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

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Supplementary Information

S1. Model representation of demand-side sectors

This section provides an overview of how demand-side sectors are represented in the models used in this study , as well as how the different scenarios are implemented. Table S1 cover the key model characteristics. Table S2 and Table S3 outline the representation of the buildings and transport sectors. Table S4, Table S5 and Table S6 describe the implementation of the three policy strategies. Additional detailed documentation of the IAMs is available at https://www.iamcdocumentation.eu/.

Table S1: Overview of the models involved in the study.

	COFFEE	**IMACLIM-R**	**IMAGE**	**MESSAGEix-Buildings**	**PROMETHEUS**	**REMIND**	**WITCH**
Institution	COPPE	CIRED	PBL	IIASA	E3M	PIK	CMCC
Solution method	Perfect foresight optimization	Recursive dynamic simulation	Recursive dynamic simulation	Forward-looking LP	Recursive dynamic Simulation	Nested Weibull-based choice model	Perfect foresight
Model concept	Partial equilibrium	Multi-sectoral computable general equilibrium	Partial equilibrium	Partial equilibrium	Partial equilibrium	Partial equilibrium	General Equilibrium
Model approach	Bottom-up	Hybrid	Hybrid	Bottom-up	Top-down	Top-down	Hybrid
Base year	2010	2014	2018	2015	2015	2015	2015
End year	2100	2100	2100	2100	2050	2100	2100
Time step (years)	5-10	1	1	5-10	1	5-10	5
Coverage	Global	Global	Global	Global	Global	Global	Global
Regions	18	12	26	60	10	12	17

Table S2: Key features and dynamics in building sector models. For models that distinguish between the subsectors, these are labeled as R (Residential) and C (Commercial).

Model	Building stock representation	Relevant additional model dimensions (explicitly modeled)	Floorspace projections	Stock-turnover	Energy efficiency improvements and household renovation decisions	Ref.
COFFEE	Aggregated (measured in built area)	-	Exogenous	Simplified and exogenous	Constrained optimization with technology options for energy conversion and simplified representation of other efficiency options	[1]
IMACLIM-R	**R**: 3 building types **C**: none	-	**R**: endogenous, driven by regional income growth, preferences, population growth **C**: none	**R**: Explicit flows and dynamics **C**: None	**R**: logit function to choose between different standards for new construction and renovation **C**: exogenous and autonomous trend of energy efficiency improvement and fuel switching.	[2,3]
IMAGE	**R**: tracked as an aggregate of building types, technology and efficiency choices; 6 insulation levels **C**: none	**R**: climatic zones, urban/rural, 5 household income quintiles.	**R**: endogenous, related to GDP and population density. **C**: none	**R**: dynamic stock modelling based on changes in floorspace requirement; Material Flow Analysis (MFA) **C**: none	**R**: discrete choice for insulation decisions; possibility to renovate insulation levels, heating and cooling appliances; constraints on minimum lifetime of capital **C**: aggregate improvements according to scenario narrative	[4]
MESSAGEix-Buildings	**R-C**: 7 building archetypes	**R-C**: 20 climatic zones, urban and rural areas **R**: 3 household income tertiles, tenure	**R**: exogenous by country, urban/rural, and housing type. **C**: endogenous, related to GDP.	**R-C**: dynamic material flow analysis (MFA)	**R**: discrete choice models for energy efficiency decisions. **C**: exogenous projections.	[5]
PROMETHEUS	None	-	Exogenous driven by GDP and income	None	Improvement of aggregated U-value according to scenario specifications	[6]
REMIND	None	-	Driven by income and population density; scenario-dependent reduction of historic elasticities for future	None	Improvement of aggregated U-value	[7]
WITCH	Building vintages		Driven by income, population and scenario assumptions	Tracking of new constructions and renovation by building vintage	Improvement of U-value by building vintage	[8]

Table S3: Overview of the transport sector representation in the models.

Model	Passenger travel modes	Freight modes	Key model concept	Main drivers	Ref.
COFFEE	Non-motorized, LDV, bus, trains, motorcycles, three-wheels, aircraft	International ship freight, light truck, medium truck, heavy truck, rail freight	Price elasticity for demand; constrained optimization	Population, GDP	[1]
IMACLIM-R	Non-motorized, cars, terrestrial public transport, and aircraft	Maritime, air and terrestrial	Utility maximization under travel time- and money-budgets (passenger); constant input-output coefficient (freight)	Population, household incomes (and preferences), energy costs and prices, infrastructure investments, trade and production volume (for freight)	[2]
IMAGE	Walking, cycling, bus, train, LDV, HST, aircraft	Ship freight, international ship freight, medium truck, heavy truck, rail freight, air freight	Constant travel time- and money-budget (passenger); constant elasticity of IVA (freight)	Population, GDP, IVA, energy prices, regional preferences	[9,10]
PROMETHEUS	LDV, aircrafts, other	Trucks, ship freight, other	Transport activity is driven by VA, income and price elasticities. Logit functions drive technology adoption and substitution.	Population, GDP, energy prices, regional preferences and inconvenience costs	[6]
REMIND	Walking, cycling, bus, train, LDV, HST, aircraft	Truck, ship, train	Transport activity is driven by income and price elasticities. Weibull-based choice function is used for technology adoption and substitution.	Population, GDP, energy prices, regional preferences, inconvenience costs and policies	[11]
WITCH	LDV, aircraft	Trucks, air freight, ship freight	Trade amount and passenger-kilometer demand	Population, GDP, energy prices	[8]

Table S4: Scenario implementation of the activity-focused strategy.

		COFFEE	IMACLIM-R	IMAGE
Buildings	*Floorspace reduction*	Changes in demands which are correlated to additional floorspace in the model.	Changes in household preferences and aspirations in terms of floorspace per capita.	Floorspace demand is linked to GDP growth, population density and regional parameters. Maximum floorspace limits set exogenously.
	Multi-family houses	-	-	Exogenous share of SFH/MFH.
	Temperature set points	Changes in demands which are correlated to temperature setpoints in the model.	-	New temperature set points adjust CDD and HDD, which are linked to endogenous changes in global mean temperature.
Land-based transport	*Less driving private vehicles*	Adjusted some constraints to enable higher public transport penetration and other transportation means, along with modifying demand based on changes in user preferences.	Change in preferences (decreasing the budget share dedicated to transportation) and infrastructure policies (lower impact).	Preference factors for cars are reduced. Overall travel demand is exogenously reduced with a constant factor.
	Improved freight logistics	Adjustments to our input data assumptions for freight transport and integrating these adjustments into our model.	Decreasing input-output coefficient of road freight in intermediary consumptions.	Exogenous reduction of total freight transport with a prescribed factor.
	Adoption of active modes and public transport	Adjusted some constraints to enable higher public transport penetration and other transportation means, along with modifying demand based on changes in user preferences.	Change in preference (i.e., decreasing share of expenditure dedicated to transport) and implement a set of change in transport infrastructures policies, notably in favor of public transport (but not only).	Preference factors are adjusted in the decision module. Time spent on travel is increased. Money spent on travel is reduced for higher incomes
	Car sharing	Capacity factor is increased for cars.	Increasing occupancy rate in cars.	Capacity factor is increased for cars.
International transport	*Reduced international travel*	Exogenously reduced international travel after 2030 by 10%.	Change in preferences (decreasing the budget share dedicated to transportation).	Higher fuel taxes.
	Reduced freight transport	Adjustments to our input data assumptions for freight transport and integrating these adjustments into our model.	-	Higher fuel taxes.
	Improved operations and logistics	-	Decreasing input-output coefficient of road freight in intermediary consumptions	-
	Shift short-haul flights to rail	-	-	Accelerated development of HSR infrastructure. Substitution of short-haul flights by train trips.

		PROMETHEUS	**REMIND**	**WITCH**	**MESSAGEix-Buildings**
Buildings	*Floorspace reduction*	Exogenous projection based on GDP per capita and population.	Floorspace demand is driven by GDP per capita and population density. Maximum floorspace limits are set exogenously.	Floorspace demand is driven by GDP per capita and population density, with exogenously determined maximum floorspace constraints.	Exogenous projections of per-capita floorspace.
	Multi-family houses	Exogenous projection.	No distinction of residential building types.	No heterogeneity in residential buildings type of houses.	Exogenous projections of share multi-family-houses/single-family-houses.
	Temperature set points	Change in thermostat for buildings influencing heating and cooling demand differentiated by region.	Heating and cooling demand is based on CDD and HDD, respectively. The degree-days are calculated with assumed set point temperatures.	Energy service demand for heating/cooling is calculated based on HDD/CDD with different setpoint temperatures (Shift to 20°C HDD; 25°C CDD by 2050).	Energy intensity for heating/cooling of building archetypes calculated using different setpoint temperatures using the variable degree method.
Land-based transport	*Less driving private vehicles*	Change in preferences in favor of public modes of transport.	Change in preferences in favor of public modes of transport.	Reduction in light-duty vehicle kilometer demand up to 20% with respect to reference in 2050, driven by preferences changes for public transport.	*Not implemented*
	Improved freight logistics	Exogenous reduction of total road freight energy service demand.	Exogenous reduction of total road freight energy service demand of 13.5%.	Exogenous reduction in freight vehicle kilometer demand, up to 13.5% in 2050 with respect to reference case.	*Not implemented*
	Adoption of active modes and public transport	Exogenous assumptions for adoption of active modes and public transport.	Change in preferences in favor of active modes.	Reduction in light-duty vehicle kilometer demand, due to modal changes in favor of active modes.	*Not implemented*
	Car sharing	Increase of load factor for private cars by 30%.	Increase of load factor for private cars by 40%.	Reduction in light-duty vehicle kilometer demand driven by an increase in the load factor for passenger cars.	*Not implemented*
International transport	*Reduced international travel*	Exogenous reduction of total aviation energy service demand of 30% (international) and 40% (domestic).	Exogenous reduction of total aviation energy service demand of 30% (international) and 40% (domestic).	Reduction in revenue person kilometer per capita of 30% (international) and 40% (domestic).	*Not implemented*
	Reduced freight transport	Exogenous reduction of total shipping energy service demand of 10%.	Exogenous reduction of total shipping energy service demand of 10%.	Reduction in revenue tonne-kilometers traded of 10%.	*Not implemented*
	Improved operations and logistics	Higher energy efficiency for shipping fleet.	Higher energy efficiency for shipping fleet (15%).	Reduction in shipping fuel consumption of 15%.	*Not implemented*
	Shift short-haul flights to rail	Strong change in preferences away from domestic aviation.	Strong change in preferences away from domestic aviation.	*Not implemented*	*Not implemented*

Table S5: Scenario implementation of the technology-optimizing strategy.

		COFFEE	**IMACLIM-R**	**IMAGE**
Buildings	*Improved insulation*	Changes in demands which are correlated to the topic, impacting household space heat and/or cooling.	Included in the whole energy efficiency improvement. [Logit function to choose between three types of buildings for the building stock to be refurbished or built (standard, low energy and very low energy). Energy prices (including taxes) and an amount of investment are taken into account. An increased renovation rate can be exogenously ordered.]	Investments into 6 different insulation levels. Based on costs of (i) investments (ii) savings in heating/cooling. For renovation, remaining lifetime of building also taken into account.
	Improved HVAC (new construction and renovation)	Technological shift towards higher efficiency technologies.	Idem, as efficient building types are mostly or fully supplied by electricity	Efficiency changes in heating/cooling technologies.
	Increased renovation rate	-	Represented through (1) exogenous "boost" in maximum renovation pace (e.g., due to household sensitization, incentives); (2) lower investment costs for the most efficient building (e.g., due to subsidies)	Investments for renovation depend on the economic competitiveness of higher insulation rates. This can be promoted via (i) subsidies, (ii) Increasing energy costs, (iii) decrease discount rates.
Land-based transport	*Vehicle efficiency*	Technological shift towards higher efficiency vehicles.	Higher speed of energy efficiency improvements.	Prescribed efficiency improvements
International transport	*Vehicle efficiency*	Technological shift towards higher efficiency vehicles.	-	Prescribed efficiency improvements
	Fleet efficiency	Improvements in fleet efficiency.	New energy efficiency improvements or acceleration of these improvements.	Prescribed efficiency improvements

		PROMETHEUS	**REMIND**	**WITCH**	**MESSAGEix-Buildings**
Buildings	*Improved insulation*	Modelled through a logit function based on costs of different options and on climate conditions. Insulation can be additionally pushed through subsidies or carbon pricing.	Aggregated U-value for the building stock, baseline decrease over time driven by climate (HDD + CDD) and GDP/cap, additional push through lower limit of long-term U-values and faster speed of decline.	Explicit representation of the building stock development over time, affected by construction and demolition cycles, along with a thermal insulation investment module. U-value calculation is related to regional climate, income levels and optimal investment in building insulation. Minimum energy saving for renovation are set for different insulation options.	Residential: Discrete choice model to represent household decisions on insulation in new construction and renovation based on life cycle costs. Commercial: Penetration of buildings with improved insulation exogenously given.
	Improved HVAC (new construction and renovation)	Based on renovation costs and consumer preferences and the Rate of Return (RoR) on renovation which changes with climate policies (e.g., carbon pricing).	End-use efficiencies of AC and electric space heating in the stock approach exogenous target values with increases in GDP/cap; these targets are increased in the TEC scenarios.	Exogenously determined conversion efficiencies of electricity for cooling and heating affect the computation of the final energy from the useful energy requirements. The conversion efficiencies are increased in the TEC scenario.	Residential: Discrete choice model to represent household decisions on heating systems (type and fuels) in new construction and renovation based on life cycle costs. Improvements in conversion efficiency of specific system types exogenously given based on technology learning rates both for heating and cooling. Commercial: Penetration of buildings with improved HVAC exogenously given.
	Increased renovation rate	Exogenous increase of renovation rate in buildings by region. Increased renovation rate can be pushed through various policy instruments (e.g., subsidies or carbon pricing)	No representation of construction or renovation flows, only stock evolution; The U-value parameterization is adjusted to get a similar reduction calculated with a model that explicitly represents the increased renovation activity.	Revised renovation rates boundary assumptions (renovation rate itself is endogenous). Greater subset of building stock eligible for renovation.	Residential: Renovation rates endogenously calculated with a discrete choice model representing household decisions on energy efficiency based on life cycle costs. Constraints are given on minimum renovation rate to force renovation rate increase. Commercial: Renovation rates exogenously given.
Land-based transport	*Vehicle efficiency*	Increased energy efficiency of vehicles.	Vehicle efficiency improvement of 1.5%/yr and for trucks 2%/yr till 2050.	Annual increase in fuel efficiency of 1.5%/year for passenger vehicles, of 2%/year for trucks till 2050.	*Not implemented*
International transport	*Vehicle efficiency*	Increased efficiency of vehicles.	Fleet efficiency annual improvement aircraft 1%/yr; new ship efficiency 1.3%/yr	*Not implemented*	*Not implemented*
	Fleet efficiency	-	- (no stock modeling)	Annual fleet efficiency improvements of 0.7 %/year for aviation and 1.1 %/year for shipping.	*Not implemented*

Table S6: Scenario implementation of the electrification-focused strategy.

