].

Changes in household preferences, along with policies that limit new construction of single-family houses will lead to a higher share of multi-family housing. The proportion of the population living in multi-family houses will increase by 10% across the entire housing stock in 2050, compared to the reference scenario. This is broadly consistent with two other studies[72,73].

Stimulated by policies limiting set-point temperatures and information campaigns, the set-point temperatures in buildings shift to 20 °C (heating) and 25 °C (cooling) by 2050[71,73].

Demand for private vehicles driving within cities decreases, driven by measures such as congestion charges and growing prevalence of remote working. The combination of these measures leads to a 20% reduction in passenger kilometres (pkm) for private cars by 2050 with respect to the reference scenario. This is loosely based on the High Shift Scenario[74], which assumes a 50% reduction in urban vehicle travel compared to their baseline in 2050 in all regions. The High Shift Scenario focuses on urban transport and 'considers what could be if the policies and investments currently in place in the nations with the most efficient urban transport, were replicated throughout the world'[74]. Because by 2050, still a third of the world population is expected to be rural (according to UN projections), and distances travelled are generally longer in rural areas, we assume a lower overall reduction in passenger kilometres than the High Shift Scenario.

Additionally, ride and car-sharing associated with on-demand AV (autonomous vehicles), incentivized carpooling by private operators, Park + Ride and more HOV (high-occupancy vehicle) lanes will increase the number of passengers per vehicle. We assume that the occupancy rate will gradually increase until 2050 by around 40% with respect to the reference scenario. This is in line with results from Akimoto et al.[75], estimating the impact of ride and car-sharing associated with fully autonomous cars.

More bike lanes and pedestrian zones increase the adoption of active modes (bicycles, e-scooters and walking). Improvements in public transport infrastructure, last-mile services and free/lower public transport fares increase the adoption of public transport. We assume that the modal shares, as a percentage of total passenger kilometres (pkm), for the active mode and public transport converge by 2050 to the levels given in Supplementary Table 9, depending on the region. The shares are based on projections from the High Shift Scenario[74], where gradual shifts to public transit and active modes are assumed.

Improvements in road freight logistics reduce road freight transport, measured in tonne kilometres (tkm), by 13.5% in 2050 with respect to the reference scenario, following the Modern Trucking Scenario[76]. The Modern Trucking Scenario is an ambitious road freight scenario laying out a modernization strategy aiming at increased energy security and prevention of climate change with 'rapid adoption of the technological and system-wide measures'.

In the aviation sector, passenger transport is reduced through the introduction of fuel taxes (by abolishing tax exemptions), the implementation of movement taxes such as a frequent flyer levy and development of increased virtual connectivity. This results in higher fuel prices and reduced RPK (revenue passenger kilometres). Following the Green Push Scenario[14], the scenario strives for approximately 30% (international) and 40% (domestic) reductions of RPK on the global level by 2050 with respect to the reference scenario.

Similarly, freight transport is also affected by fuel taxes and movement taxes. In combination with policies that encourage development of local manufacturing and storage, these measures result in a global reduction in revenue tonne kilometres (RTK) of 10% with respect to the reference scenario. This assumption is based on the findings of three studies. One study, based on the Beyond 2 °C Scenario, which is in line with countries' more ambitious aspirations, projects 8% lower freight demand by 2060 with respect to their baseline scenario, primarily driven by diminishing trade requirements in fossil fuels[77]. A second study by Müller–Casseres et al. shows that in a well-below 2 °C SSP2 scenario a substantial portion of fossil energy trade can be avoided (20% by 2050 and 25% by 2100)[32]. A third study by Walsh et al. projects a decrease of over 15% in imported and domestic trade for the United Kingdom, based on their analysis of low carbon futures for shipping from a UK perspective[78].

We assume that speed restrictions in maritime transport (slow steaming shipping) lead to 15% reduction in energy consumption on fleet basis with respect to the reference scenario, based on comprehensive scenarios from CE Delft assuming a 20–25% speed reduction[79]. The assumed speed reduction is also in line with scenario assumptions from Walsh et al.[78].

Further, we assume phase out of short-haul air travel by 2030 by closing the price gap between rail and aviation and policies limiting short-haul air travel[73].

