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RESEARCH ARTICLE

Towards net-zero emissions in global residential heating and cooling: a global scenario analysis

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Abstract

Accounting for 21% of global greenhouse gas (GHG) emissions, buildings play a crucial role in climate change mitigation. Demand-side policies offer large energy and GHG emission reduction potentials. The effects of broader sectoral policies at the global level beyond energy efficiency improvements, including sufficiency and structural changes, and their interaction with cross-sectoral climate policies are, however, still unclear. Here, we assess a comprehensive set of scenarios to reduce residential space heating and cooling emissions towards net-zero targets. We find that activity reductions, fuel shifts, and technological improvements can reduce current global residential space heating and cooling CO_2 emissions by 57% relative to a reference scenario in 2050. Combining these demand-side policies and stringent climate policies could result in CO_2 emission reductions up to 91% relative to the reference scenario in 2050. Neutralizing residual direct CO_2 emissions would require additional interventions targeting fossil fuel-based heating systems still in use in 2050.

Keywords Buildings · Climate change mitigation · Energy demand · Integrated assessment modelling

1 Introduction

The building sector accounted for 21% of the global greenhouse gas (GHG) emissions in 2019. Despite continuous improvements in energy efficiency (Saunders et al. 2021), GHG emissions from buildings have been increasing due to other factors, such as floorspace and population growth (IEA 2019). Urgent action is required to reduce the total energy demand in buildings and to contribute to mid-century net-zero targets (Cabeza and Chàfer 2020; Ürge-Vorsatz et al. 2020; Mata et al. 2020; Creutzig et al. 2022). Energy demand reductions are central to carbon mitigation and can support avoiding the need for uncertain negative

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emission technologies (Grubler et al. 2018; Mundaca et al. 2019; Cabeza and Ürge-Vorsatz 2020).

The building sector offers multifaceted mitigation options that are covered by the Avoid-Shift-Improve framework (Creutzig et al. 2021, 2022), including: activity reduction through building design, size and use (*avoid*); electrification and fuel shifts (*shift*); and technological improvements of energy efficiency in building envelopes and technical systems (*improve*). The estimated global mitigation potential for buildings amounts to 8.2 $GtCO_2$ by 2050, equivalent to 61% of their baseline scenario (Cabeza et al. 2022). The assessment of buildings energy efficiency improvements and their mitigation potentials has a broad literature and detailed modelling (Mata et al. 2018; Cabeza and Chàfer 2020; Edelenbosch et al. 2021; Chatterjee et al. 2022a). Conversely, activity level reductions – also known as sufficiency (Samadi et al. 2017; Lorek and Spangenberg 2019; Gaspard et al. 2023) – and structural changes (Francart et al. 2018; Kikstra et al. 2021) have been more scarcely investigated and mostly represented in a simplified way in existing models (Mastrucci et al. 2023). These interventions can deliver energy reductions additional to energy efficiency improvements and contribute to covering the full mitigation potential (Cabeza et al. 2022). Thus, the reduction potential of combined demand-side policies and their interaction with cross-sectoral climate policies is also unclear (Levesque et al. 2021).

The building sector is characterized by a multitude of different building types and actors, has high inertia and lock-ins, and is tightly linked to the local context, making the modelling of GHG emissions and reduction potential challenging at large scales. At the global level, integrated assessment models (IAMs) are commonly used for exploration of mitigation scenarios, but they have traditionally focused on energy supply changes and decarbonization (Creutzig et al. 2018). The simplified accounting of the building sector in many IAMs has limitations in considering heterogeneities and key dynamics, including stock turnover, and energy efficiency investment decisions. In contrast, sectoral modelling has been used for investigating a range of mitigation policies, including energy efficiency, structural changes, and sufficiency (Levesque et al. 2019; Camarasa et al. 2022). However, it is often limited in geographical coverage and in the lack of or inconsistent representation of the energy supply-side (Levesque et al. 2021). Recently, the modelling of end-use sectors in IAMs has been enhanced for stock turnover, buildings heterogeneity, and energy efficiency improvements (Knobloch et al. 2019; Edelenbosch et al. 2021; Mastrucci et al. 2021; Daioglou et al. 2022), though most of these studies only consider a narrow range of building sectoral policies (energy efficiency improvements) and don't investigate deep decarbonization scenarios. The trade-offs and synergies between demand-side and supply-side policies, have been ignored or investigated with simplified approaches (Levesque et al. 2021), while more detailed approaches focus mostly on national or regional scales (Berrill et al. 2022).