		COFFEE	**IMACLIM-R**	**IMAGE**
Buildings	*Electrification*	Technological standards towards household electrification.	The additional switch towards electrification is driven by an exogenous assumption of higher share of electricity in the energy mix of the two most efficient types of buildings (then the choice between building types is driven by the energy prices and building costs).	Electrification of energy services (heating, cooking) depends on competitiveness of electricity-based technologies. Can promote via subsidies, preference factors, or blocking certain technologies.
	On-site/building integrated renewables	Subsidies for rooftop PV.	-	Rooftop PV. Investment rate depends on costs vs price of electricity and a rooftop suitability factor reflecting architectural constraints.
	Heating fuel switching (non-clean fuels phase-out)	Constraints to limit/accelerate non-clean fuels phase-out are used.	More optimistic assumptions are considered in the "non-clean fuel phase-out" module also available in all scenarios (lower triggering fuel price, and quicker phase-out).	Market shares of fuels to meet cooking/heating demand based on relative costs (capital + fuel costs).
Land-based transport	*Electrification of vehicles*	Technological standards towards transport electrification are used.	Logit function.	Preferences are endogenously adjusted to meet the targets.
	Electrification of trucks	Technological standards towards transport electrification are used.	New electrification options for road freight.	Preferences are endogenously adjusted to meet the targets.
International transport	*Electrification (planes and ports)*	-	New electrification options for air and shipping sectors.	Exogenous fuel reduction by cold ironing.
	Alternative fuels (biofuels/electrofuels) (drop-in or full)	Limited fossil fuel use in international shipping.	-	Preference for new ships and planes are endogenously adjusted to meet hydrogen and biofuel targets. Cryoplanes and improved bio-planes become available.

		PROMETHEUS	**REMIND**	**WITCH**	**MESSAGEix-Buildings**
Buildings	*Electrification*	Endogenous based on additional push for heat pumps.	For each end use, carrier shares in final energy approach exogenous target values over time. The target share of electricity and the speed of approaching it are increased.	Increasing shares of heat pump adoption and of electrification of space and water heating are set by an exogenous change in the target energy carrier share for each service in new buildings.	Revised U-values assumptions.
	On-site/building integrated renewables	No representation of on-site renewables (apart from heat pumps).	No representation of on-site renewables (apart from heat pumps).	No representation of on-site renewables (apart from heat pumps).	Revised final-useful energy coefficients.
	Heating fuel switching (non-clean fuels phase-out)	Endogenous, based on additional push for clean fuels and phase-out of fossil boilers.	Non-clean heating fuels are the first to be phased out with increase in GDP/cap (energy ladder); a full phase-out until 2050 is forced.	Explicit fossil fuels phase-out assumptions, set though the target energy carrier share for all buildings end-uses. When not reached endogenously, the target phase out is imposed exogenously.	Revised bounds for renovation rates (renovation rate itself is endogenous). Greater subset of building stock eligible for renovation.
Land-based transport	*Electrification of vehicles*	Endogenous, based on technological progress of EVs. In addition, ICE bans can be imposed.	ICE ban via inconvenience cost.	Explicit phase-out of ICE light-duty vehicles, after 2040 only battery electric vehicles are allowed.	*Not implemented*
	Electrification of trucks	Endogenous based on technology progress of EVs.	Change in preferences in favor of BETs.	Explicit phase-out of ICE freight vehicles, after 2040 only battery electric trucks are allowed.	*Not implemented*
International transport	*Electrification (planes and ports)*	Exogenous assumptions while bans on fossil technologies can be imposed.	-	*Not implemented*	*Not implemented*
	Alternative fuels (biofuels/electrofuels) (drop-in or full)	Based on assumptions for biofuel mix and blending mandates. Hydrogen becomes available after 2035.	Hydrogen planes become available. Endogenous increase of biofuel shares.	Lower bounds on share of hydrogen and biofuels for aviation and shipping demand.	*Not implemented*

S2. Stakeholder survey

We distributed a survey to stakeholders who have a unique expertise in areas important for scenario development for IAMs: mobility, international transport, buildings, industry, agriculture, and food consumption. The list of stakeholders was collected from a variety of channels: suggestions from all contributors to the NAVIGATE project, including the European Climate, Infrastructure and Environment Executive Agency (CINEA), and individuals who had subscribed to the NAVIGATE newsletter. The survey asked them to rate different narratives and measures regarding their feasibility and expected impact on reducing emissions. The survey also contained questions about impacts on inequality by climate impacts and policies like carbon revenue redistribution schemes, as well as questions about socio-economic trends and structural changes of the economy. The stakeholder survey was sent out in December 2021. Out of the stakeholders contacted, 30 responded, though not all of them answered every question.

The results of the survey are summarized in Table S7 and Table S8. The narratives that experts were asked to rate on consistency and relevance are:

1. *Consumer, lifestyle driven transition*
   Awareness on environmental issues result in a consumer, lifestyle driven transition. Community and neighborhood initiatives allow for comprehensive refurbishments, on site electricity generation and the constitution of energy communities that improve the affordability of these long-term investments. The bottom-up movement creates broader awareness, changing habits and voting preferences where policy further incentivizes the transition (e.g., through financial initiatives, labelling, R&D investments, improved bike lanes and rail connectivity, city planning). Increased digitalization and urbanization provide the infrastructure to share services (such as appliances, spaces and rides), reduce travel distances but also share knowledge and experiences. High quality products are more valued with long lasting design, availability of spare parts and repair services.
2. *Technology, regulated transition*
   Legally binding international agreements pressure policy makers to enforce reduction measures through a regulated technology-driven transition, with limited changes in citizen behavior to maintain public support. An all-electric transition of public transport and private cars takes place, incentivized by emission standards, and the roll out of fast charging points throughout urban and rural areas. Mandatory building standards, new construction codes combined with subsidies result in large scale implementation of high-performance insulation and deep renovation. Tariff schemes that index energy markets results in hourly changes in energy prices incentives the installation of smart meters and efficient energy use. There is a harmonized implementation of aviation technology standards and distance-based air-passenger taxes across all countries.

Table S7: Results from the stakeholder survey. In the stakeholder survey expert stakeholders were asked to rate measures on feasibility and decarbonization impact. The five rightmost columns show how many expert stakeholders rated the feasibility and decarbonization impact of measure as very low, low, medium, high and very high respectively.

Area	**Measure**	**Aspect**	**Score**				
			Very low	***Low***	***Medium***	***High***	***Very high***
Mobility: mitigation options	Reduced private vehicle activity within cities: Congestion charge, higher fuel taxes, free/lower public transit, high occupancy vehicle lane (HOV lane), providing mobility service on a per-use basis, increase accessibility	Feasibility	1	4	6	7	10
		Decarbonization impact	1	5	5	12	5
	Increased adoption of active mode (bicycles, e-scooters, walking): bike lanes, pedestrian zones	Feasibility	0	4	7	9	8
		Decarbonization impact	0	9	4	12	3
	Shared car fleets increasing capacity factors: HOV lane, incentivized carpooling by private operators (e.g. Uber pool), park and ride	Feasibility	1	6	8	9	4
		Feasibility	2	7	11	5	3
	New clean vehicle technologies (EV, H2FCV) for vehicles and trucks: Subsidies to the costs of vehicle purchase, infrastructure policy (incentives, mandates, R&D, government roll out), CO2 tax, vehicle emission standards	Decarbonization impact	0	3	8	10	7
		Feasibility	0	4	5	15	4
	Vehicle efficiency: Vehicle efficiency standards for cars and trucks	Decarbonization impact	0	2	9	10	6
		Feasibility	1	4	11	9	3
	Increased used of shared on-demand alternative fueled vehicles: Congestion charge, higher fuel taxes, Mobility as a Service (MaaS)	Feasibility	0	5	13	7	3
		Decarbonization impact	2	8	12	4	2
	Reduced transport activity as a result of increasing remote working: Congestion charge, higher fuel taxes	Feasibility	0	1	8	10	9
		Decarbonization impact	0	7	9	7	5
	Increase urbanization: Urban infill policies	Feasibility	1	9	10	5	3
		Decarbonization impact	1	9	13	3	2
International transport	Reduction of transport activity: Fuel taxes (abolition of exemption), movement taxes, development of virtual connectivity, alternative tourism, local supply chains (local manufacturing and storage), remote working	Feasibility	3	3	10	9	3
		Decarbonization impact	3	1	8	12	4
	Shifting from aviation (high-speed) rail: Rail and road infrastructure development and connectivity, close price gap between aviation and rail, reduced business trips with aviation (teleworking and teleconferencing)	Feasibility	0	4	11	11	2
		Decarbonization impact	1	2	10	11	4
	Operational and logistic improvements: Maritime speed	Feasibility	1	3	8	11	5

	restrictions, airline operation or air traffic control 2)	Decarbonization impact	3	8	7	7	3
	Improved vehicle efficiency: Efficiency standards, carbon or fuel taxes, aircraft design such as weight reduction, improved aerodynamics	Feasibility	0	3	2	19	4
		Decarbonization impact	0	8	7	8	5
	Improved fleet efficiency: Environmental certification for using airports & ports	Feasibility	0	4	9	10	3
		Decarbonization impact	1	7	13	4	2
	Increased use of biofuels, electro fuels (drop-in or full): Fuel standards, fuel mandates, infrastructure development for fuel production and supply, effective implementation of blending restrictions, CO2 taxes/ participation in ETS	Feasibility	0	3	12	7	6
		Decarbonization impact	3	6	8	6	5
	Shift to electric (hybrid): R&D investment, environmental certification for using airports & ports (Zero-emission berth standards), subsidies for purchase, infrastructure policy (incentives, mandates, R&D, government roll out), CO2 tax, vehicle emission standards	Feasibility	0	7	7	8	6
		Decarbonization impact	1	1	9	11	6
Buildings	Reduction of residential floorspace: Co-housing, provision/ promotion of shared spaces (e.g., for washing), tracing of second homes, ban of commercial use, urbanization or shift to smaller dwellings	Feasibility	4	11	4	4	4
		Decarbonization impact	4	3	13	5	2
	Rehabilitation of unused/vacant spaces: Tax relief, assistance for new functions	Feasibility	1	4	12	6	4
		Decarbonization impact	3	4	12	5	3
	Rehabilitation of unused/vacant spaces: Tax relief, assistance for new functions	Feasibility	0	5	8	10	4
		Decarbonization impact	1	8	8	5	4
	Change temperature set points, reduced use of light or appliances: Informational campaigns, disseminations, smart meters with automatic regulations	Feasibility	0	2	4	15	5
		Decarbonization impact	1	5	10	10	0
	Reduction of appliance/consumer goods ownership: Sharing of appliances, development of share apps	Feasibility	5	8	8	5	1
		Decarbonization impact	4	8	9	4	2
	Shift to multi-family houses: New construction codes	Feasibility	4	8	12	2	1
		Decarbonization impact	3	6	14	3	1
	Increased renovation rate: Renovation subsidies, one-stop shops with support for renovation owners	Feasibility	1	3	8	12	2
		Decarbonization impact	2	5	7	9	3
	High performance insulation, full house deep renovation: Mandatory/voluntary standards, information measures, financial initiatives (subsidies, tax relief), subsidies, one stop shops	Feasibility	2	2	7	10	6
		Decarbonization impact	1	2	8	13	3
	Heat pump /electrification, improved HVAC, phase out of non-clean fuels: Mandatory/voluntary standards, information	Feasibility	1	0	4	14	8
		Decarbonization impact	1	1	7	9	9

measures, financial initiatives (subsidies, tax relief), technology assistance, mandatory audits, Limiting or banning non clean fuels, grid development						
Passive cooling (e.g., green roof, design): Information measures, financial initiatives (subsidies, tax relief)	Feasibility	0	1	11	11	3
	Decarbonization impact	0	6	9	11	1
Expansion of district heating/cooling: Financial incentives for grid expansion, obligatory connection to DH in quarters with DH grids	Feasibility	0	5	8	11	3
	Decarbonization impact	0	5	7	13	2
On-site/building integrated renewables: Subsidies, R&D development, Standards	Feasibility	0	3	9	8	7
	Decarbonization impact	0	6	8	6	7

Table S8: Results from the stakeholder survey. In the stakeholder survey expert stakeholders were asked to rate narratives on consistency and relevance. The five rightmost columns show how many expert stakeholders rated consistency and relevance as very low, low, medium, high and very high respectively.

Narrative	**Aspect**	**Score**				
		Very low	***Low***	***Medium***	***High***	***Very high***
Consumer, lifestyle driven transition	Consistency	2	3	4	15	3
	Relevance	1	1	9	13	4
Technology, regulated transition	Consistency	0	5	6	10	6
	Relevance	1	3	7	11	6

S3. Modeling of Current Policies

The Current Policies scenario considers currently implemented climate and energy policies for major economies. The policies are a selection of high-impact policies that are adopted by the government through legislation or executive orders, or are non-binding targets endorsed by effective policy instruments (see also https://climatepolicydatabase.org/). In this context, climate policy on the national level is defined as "the result of climate policy formulation and climate policy implementation that encompasses aspirational goals not secured by legislation, national targets that are secured by legislation, and policy instruments designed to implement these targets"[12]. For the implementation in the models, a harmonized protocol was used that translates all policies into model input indicators, such as CO_2 or final energy reduction[12,13]. It includes the instruments, targets and sectors associated with the policies. To ensure that the protocol reflects and aligns with the national policies in place, the protocol has also been evaluated by national experts.