Technology-optimizing strategy. As a result of building codes and standards, energy performance certification, subsidies and incentives, the useful energy intensity per area increases and (average) U-values decrease. The nearly zero-energy buildings (nZEB) level for insulation in new construction, representing the average for the building envelope, will be 0.3 W $m^{-2}K^{-1}$ on average by 2030[80]. Best practice examples of current nZEB values already reach such efficiencies today[81]. Energy savings for renovation are at least 40% by 2030.

Also the ratio between final and useful energy improves by improvements in HVAC (heating, ventilation, and air conditioning)[73]. Conversion efficiency coefficients for air conditioning and heat pumps reach 6.0 by 2100[16,30].

An increased renovation rate, stimulated by subsidies and incentives, leads to a doubling of the current retrofit rate to 2% per year in the global north[82].

We assume that efficiency standards for vehicles and trucks lead to vehicle efficiency improvements (autonomous) of 1.5% per year until 2050. For trucks we assume even higher improvements of 2% per year until 2050.

Efficiency standards result in annual autonomous efficiency improvements of 1.3% per year for new aircrafts and 1.5% per year for new ships until 2050[83,84]. The fleet efficiency improves autonomously as a result of environmental certification for using airports and ports. We assume annual fleet efficiency improvements for new and existing aircrafts and vessels of 0.7% per year for aviation and 1.1% per year for shipping until 2050[83,84].

Electrification-focused strategy. Fuel mandates accelerate electrification in buildings and switching to cleaner heating fuels[73]. By 2030, all new buildings adopt heat pumps, and by 2050, we assume that 70% of space and water heating is electricity based[71,85]. Non-clean heating fuels are phased out by 2050, and new natural gas connections for heating will be banned in the global north by 2030.

Building regulations, along with neighbourhood-based approaches, will promote the deployment of on-site and building-integrated renewable energy systems[73]. By 2050, renewable energy sources (photovoltaics and thermal solar) meet 50% of the heating and cooling demands in the global north.

Fuel/technology mandates ensure full electrification of passenger vehicles and light-duty trucks by 2040. We include both battery electric vehicles and fuel cell electric vehicles in the electrification targets. Because there are much larger hurdles for full electrification of heavy-duty vehicles[76,86], we only assume a phase-out of diesel engines in the fleet of heavy-duty vehicles by 2040.

We assume that electric short-haul planes become available after 2050 (broadly consistent two other studies[73,87]). Further, we assume full electrification of ports (and a reduction of auxiliary engines needed in ships) by 2030. In alignment with this, vessels are adapted to zero-emission berth standards by 2040. This timeline for port electrification is loosely based on a scenario study by Gillingham et al.[88] and the Global EV Outlook[89]. Assuming that ships spend approximately 15% of the time at berth and that 15% of their total fuel consumption is related to the auxiliary engine, we assume that 2.3% of the total fuel consumption can be saved by cold ironing (connecting ships to the onshore power supply). For reference, Bouman et al. report potential CO_2 reductions of 3–10% (ref. 90).

Fuel standards/mandates, infrastructure development and removing blending restrictions increase the use of alternative fuels (biofuels/electrofuels)[73]. Following the Sustainable Development Scenario[91] the share of hydrogen in final energy demand grows to 40% in the aviation sector and to 50% in the shipping sector by 2070. The share of biofuels increases to 15% for both the aviation and shipping sectors.

Model implementation

The scenario implications of the scenarios listed in Table 2 are analysed by seven global IAMs (COFFEE, IMACLIM-R, IMAGE, MESSAGEix-Building, PROMETHEUS, REMIND and WITCH), integrating the high-resolution mobility, transport and buildings modules. A description of the model representation of the transport sector and the buildings sector is shown in Supplementary Tables 1–3 of the Supplementary Materials.

Two models encountered limitations in producing output for both sectors. COFFEE generated exclusively transport-related output variables, whereas MESSAGEix-Buildings was utilized to implement the scenarios for the buildings sector only. To avoid imbalance across sectoral and total results, the results of MESSAGEix-Buildings are left out of calculated averages and ranges. MESSAGEix-Buildings results are visually presented in figures, wherever possible. Moreover, due to limited representation of other sectors, the particular MESSAGEix-Buildings version used here was only able to achieve emissions consistent with 2 °C scenarios.

The implementation of measures largely aligns with existing literature and scenarios previously developed to analyse demand-side mitigation, such as the High Shift Scenario[74], the LED scenario[82] and the lifestyle scenario explored by Van Vuuren et al.[92]. An overview of the implementation of the scenario measures by model is shown in Supplementary Table 4 (activity-focused strategy), Supplementary Table 5 (technology-optimizing strategy) and Supplementary Table 6 (electrification-focused strategy). We have made efforts to harmonize the model implementation of demand-side measures as much as possible across the models; however, some difference remains inevitable. One key distinction in the implementation is that some models use exogenous projections to model changes in energy service (for example, floorspace), whereas other models employ endogenous representations of energy service and change levers, such as preference factors, to attain the desired scenario changes. Next to this, differences in implementations also arise from the fact that some models lack the capability to explicitly represent specific measures.

The scenarios with only current policies implemented consider the current climate- energy- and land-use policies and account for only those that are secured in legislative decisions, executive orders or equivalent[93,94]. No additional measures or plans, for example, regarding Nationally Determined Contributions are considered.

In addition to this baseline, we consider scenarios in which global warming is limited to 1.5 °C with a low overshoot based on estimated carbon budgets from the IPCC's AR6 WG I report[95]. This is implemented in all models through the application of a globally uniform carbon tax, determined by an optimization process for each model and scenario. This tax ensures that cumulative emissions from 2020 onward never exceed 650 Gt CO_2 (peak budget) and that cumulative emissions between 2020 and 2100 are limited to 400 Gt CO_2 (end-of-century budget). Non-CO_2 gases, such as N_2O, CH_4 and F-gases, are priced equivalently to CO_2 using GWP100 (global warming potential over 100 years). Models that cannot achieve the end-of-century budgets aim for the lowest budgets feasible. Also, carbon dioxide removal (CDR) deployment and net-negative emissions are limited; models aim for no more than 250 Gt CO_2 net-negative emissions undercutting the end-of-century budget and aim to not have cumulated CDR (including AFOLU CDR) until 2100 exceed 500 Gt CO_2.

No-interaction estimate

The no-interaction estimate for combined emissions reductions is constructed from the NPi-ACT, NPi-TEC, NPi-ELE and NPi-REF scenarios. This estimate is derived by computing the ratio of CO_2 emissions in each scenario for the year 2050 to the emissions in the reference scenario for the same year:

$$\frac{\text{CO}_2\text{ emissions}_{\text{scenario}}\,(2050)}{\text{CO}_2\text{ emissions}_{\text{NPi-REF}}\,(2050)} \tag{1}$$

The product of these ratios approximates the total relative reduction in CO_2 emissions. This relative reduction is then multiplied by the absolute emission levels of NPi-REF in 2050 to calculate the corresponding absolute emissions when all measures are combined under the assumption of no interaction among the strategies.

Decomposition method

In this study we used the Shapley/Sun decomposition method based on the Laspeyres index to quantify the driving components between the scenarios. This method has the advantage that it is based on the familiar concept of percentage change, making it easier to interpret. Moreover, it can be applied to obtain a perfect additive decomposition, that is, the total difference is allocated to different components and no unexplained residual term appears[96,97].

For the transport sector, the activity levels are expressed in passenger kilometres (pkm), which yields the following equation for direct emissions:

$$\begin{aligned}&\text{CO}_2\text{ emissions}_{\text{direct}}\\&= \underbrace{\text{pkm}}_{\text{activity}} \times \sum_{n\in\text{modes}} \left(\underbrace{\frac{\text{pkm}_n}{\text{pkm}}}_{\text{modal shift}} \times \underbrace{\frac{E_n}{\text{pkm}_n}}_{\text{efficiency}} \times \underbrace{\frac{E_n - E_{\text{electricity},n}}{E_n}}_{\text{electrification}} \times \underbrace{\frac{\text{CO}_2\text{ emissions}_{\text{direct},n}}{E_n - E_{\text{electricity},n}}}_{\text{carbon intensity}} \right)\end{aligned} \tag{2}$$