Where possible, the policy instruments are explicitly included in the models. For example, carbon taxes or fuel-efficiency standards can be explicitly represented by many models. But where this was not possible, it is ensured that the impact on greenhouse gases and energy aligns as closely as possible with the protocol. In cases where it is also not possible to estimate the direct impact of individual instruments, such as for feed-in tariffs or renewable auctions, aspirational policy targets that are endorsed by effective policy instruments are assumed to represent currently implemented policies.

S4. Scenario design

Table S1 illustrates the complete workflow for designing, simulating, and analyzing the scenarios. The process starts with literature evaluation and identification of key measures, followed by scenario creation, and finally, model simulation and analysis.

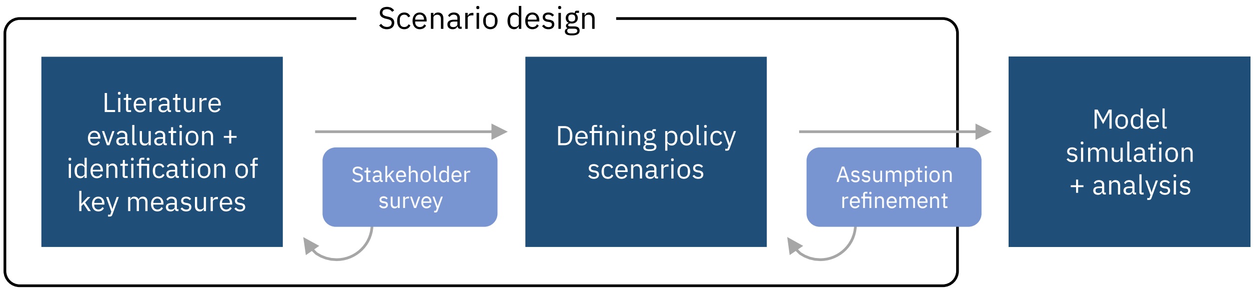

Figure S1: Schematic representation of the scenario development.

Table S9 shows the modal shares for active modes and public transport that are assumed in the ACT-scenario by 2050. These estimates are based on the High Shift Scenario[14], where a gradual increase in the use of public transit and active modes is projected.

Table S9: Assumed modal shares for active modes public transport in 2050 per world region.

	Anglo-America	**Latin-America**	**Europe**	**China**	**India**	**Other Asia**	**Africa / Middle East**
Active modes (% of total pkm)	5	10	10	18	10	15	20
Public transport (% of total pkm)	20	50	50	40	50	55	60

S5. Baseline projections

Activity patterns within the reference (NPi) scenario are provided for all models equipped to generate such projections. Specifically, Figure S2 presents model projections of residential floorspace under the NPi reference scenario. For transport activities, Figure S3 and Figure S4 show projections for passenger-kilometers and tonne-kilometers, respectively.

We compared projections with historical patterns to confirm that the model's emission projections are comparable. Global energy demand for buildings and transport has increased steadily in the past decades, except for a sharp decline in the transport sector during the COVID-19 pandemic. Figure S5 and Figure S6 show the historic trends from the IEA Energy Balances for buildings and transport respectively, alongside the model projections in the default Current Policies scenario. For both sectors, a linear fit to the historical data between 1970 and 2018 is included, and for the transportation sector, an exponential fit is also added.

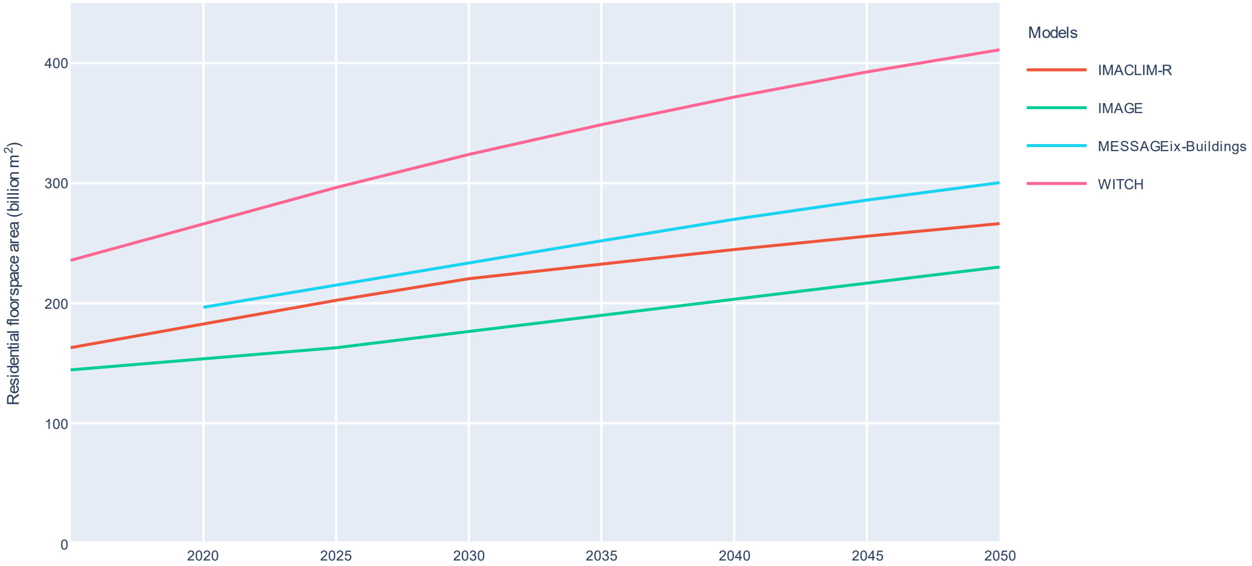

Figure S2: Model projections for residential floorspace area by each model under the reference scenario that considers current national policies.

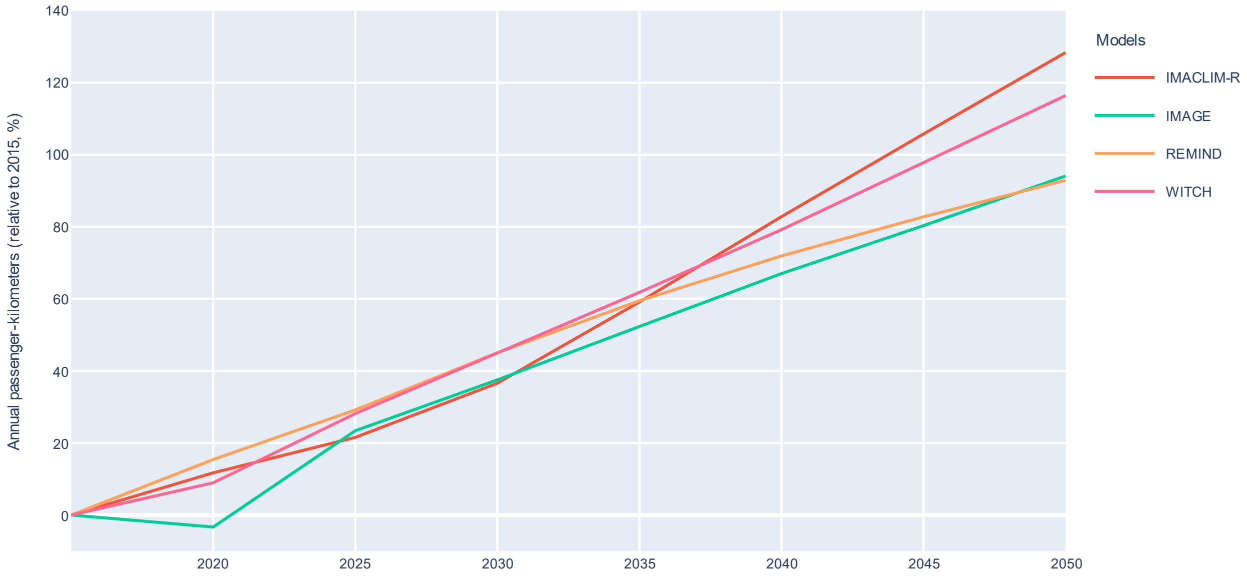

Figure S3: Model projections for annual passenger-kilometers under the reference scenario that considers current national policies.

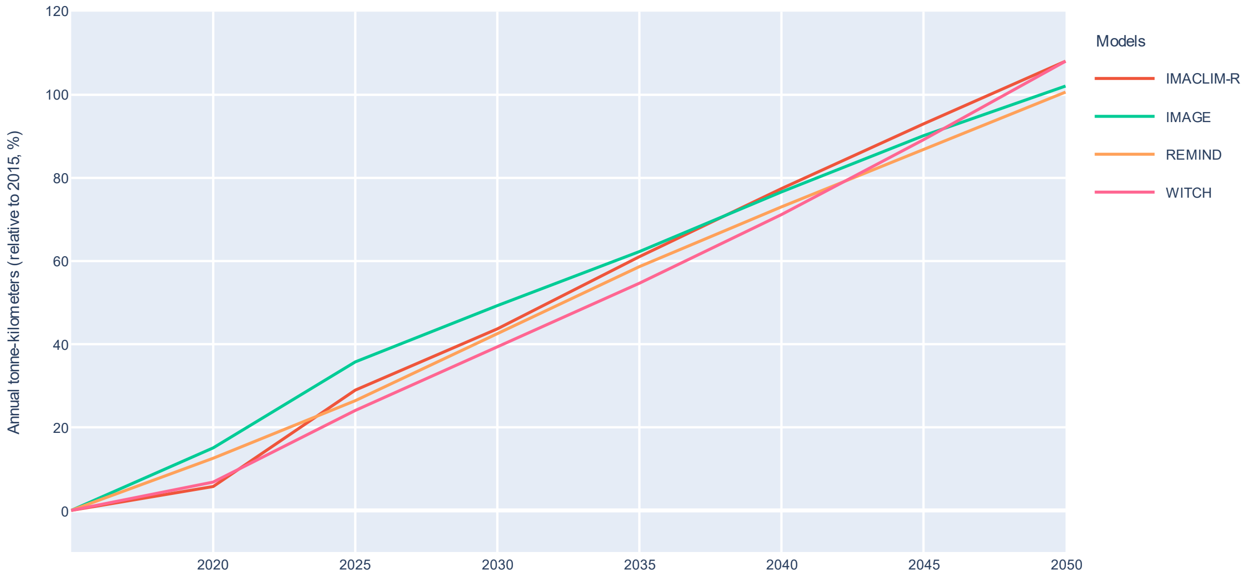

Figure S4: Model projections for annual freight tonne-kilometers under the reference scenario that considers current national policies.

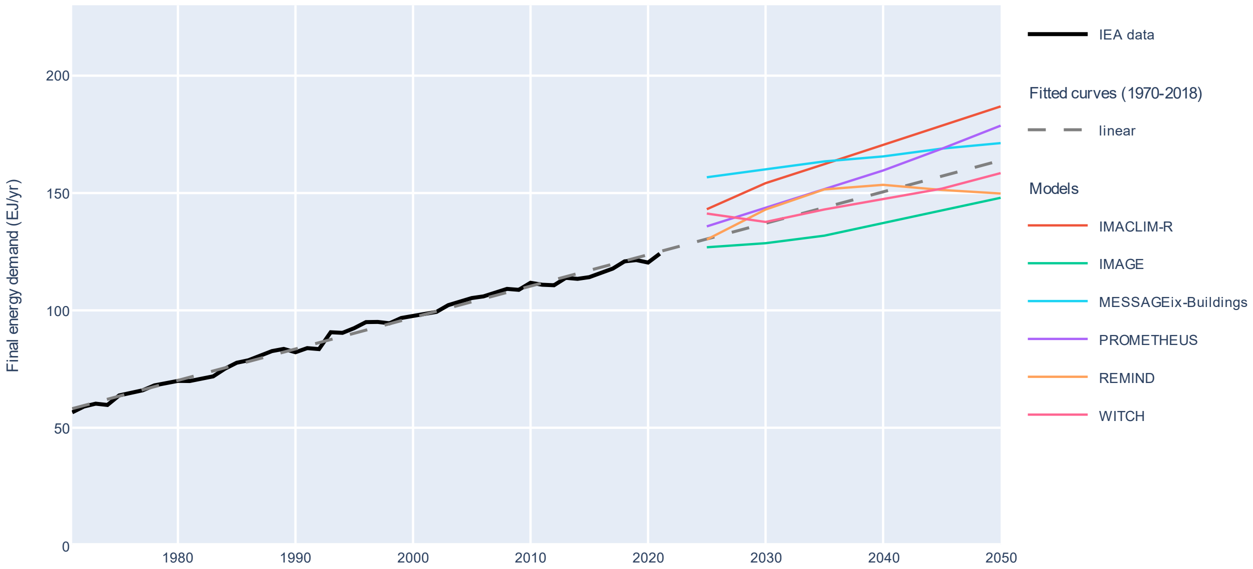

Figure S5: Historic global final energy demand for the buildings sector and its future projections by each model under the reference scenario that consider current national policies.

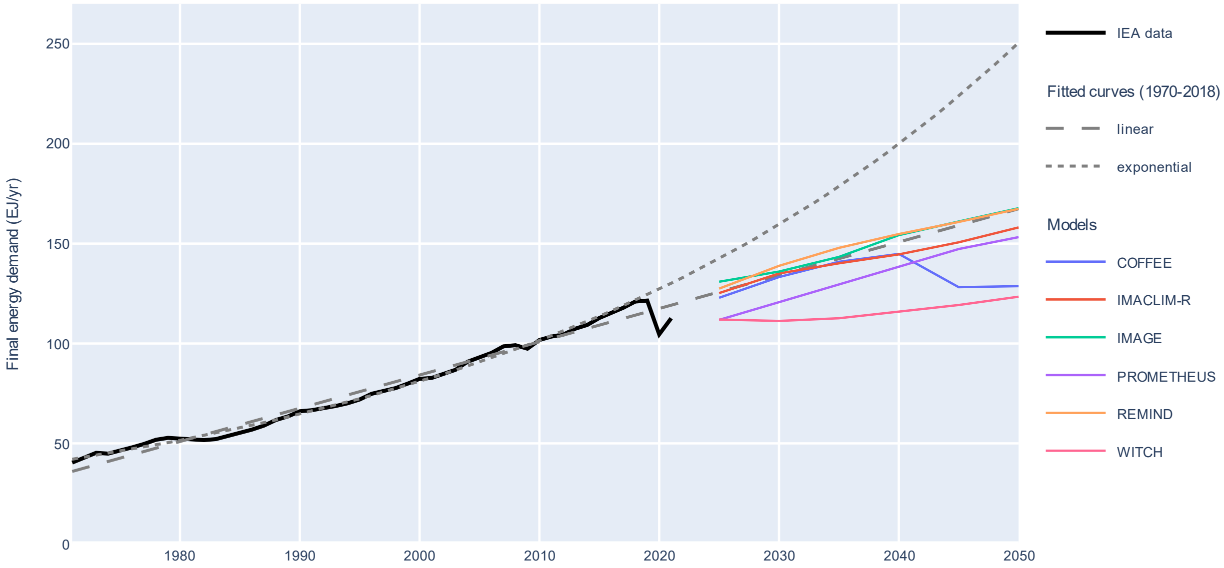

Figure S6: Historic global final energy demand for the transport sector and its future projections by each model under the reference scenario that considers current national policies.

S6. Comparison of CO_2 emissions across scenarios

To show that the ELE strategy consistently yields a greater reduction in emissions compared to implementing each strategy individually (under current policies) across the models, Figures S7-S10 depict the CO2 emissions relative to the REF/ACT/TEC/ELE scenarios. Similarly, the combined implementation of all three strategies (ALL) consistently yields greater emission reductions than the individual strategies. For the scenarios constrained to achieve a 1.5 °C temperature target, the models show varying results regarding the optimal strategy. This can be linked to differences in how models respond to a carbon tax, influencing their selection and deployment of mitigation measures, potentially including demand-side options from our strategies.

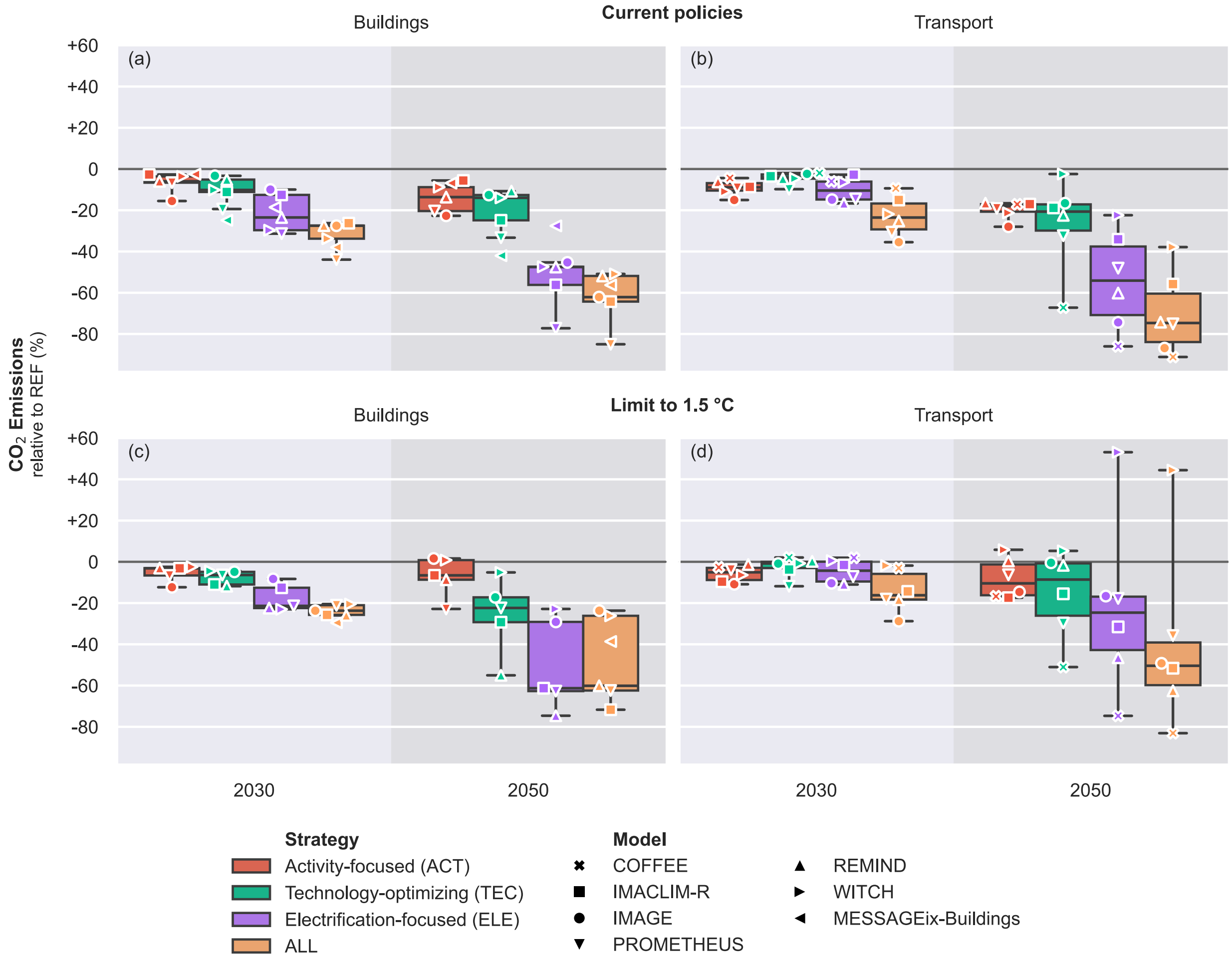

Figure S7: Deviation in global direct emissions for buildings (a, c) and transport (b, d) in 2030 and 2050 for the different intervention strategies, relative to the reference scenario. The upper panels (a, b) show results for implementation under current policies, while the lower panels (c, d) show results under scenarios constrained to achieve a 1.5 ˚C temperature target. Note that the reference scenario differs between the upper and lower panels. 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 with markers, with the boxplots based on data from 5 models for buildings and 6 models for transport. MESSAGEix-Buildings results are shown, but for cross-sectoral consistency not factored into the averages and ranges (see Methods for details).

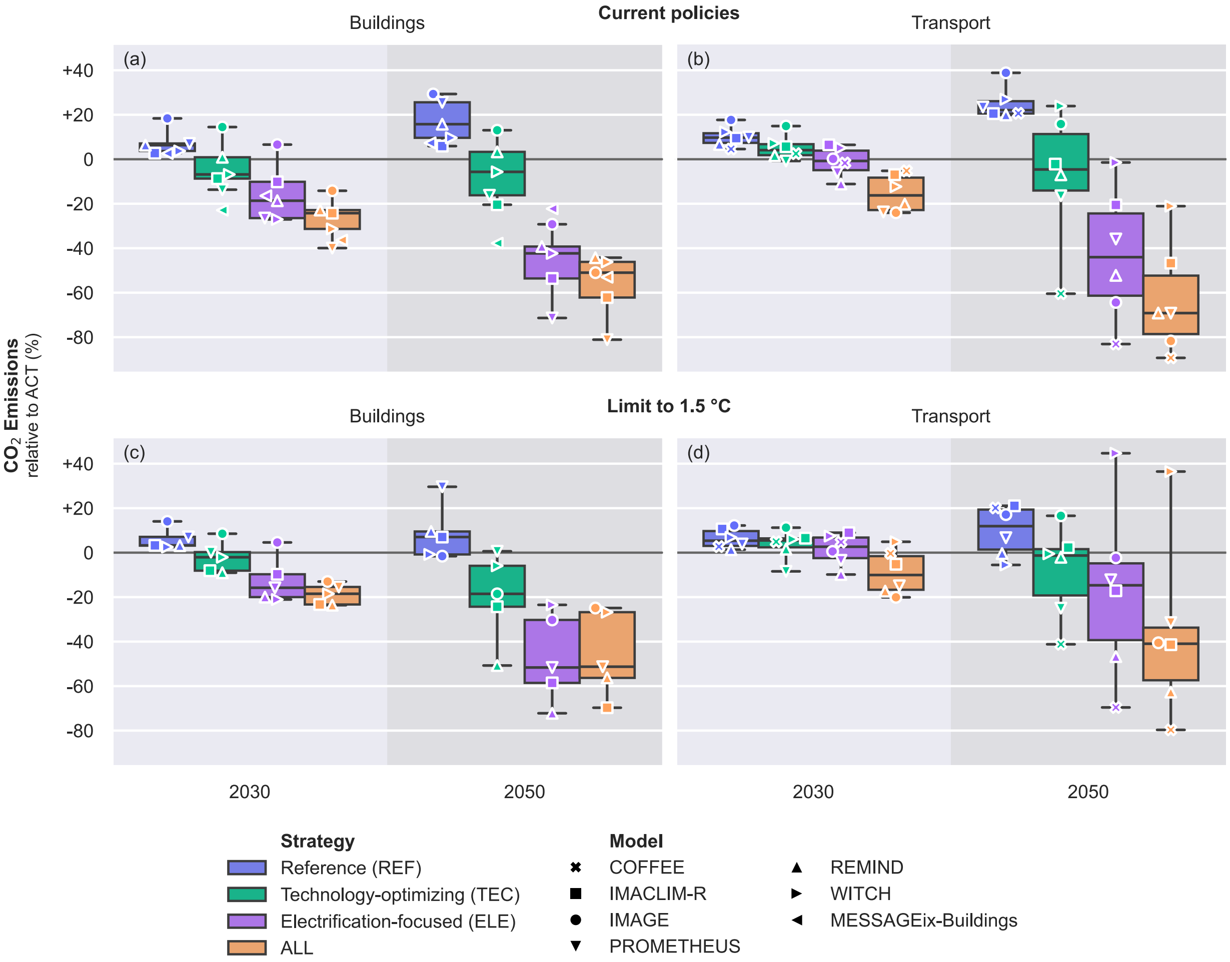

Figure S8: Deviation in global direct emissions for buildings (a, c) and transport (b, d) in 2030 and 2050 for the different intervention strategies, relative to the ACT scenario. The upper panels (a, b) show results for implementation under current policies, while the lower panels (c, d) show results under scenarios constrained to achieve a 1.5 ˚C temperature target. Note that the ACT scenario (and thus the reference point) differs between the upper and lower panels. 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 with markers, with the boxplots based on data from 5 models for buildings and 6 models for transport. MESSAGEix-Buildings results are shown, but for cross-sectoral consistency not factored into the averages and ranges (see Methods for details).

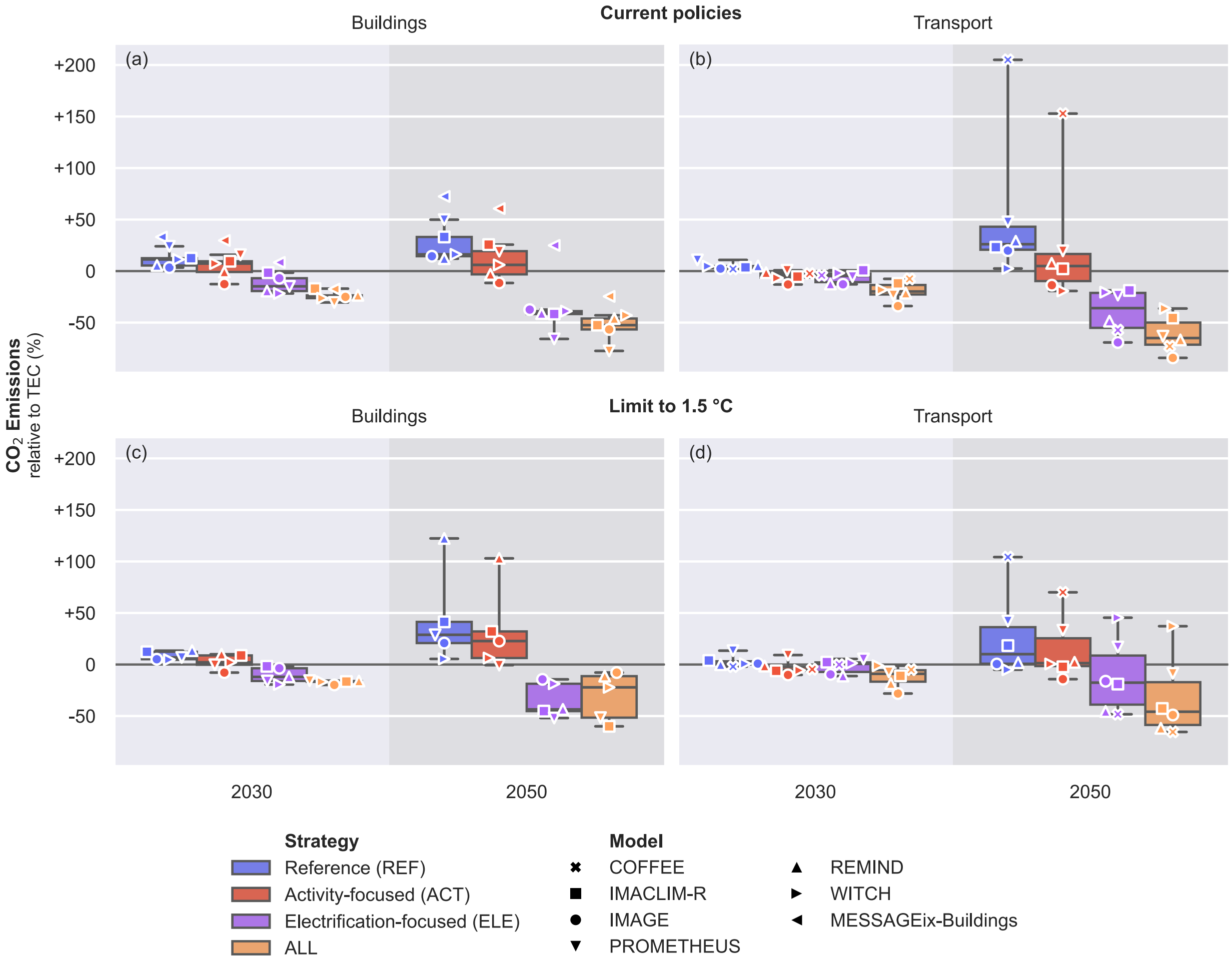

Figure S9: Deviation in global direct emissions for buildings (a, c) and transport (b, d) in 2030 and 2050 for the different intervention strategies, relative to the TEC scenario. The upper panels (a, b) show results for implementation under current policies, while the lower panels (c, d) show results under scenarios constrained to achieve a 1.5 ˚C temperature target. Note that the TEC scenario (and thus the reference point) differs between the upper and lower panels. 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 with markers, with the boxplots based on data from 5 models for buildings and 6 models for transport. MESSAGEix-Buildings results are shown, but for cross-sectoral consistency not factored into the averages and ranges (see Methods for details).