where pkm denotes the number of passenger kilometres travelled in a year, E the final energy demand in transport and $E_{\text{electricity}}$ the electricity demand in transport. Electrification is treated as a distinct factor, following an approach similar to Edelenbosch et al.[98], measuring the share of electricity in final energy. For simplification, alongside direct emissions, we include only emissions from electricity generation in the decomposition. This yields:

$$\begin{aligned}&\text{CO}_2\text{ emissions}_{\text{electricity}}\\&= \underbrace{\text{pkm}}_{\text{activity}} \times \sum_{n\in\text{modes}} \left(\underbrace{\frac{\text{pkm}_n}{\text{pkm}}}_{\text{modal shift}} \times \underbrace{\frac{E_n}{\text{pkm}_n}}_{\text{efficiency}} \times \underbrace{\frac{E_{\text{electricity},n}}{E_n}}_{\text{electrification}} \times \underbrace{\frac{\text{CO}_2\text{ emissions}_{\text{electricity},n}}{E_{\text{electricity},n}}}_{\text{carbon intensity}} \right)\end{aligned} \tag{3}$$

The factors electrification and carbon intensity are defined differently from the former equation, but they share a similar meaning. Because the level of detail in the buildings sector varies strongly across the IAMs, a detailed decomposition in different end uses is not possible and we use the amount of floorspace as a proxy for activity instead. For the residential sector we use the following equation:

$$\begin{aligned}&\mathrm{CO_2\ emissions_{direct}}\\&=\underbrace{\text{floorspace}}_{\text{activity}}\times\underbrace{\frac{E}{\text{floorspace}}}_{\text{efficiency}}\times\underbrace{\frac{E-E_{\text{electricity}}}{E}}_{\text{electrification}}\times\underbrace{\frac{\mathrm{CO_2\ emissions_{direct}}}{E-E_{\text{electricity}}}}_{\text{carbon intensity}}\end{aligned}\quad(4)$$

where floorspace denotes the average floorspace used per capita, E the final energy demand in the residential sector and $E_{\text{electricity}}$ the electricity demand in the residential sector. Similarly, this yields for emissions from electricity generation for:

$$\begin{aligned}&\mathrm{CO_2\ emissions_{electricity}}\\&=\underbrace{\text{floorspace}}_{\text{activity}}\times\underbrace{\frac{E}{\text{floorspace}}}_{\text{efficiency}}\times\underbrace{\frac{E_{\text{electricity}}}{E}}_{\text{electrification}}\times\underbrace{\frac{\mathrm{CO_2\ emissions_{electricity}}}{E_{\text{electricity}}}}_{\text{carbon intensity}}\end{aligned}\quad(5)$$

The components are not independent from each other. For example, subsidies for electric vehicles can lead to modal shifting, more electrification, higher efficiency and potentially higher activity. Caution is needed when interpreting results from two separate decompositions. Similar changes in specific components (for example, activity levels drop by 10%) may not necessarily result in identical magnitudes for those components. This is because interactions with other components (such as efficiency) can lead to varying magnitudes for the attributed change within different decomposition contexts.

Data availability

Scenario output data are available directly from the IIASA NAVIGATE database at https://data.ece.iiasa.ac.at/navigate.

Code availability

Extensive documentation of integrated assessment models is available at https://www.iamcdocumentation.eu/. The source code for some models is available directly from their developers. Custom code for plotting (including post-processing steps implemented for decomposition analysis) can be provided upon request.

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R.v.H., O.Y.E., G.L., A.M., B.v.R., R.S., S.Y. and D.v.V. conceived and designed the experiments. R.v.H., V.D., T.L.G., L.B.B., A.D.B., F.P.C., J.E., P.F., R.H., J.H., P.K., F.L., J.L., G.M., A.M., R.P., P.R. and E.Z. performed the experiments. R.v.H., O.Y.E., V.D., T.L.G., L.B.B., A.D.B., F.P.C., J.E., P.F., R.H., J.H., P.K., F.L., J.L., G.M., A.M., R.P., P.R. and E.Z., analysed the data. R.v.H., H.P. and C.W. contributed materials/analysis tools. All authors wrote the paper.

Competing interests

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Additional information

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