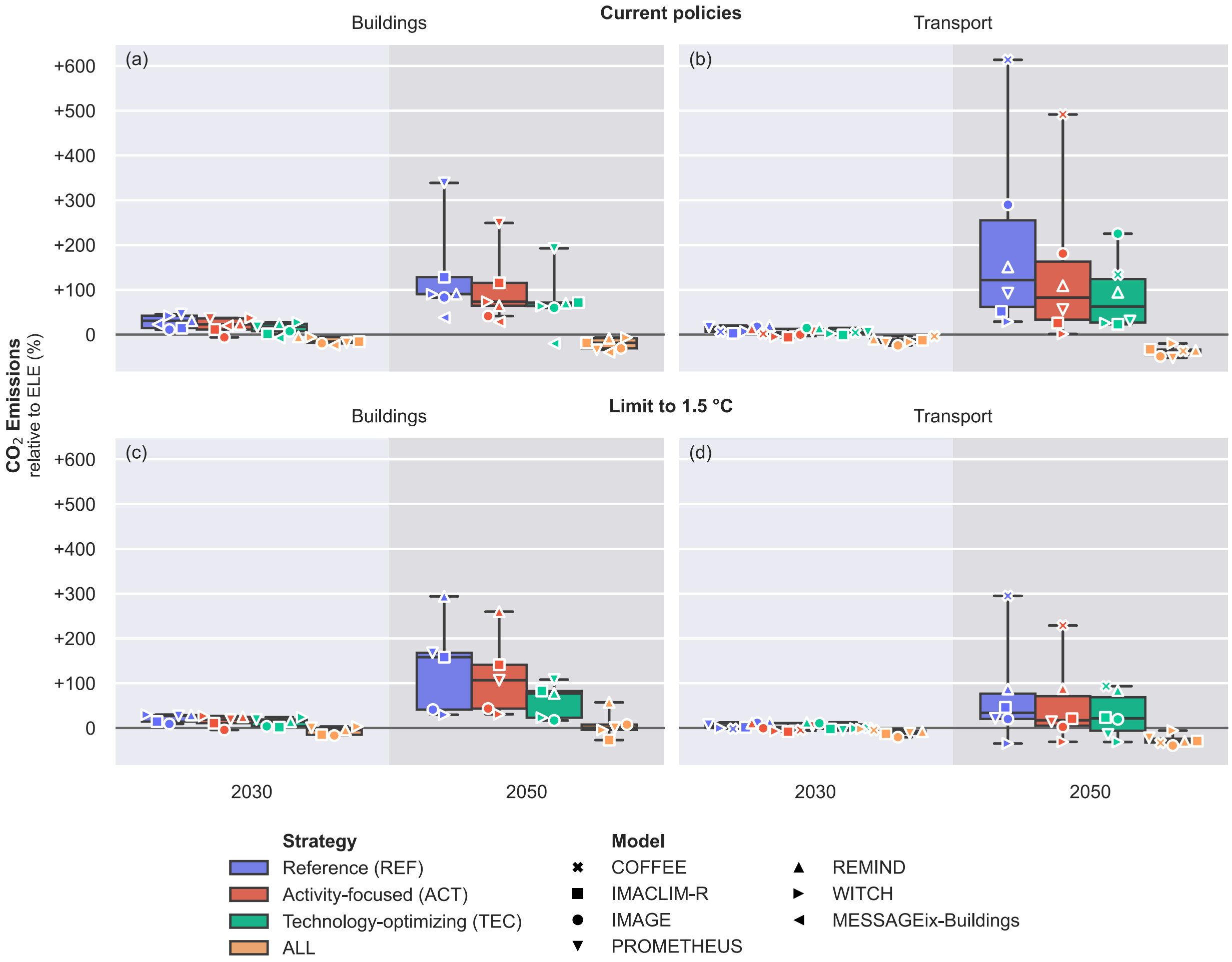

Figure S10: Deviation in global direct emissions for buildings (a, c) and transport (b, d) in 2030 and 2050 for the different intervention strategies, relative to the ELE scenario. The upper panels (a, b) show results for implementation under current policies, while the lower panels (c, d) show results under scenarios constrained to achieve a 1.5 ˚C temperature target. Note that the ELE scenario (and thus the reference point) differs between the upper and lower panels. 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 with markers, with the boxplots based on data from 5 models for buildings and 6 models for transport. MESSAGEix-Buildings results are shown, but for cross-sectoral consistency not factored into the averages and ranges (see Methods for details).

S7. Decomposition analysis

To better understand the interdependence between the strategies, we also decomposed the difference between the reference scenario and the different strategies in 2050 into contributing factors (Figure S11 and Figure S12).

Models that attain larger emission reductions show more emission reductions through efficiency improvements, electrification and the use of alternative fuels such as hydrogen. The latter, for example, results in larger emission intensity reductions for IMAGE. Furthermore, those models tend to have more detailed representations of the transport sector and consider a wider range of mitigation options.

In the activity-focused strategy, reduced travel activity and modal shifting stand out as key drivers for emission reductions. Reduced air travel and private car usage are the main factors reducing emissions, although there is a slight trade-off from increased bus travel. Efficiency changes also contribute to reducing emissions through higher occupancy factors by car sharing and shared buildings spaces. Since the lack of detail in most models does not allow further disaggregation of residential service demand into subcategories such as heating, cooking, the effect of many measures is accumulated under efficiency. Furthermore, less air travel and mode shifts are key to reduce emissions from the aviation sector by 2050. Together with technological improvements, they can significantly reduce the aviation emissions, that still account for a large portion of the remaining emissions in the ALL-scenario.

In the technology-optimizing strategy, efficiency gains are the main driver for emission reductions. Lower travel costs, however, lead to a limited rebound effect due to higher activities and mode shifting. Variation in the estimated scenario impact can, to some extent, be explained by differing assumptions on technological improvements in the baseline. WITCH, for example, shows limited effect of the technology-optimizing strategy since the assumed efficiency improvements over time are relatively close to its baseline assumptions. Another factor in play is the vehicle stock turnover that is modeled differently across models. A more inflexible stock model requires a longer time for efficiency improvements in new vehicles to manifest in the average fleet. Similarly, this affects electrification of the vehicle fleet that plays a major role in the electrification-focused strategy.

Decomposition of the electrification-focused strategy shows that both electrification and fuel shifting (through decreased emission intensity) can play an important role in reducing emissions. Despite the phaseout of internal combustion engines in light-duty vehicles, many models indicate substantial residual emissions from older cars still in the fleet. This underscores the importance to establish timely policy goals.

For the buildings sector, Chapter 9 of the AR6 WG III report (on Buildings)[15] also includes decomposition analyses for several relevant scenarios, similar to our approach.

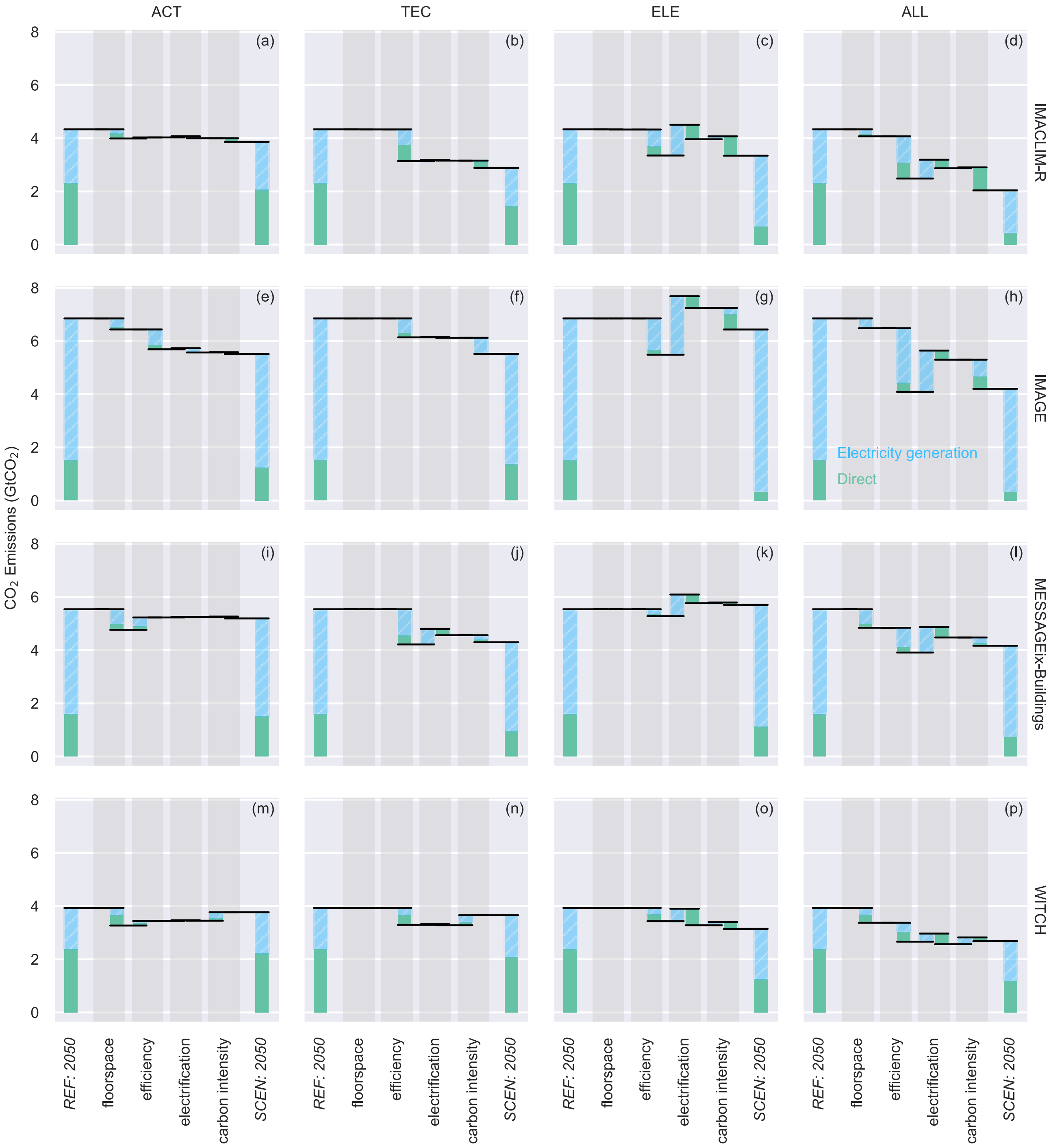

Figure S11: Decomposition of global residential CO_2 emissions for all current policies scenarios. Figures include emissions from electricity generation (hatched). Changes in emissions are attributed to the factors floorspace, efficiency, electrification and carbon intensity. Carbon intensity is the average amount of CO_2 emission per unit energy of fuel combusted or, for emissions from electricity generation, the average emission intensity of electricity generation. Floorspace use serves as a proxy for activity changes since 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.

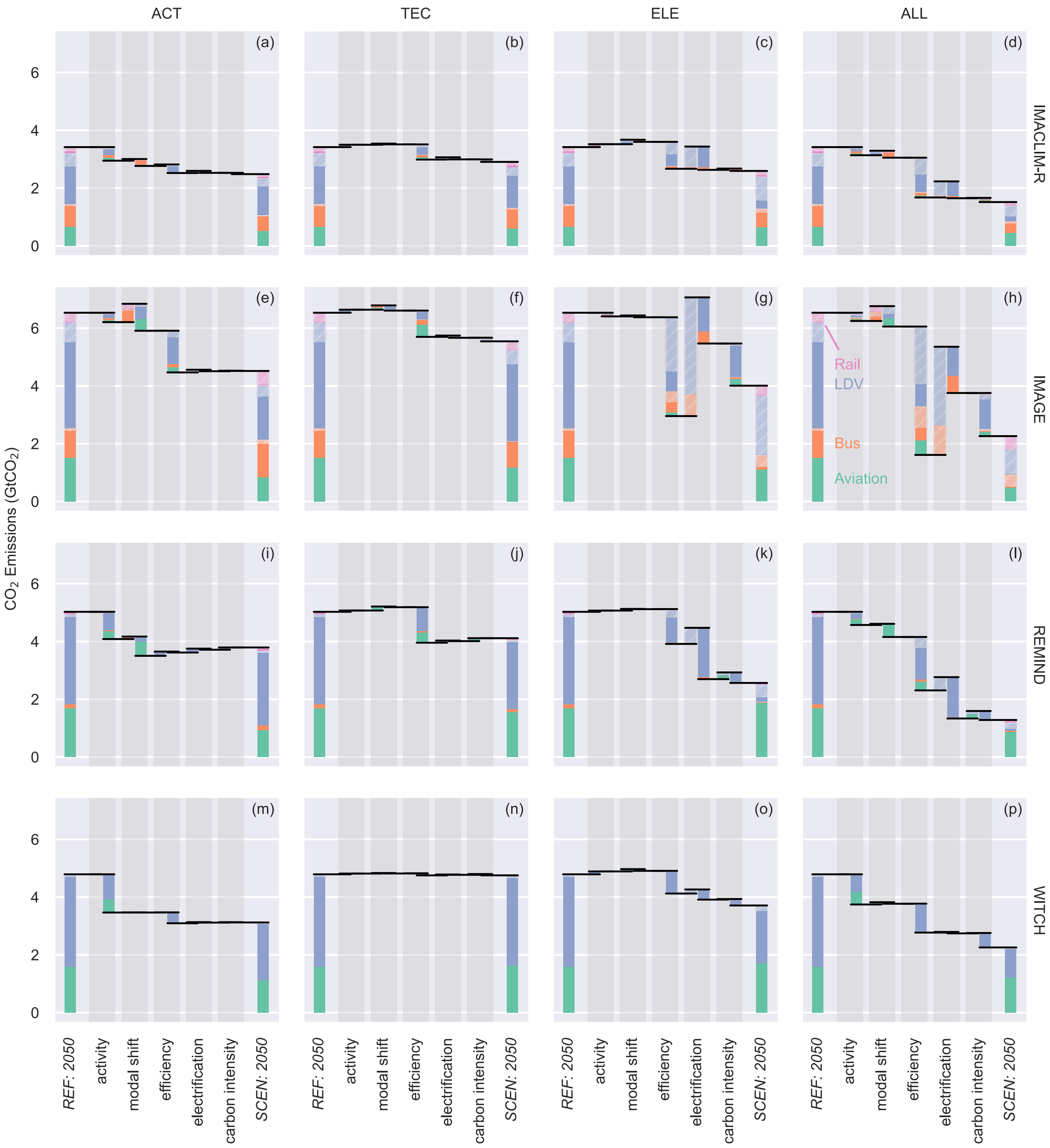

Figure S12: Decomposition of global passenger transport CO_2 emissions for all current policies scenarios. Figures include emissions from electricity generation (hatched). Changes in emissions are attributed to the factors activity, modal shifts, efficiency, electrification and carbon intensity. Carbon intensity is the average amount of CO_2 emission per unit energy of fuel combusted or, for emissions from electricity generation, the average emission intensity of electricity generation. Four modal categories are considered: aviation, bus, light-duty-vehicle (LDV) and rail.

S8. Subsectoral results

A few models offer the capability to disaggregate results into subsectoral projections for final energy and CO_2 emission. Figure S13 shows projections for the residential and the commercial sectors across the five scenarios (NPi) from IMACLIM-R, IMAGE and WITCH. Energy demand in the commercial sector increases more sharply than in the residential sector, yet the growth in emissions in 2050 remains relatively modest in the commercial sector. Notably, with the integration of all three strategies (ALL) in IMACLIM and IMAGE, emissions from residential buildings see a greater decrease than those from commercial buildings.

Figure S14 shows projections for passenger transport and freight transport from COFFEE, IMACLIM-R, IMAGE and REMIND. In all scenarios, energy demand and emissions increase more for passenger transport than for freight transport, primarily due to higher growth in the baseline. This difference is more pronounced for energy demand, indicating decarbonization trends within the freight sector in the reference scenario. An activity-focused strategy is more effective in reducing energy demand and emissions from passenger transport than from freight transport.

For models that report bunkers separately, Figure S15 presents projections for both transport excluding bunkers and for bunkers themselves. Final energy use and CO2 emissions for bunkers increase at a faster rate and are more challenging to reduce compared to other forms of transportation, primarily because there is less potential for the electrification-focused strategy (ELE) in this subsector.

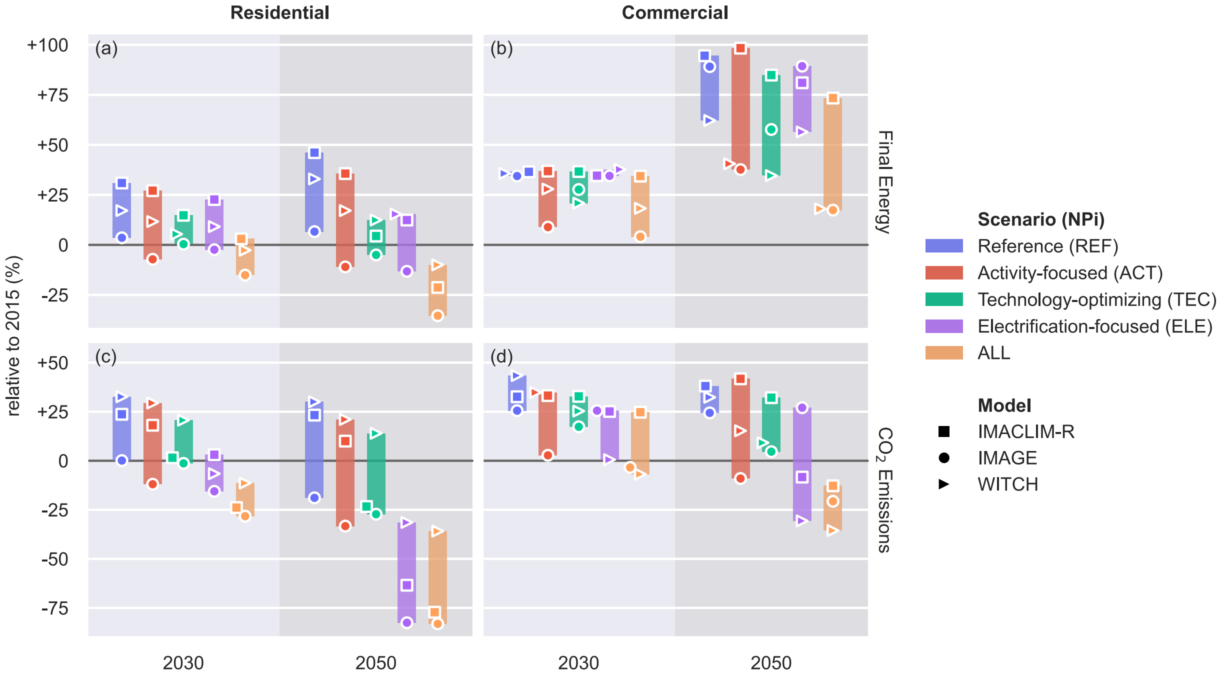

Figure S13: Change in global final energy (top: a, b) and direct CO_2 emissions from fuel combustion (bottom: c, d) from residential (left: a, c) and commercial (right: b, d) buildings in 2030 and 2050, relative to 2015 levels. All scenarios have current national policies implemented (NPi). Markers indicate individual model results and bars depict the model ranges.

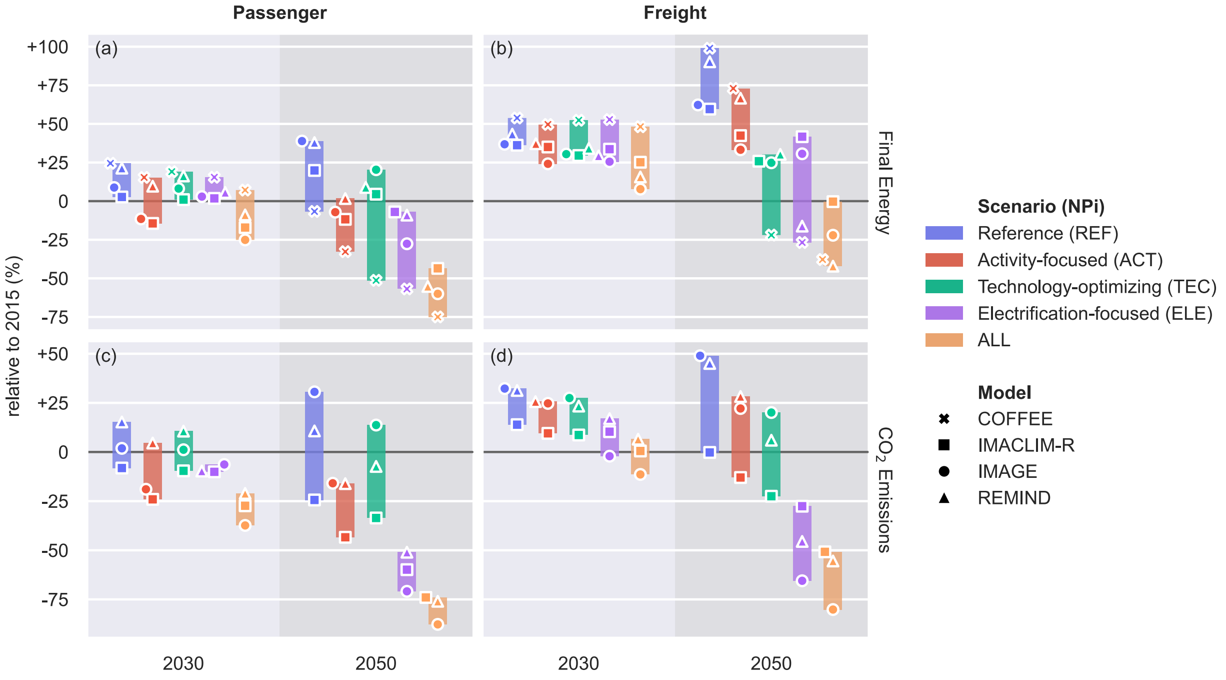

Figure S14: Change in global final energy (top: a, b) and direct CO_2 emissions from fuel combustion (bottom: c, d) from passenger (left: a, c) and freight (right: b, d) transport in 2030 and 2050, relative to 2015 levels. All scenarios have current national policies implemented (NPi). Markers indicate individual model results and bars depict the model ranges.

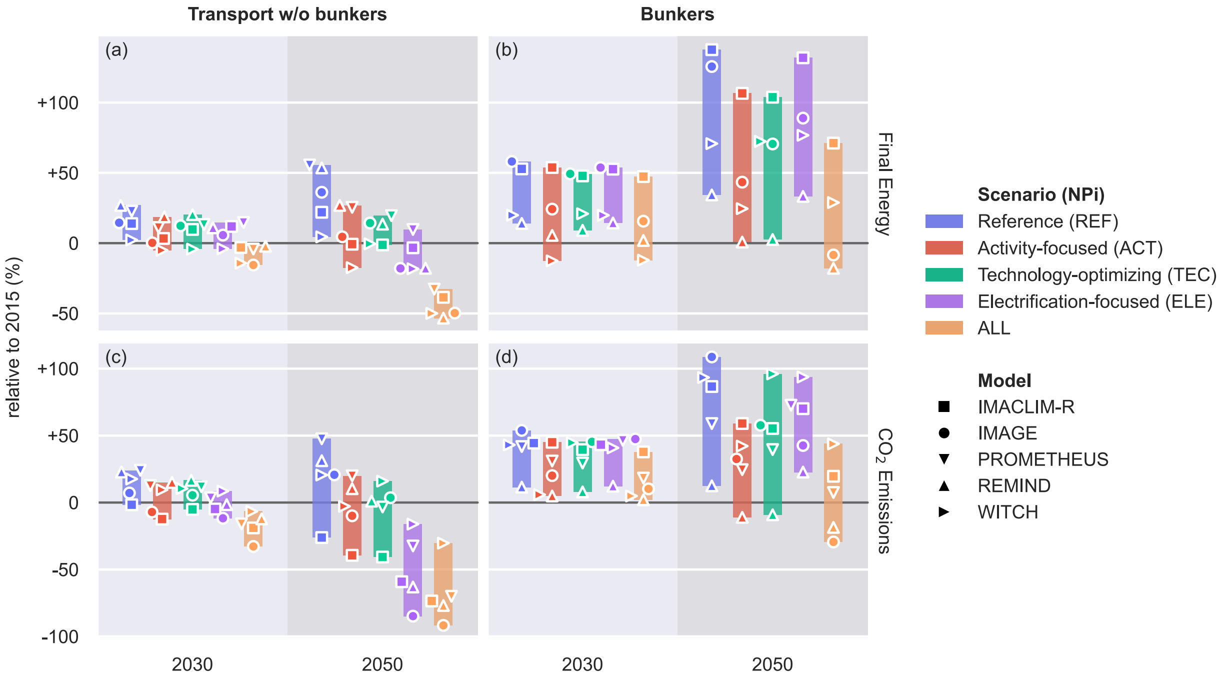

Figure S15: Change in global final energy (top: a, b) and direct CO_2 emissions from fuel combustion (bottom: c, d) from transport without bunkers (left: a, c) and from bunkers (right: b, d) in 2030 and 2050, relative to 2015 levels. All scenarios have current national policies implemented (NPi). Markers indicate individual model results and bars depict the model ranges.

S9. Feasibility of growing electricity demand

Although the electrification-focused scenarios require a rapid increase in electricity supply, the yearly growth of final energy demand remains consistent with historical figures (Figure S16). The model-average global compound annual growth rate of final electricity demand between 2025 and 2050 is highest for ELE with 2.8 %/yr, which is even lower than the historical rate of 3.5 %/yr between 1971 and 2021. However, at the regional level, we note that particularly less developed regions require higher growth rates (Figure S17). With more than a billion people worldwide still lacking access to power, extension of power grids and development of mini-grids is imperative for rapid electrification, which will present many organizational and technological challenges[16-18].

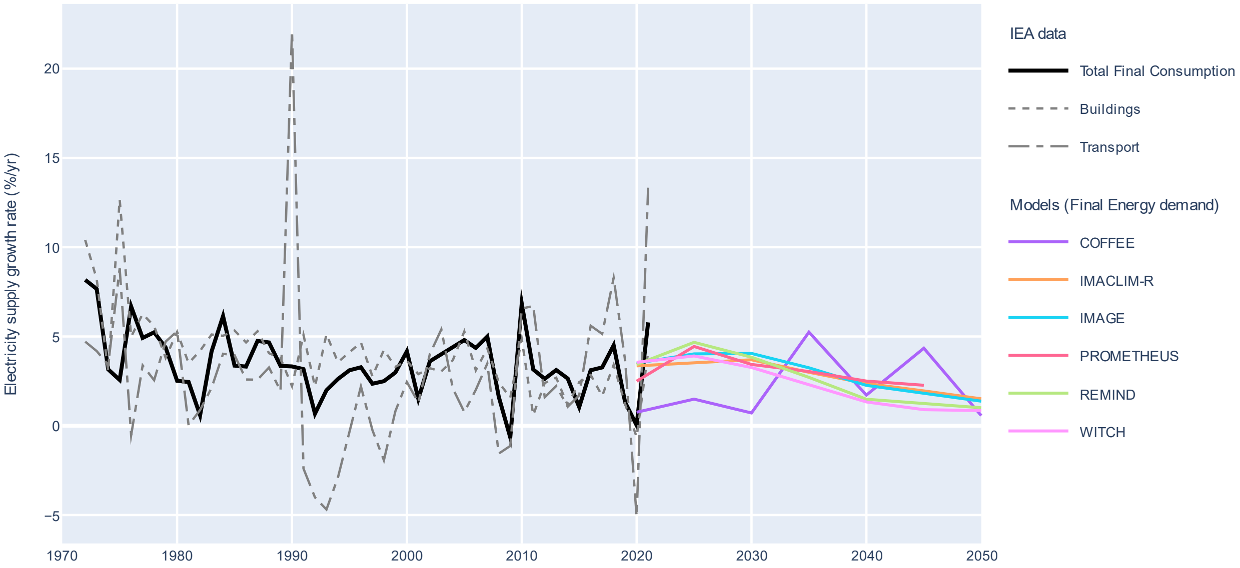

Figure S16: Yearly global electricity demand growth in the NPi-ELE scenario attains similar levels as historical electricity consumption growth. Dotted and dashed lines indicate the historical growth rates for consumption by buildings and transport respectively. Historical data is derived from the IEA Energy Balances[19].

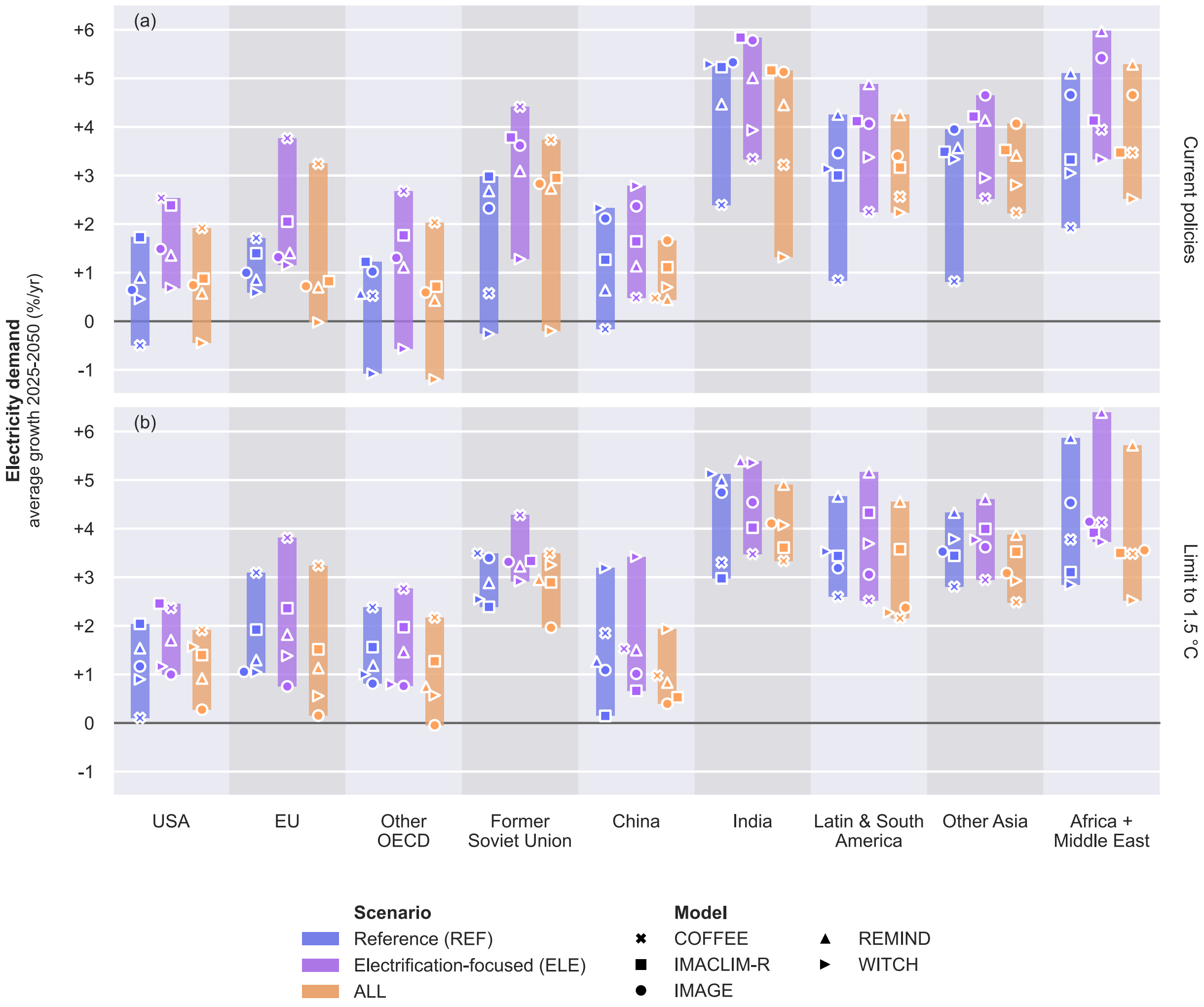

Figure S17: Compound growth rate of regional electricity demand between 2025 and 2050 is higher in developing regions, especially in the electrification-focused scenarios. Panel (a) shows results for implementation under current national policies (NPi) and panel (b) shows results for 1.5 °C climate ambition scenarios. Results are shown for the United States of America (USA), the European Union (EU), 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.

S10. Including indirect emissions

To avoid unclarity in the meaning of mitigation potentials, this study does not take into account indirect emissions. In assessing the potential of mitigation through demand-side policies, the distinction between demand-side and supply-side mitigation is not always clear. Emissions arising from on-site fuel combustion, such as for cooking or powering vehicle engines, are usually clearly linked to a specific service demand. However, this link is much less obvious for emissions stemming from the generation of electricity and heat, or the production of hydrogen. In practice, the source of the energy carrier cannot be determined once it is fed into the transmission system. For example, an issue arises in the accounting of on-site renewables. By "offsetting" these with the electricity demand of buildings, the estimated mitigation potential will be larger than when the avoided emissions are indirectly considered through a reduction in the emission intensity of the electricity supply.

Such issues complicate the allocation of avoided emissions to reductions in electricity demand. By calculating the average emission intensity of electricity production, a value can still be assigned. Yet, this relies heavily on the decarbonization of the supply sector. Especially in the buildings sector, where a significant portion of the energy demand is fulfilled by electricity, the estimated potentials would thus heavily depend on the decarbonization rate of the electricity grid, if indirect emissions were included as well. This is evident when comparing the implied reduction potentials (particularly for ELE and ALL) that include indirect emissions, assuming model-average power grid decarbonization in the current policies scenarios (Figure S18) and a fixed reduction in power grid emission intensity of 80% by 2050 (Figure S19).

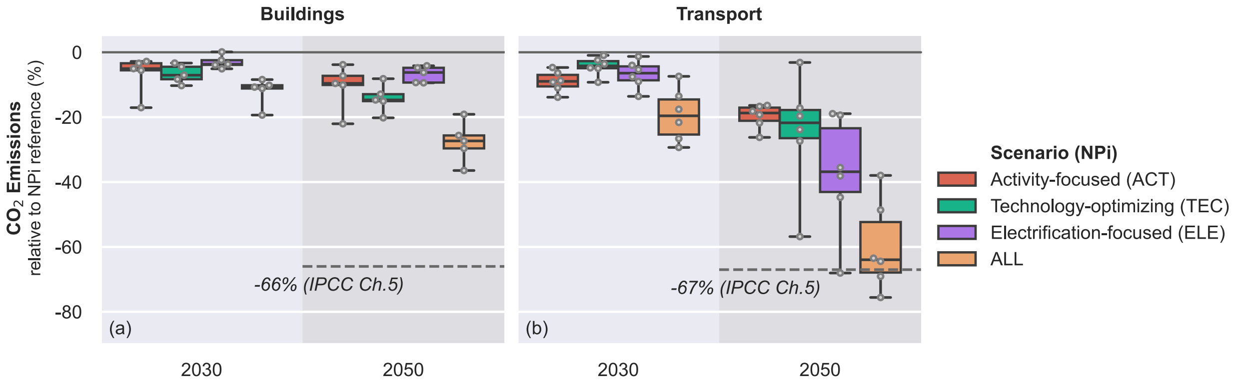

Figure S18: Emission reduction potentials for buildings (a) and transport (b) in 2030 and 2050 for the different intervention strategies and the combination of all interventions, including indirect emissions from electricity, heat and hydrogen generation. The power grid emission intensity shows improvements between 50% and 60% in 2050 compared to 2020 levels, depending on the scenario. All scenarios have current national policies implemented (NPi). 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 5 models for buildings and 6 models for transport. Dashed lines provide comparisons with estimated mitigation potentials from the IPCC's AR6 WG III report (Chapter 5: Demand).

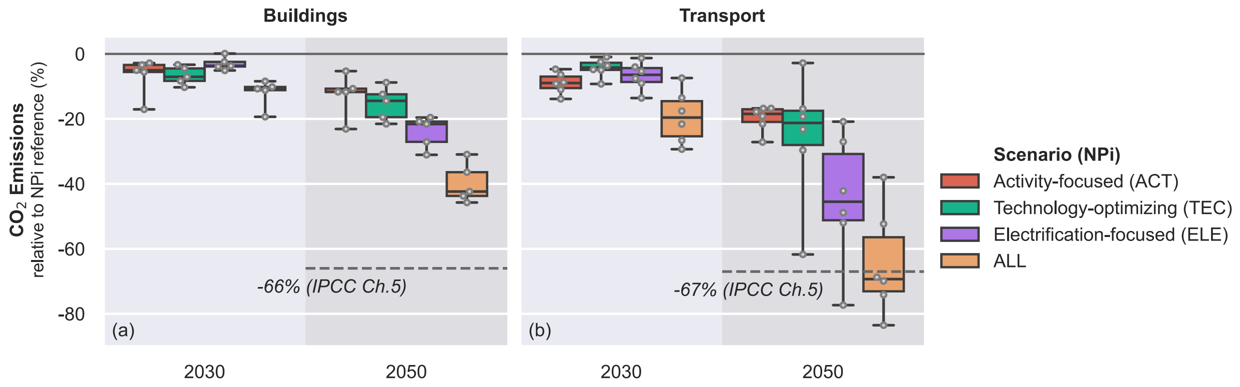

Figure S19: Emission reduction potentials for buildings (a) and transport (b) in 2030 and 2050 (including indirect emissions), assuming an 80% reduction in power grid emission intensity by 2050 compared to current levels. All scenarios have current national policies implemented (NPi). Boxes represent 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 5 models for buildings and 6 models for transport. Dashed lines provide comparisons with estimated mitigation potentials from the IPCC's AR6 WG III report (Chapter 5: Demand).

Under 1.5 °C policies, the electricity supply is projected to be largely decarbonized by 2040. This leads to a significant reduction in supply-side emissions from the use of electricity in buildings and transport. Figure S20 illustrates that emission reductions for both sectors, including indirect emissions as well, are thus considerably larger in all scenarios with 1.5 °C climate ambition.

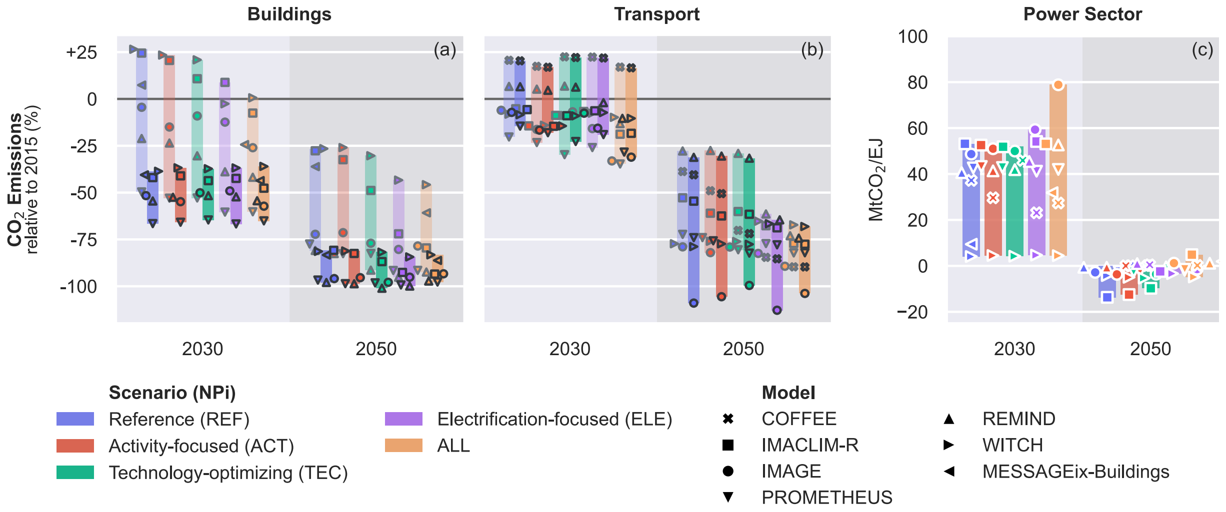

Figure S20: Global CO2 emissions in buildings, transport, and the power sector relative to 2015 levels in 1.5 °C climate ambition scenarios. Panels (a) and (b) show changes in global CO_2 emissions in the building (a) and transport (b) sectors including emissions from electricity, heat and hydrogen generation in 1.5 °C climate ambition scenarios. The indirect emissions are computed using model-average emission intensities. The lighter shaded bars only consider direct emissions. Results are shown for 2030 and 2050 relative to 2015 levels. Markers indicate individual model results and bars depict the model ranges. Panel (c) shows global CO_2 emissions from the power sector in 1.5 °C climate ambition scenarios.

S11. Non-electric energy demand

Figure S21 shows the non-electric energy demand in buildings and transport for both the current policies scenarios and those aligned with a 1.5 °C climate ambition. The strategies, especially the electrification-focused one, reduce this demand substantially compared to the reference scenario. Furthermore, comparison between the reference 1.5 °C scenario and the default current policy scenario shows that such reductions are instrumental in mitigating climate change.

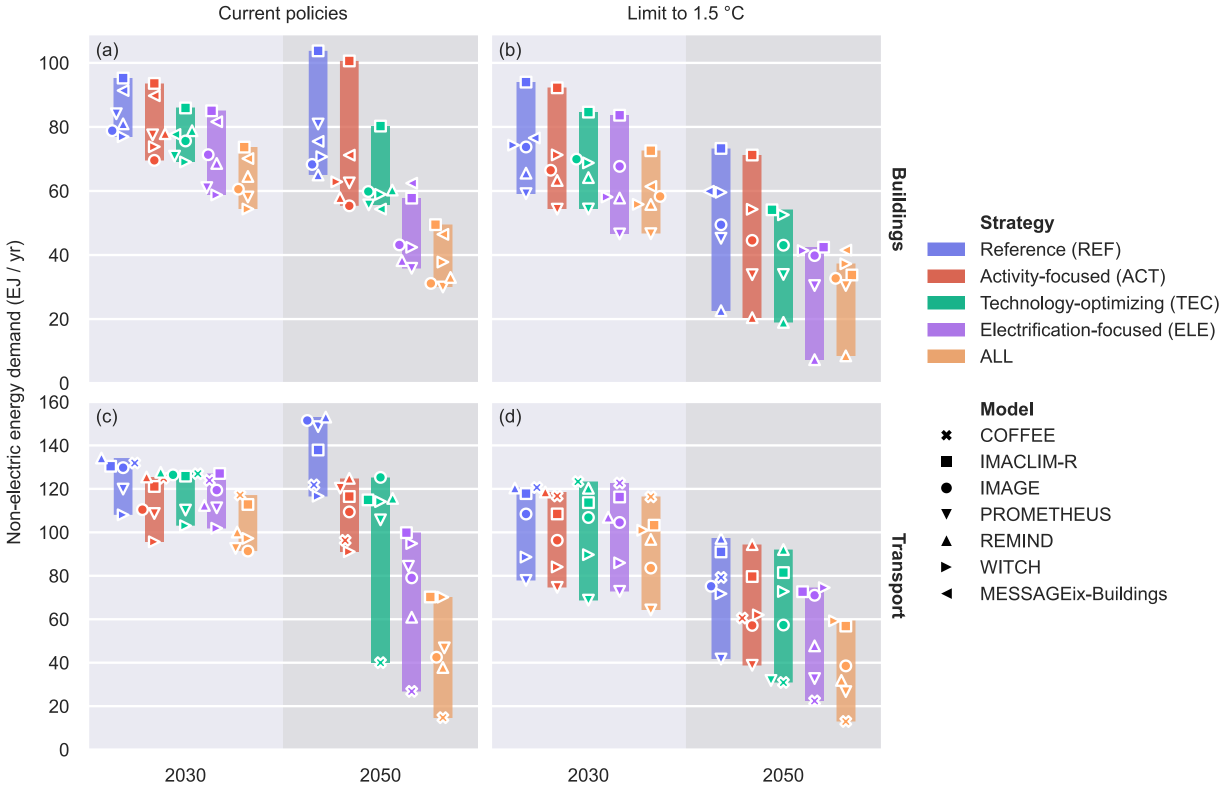

Figure S21: Global non-electric energy demand, i.e., excluding electricity, in buildings and transport in 2030 and 2050 under two different climate ambitions. The left panels (a, c) show scenarios under implementation of current national policies and the right panels (b, d) show in 1.5 °C climate ambition scenarios. The upper (a, b) and lower (c, d) panels show the buildings and transport sector, respectively. A dashed line shows the 2015 levels. Markers indicate individual model results and bars depict the model ranges.

S12. Regional CO_2 reduction potentials

Figure S22 shows the change in CO2 emissions per capita for nine world regions. Some models indicate potentially higher emissions from buildings in the ACT and TEC scenarios. This is the case for WITCH (Former Soviet Union, India, Latin & South America, Other Asia, and Africa + Middle East), IMACLIM-R (India, Other Asia, and Africa + Middle East). For transportation, increased emissions are noted in the USA under the ACT scenario by COFFEE and in the EU under the TEC scenario by WITCH.

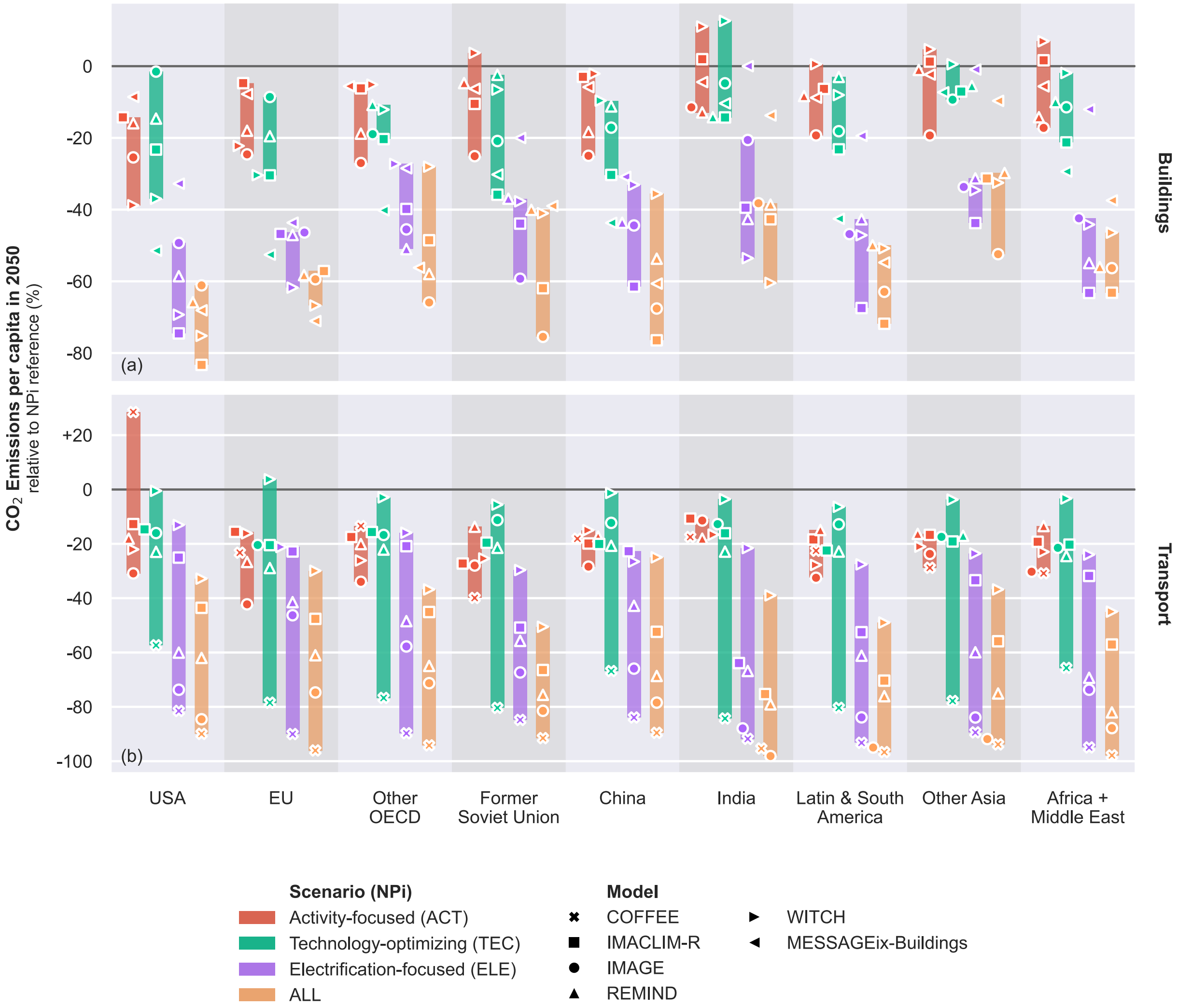

Figure S22: Change in CO_2 emissions per capita in 2050 for nine world regions with respect to the reference scenario. All scenarios have current national policies implemented (NPi). Panel (a) shows results for buildings and panel (b) for transport. Results are shown for the United States of America (USA), the European Union (EU), 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.

S13. Implications of demand-side strategies for low-carbon values and norms using the LIFE model

The demand-side strategies represented in the scenarios – particularly ACT (activity reduction and shifts) – are part of a wider transition towards low-carbon lifestyles that include changes not just in discrete behaviors and end-use technologies adopted in building and transport sectors, but also changes in values, norms and beliefs – for example on the importance and prevalence of climate action. This cognitive dimension is an important enabler of demand-side strategies, but is not captured within IAM analysis; rather, studies to date exploring the emission reduction potentials of lifestyle change do so via narrative storylines translated exogenously into assumptions under which the models are run[20,21].

Here, we present additional analysis using the 'LIFE' model of low-carbon lifestyles to show how experience with demand-side strategies helps strengthen normative values which in turn support further adoption of demand-side measures.

However, this positive feedback effect is uneven across lifestyle groups, only weakly benefiting those groups facing adoption constraints due to a lack of income, skills, capabilities, access to infrastructure, or motivations. This raises important issues of (in)equality of access to the demand-side strategies discussed in the main text. It is important that measures enabling demand-side change do not inadvertently marginalize certain groups.

'LIFE' is an empirical model based on large-scale social survey data and generalizable to world regions[22]. It distinguishes four lifestyle groups with varying propensities towards low-carbon behaviors and associated low-carbon cognitions such as norms and values. The low-carbon behaviors on which the LIFE model is built include Avoid, Shift and Improve (A-S-I) type measures which are covered by the slightly different but related taxonomy of ACT, TEC, and ELE demand-side strategies used in this paper.

LIFE was designed for coupling with a global IAM to enable endogenous representation of both lifestyle heterogeneity and different mechanisms of low-carbon lifestyle change. These mechanisms include both the effect of strengthening norms on low-carbon behaviors (the 'identity' effect), and the effect of experience with low-carbon behaviors feeding back to strengthen low-carbon norms (the 'familiarity' effect).

This coupling and endogenous simulation of low-carbon lifestyle change has been demonstrated elsewhere[23]. Here, we use the LIFE model as a stand-alone tool for post-processing IAM scenario output to explore implications for low-carbon norms and values (the 'familiarity' effect).

We focus on results from a single IAM, MESSAGEix-Buildings, calibrated to the LIFE model formulation. We take changes in final energy in the residential sector from 2020 to 2050 as an aggregate proxy for the extent of lifestyle changes across all A-S-I measures. We focus on a single scenario NPi-ALL which assumes current policies and the integrated package of ACT, TEC, and ELE demand-side strategies (reduction in activity levels, increased energy efficiency and technological improvements, and electrification of end-use), but without additional climate policy for reaching the 1.5°C target.

As in the main text (Figure 1), we compare NPi-ALL to a baseline scenario without demand-side measures (NPi-REF). We find that under scenario NPi-ALL (with demand-side strategies) the strength of normative values consistent with low-carbon lifestyle change increase by 2050 relative to baseline (NPi-REF). This is driven by the decrease over time in residential final energy in MESSAGEix-Buildings between 2020 and 2050. Reductions in activity, increased energy efficiency and technological improvements create improved learning, familiarity and experiences which subsequently shape and align normative values in the four lifestyle types (Figure S23). These four types have characteristically differing levels of receptiveness to cognitive changes of this type. In Figure S23 this is seen as a differentiated change in low-carbon cognitions within the four lifestyle types. We see higher levels of change in the more engaged 'Resourceful' and 'Active' types, who are more likely to have experienced low-carbon behaviors simulated at the aggregate population level in the IAM. In the LIFE model, these two groups combined comprise around 65% of the global population by 2050. In contrast the more disengaged 'Constrained' and 'Cautious' types remain resistant to cognitive changes due to other constraints. These groups have characteristically low levels of agency and efficacy (perceived ability to act). They also face stronger contextual constraints. For example, they have lower levels of income, are less educated and have lower access to technology and related skills[22].

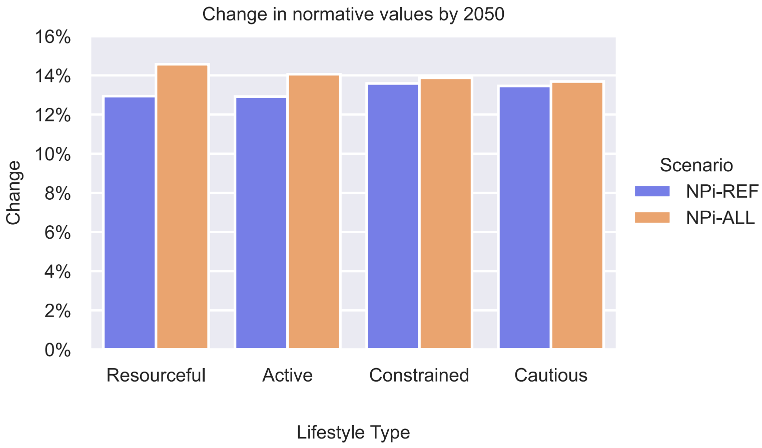

Figure S23: Change in low-carbon values (2020 to 2050) in NPi-REF and NPi-ALL scenarios within four lifestyle types with decreasing propensities towards low-carbon lifestyles from Resourceful to Cautious.

In summary, our LIFE model analysis shows how demand-side strategies impact normative values, but this varies widely across lifestyle types. Low-carbon lifestyle change occurs at different speeds among population segments as a result of variation in means, motivation, and opportunity. More 'disengaged' groups risk being marginalized in the absence of strong and universal social learning on climate action alongside the integrated package of demand-side strategies modelled by the IAMs in this paper. This raises important considerations of equity and access to the benefits of demand-side policies, particularly those with strong economic or social co-benefits.

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