Here, we perform a comprehensive quantitative assessment of mitigation policies for the global residential sector towards mid-century net-zero targets, combining broad sectoral demand-side policies and ambitious climate policies. We include building sector policies for all three dimensions of the ASI framework, targeting activity reduction (avoid), electrification and fuel shifts (shift), and technological improvements and energy efficiency (improve). We focus on two end-use services, space heating and cooling, which are respectively the largest and the fastest growing residential demand categories (IEA 2019), while they are both crucial for thermal comfort and well-being of occupants. We use the global building sector modelling framework MESSAGEix-Buildings (Mastrucci et al. 2021) soft-linked to the MESSAGEix-GLOBIOM IAM (Huppmann et al. 2019). This linkage further enables for accounting energy supply-side system transformation and interplay with the building demand-side for a more comprehensive assessment of decarbonization strategies.

This study contributes to advancing assessment of climate change mitigation in the building sector in three ways: (1) by improving the representation of the global building sector in IAMs, via enhanced model granularity and dynamics, including building stock turnover and energy efficiency investments; (2) by integrating the effects of a set of demand-side mitigation policies ranging across activity reduction, fuel shifts and technology improvements that are exemplified with real life examples; (3) by showing the combined effects of policies targeting the demand and the supply-sides on energy demands and CO_2 emissions.

2 Methods

MESSAGEix-Buildings (Mastrucci et al. 2021) is a bottom-up framework to model energy demand and CO_2 emissions of the building sector in global climate change mitigation and sustainable development scenarios. In this study, we use two modules of MESSAGEix-Buildings: CHILLED (Cooling and Heating gLobaL Energy Demand model), a spatially-explicit energy demand model for space heating and cooling; and STURM (Stock TURnover Model of global buildings), a building stock turnover model including energy efficiency investment decisions assessment. MESSAGEix-Buildings is soft-linked to MESSAGEix-GLOBIOM (Huppmann et al. 2019), an IAM framework for the assessment of energy-environment-economy systems and the development of global-change scenarios, enabling energy price feedback and explicit accounting of energy-supply side transformations in CO_2 emission calculations.

MESSAGEix-Buildings has high level of detail in representing building dynamics, including stock turnover, energy-efficiency investment decisions, and energy demands, and has high granularity in geographical (regions, climates, urban and rural locations), socio-economic (income and tenure) and building characteristics (housing type, energy efficiency level, and energy carriers for heating), enabling the exploration of a broad set of policies and their effects on a global scale.

Here, we run the model for 61 regions (Supplementary Information 1, section 1) with a 5-year timestep from the base year 2020 to 2050. We perform model calibrations for the base year 2020 using statistical data on housing stock characteristics, floorspace, and final energy demand. Energy demand values for 2025 are extrapolated based on current observed trends (see Supplementary Information 1, section 2.3). An overview of model data inputs and data sources is available in the Supplementary Information 1, section 3. Comprehensive descriptions of the methods and data inputs are available in prior studies (Mastrucci et al. 2019, 2021), to which we refer the reader for more details.

2.1 Energy demand modelling

The CHILLED model calculates energy demand for space heating and cooling using the variable degree days (VDD) method (Al-Homoud 2001; Mastrucci et al. 2021). VDD are calculated as the annual sum of daily positive differences between outdoor temperature and a building-specific balance temperature, defined as the outdoor temperature at which neither heating nor cooling is required (Claridge et al. 1987; Al-Homoud 2001). In contrast with traditional degree days, arbitrarily assuming fixed balance temperatures, the VDD method analytically calculates the balance temperature with a simplified thermal balance calculation, allowing for a more accurate calculation accounting for building thermal characteristics and user behaviour-related parameters. The following equation is used to calculate the balance temperature $T_{bal,\,m}$ (°C) for the month m based on the indoor set point temperature T_{sp} (°C), the heat flow from solar heat sources $g_{sol,\,m}$ (W), the heat flow from internal heat sources g_{int} (W), the heat transfer coefficient by transmission H_{tr} (W/°C), and the heat transfer coefficient by ventilation H_{ve} (W/°C):

$$T_{bal,m} = T_{sp} - \frac{g_{sol,m} + g_{int}}{H_{tr} + H_{ve}} \tag{1}$$

The variable heating ($VDD_{h,\,m}$) and cooling degree days ($VDD_{c,\,m}$) are calculated on a monthly basis using the following equations, based on the average daily outdoor temperature $T_{out,\,d}$ and the number of days in the month d_m (only positive values are accounted):

$$VDD_{h,m} = \sum\nolimits_{d=1}^{dm} \left(T_{bal,m} - \bar{T}_{out,d} \right)^{+} \tag{2}$$

$$VDD_{c,m} = \sum\nolimits_{d=1}^{dm} \left(\bar{T}_{out,d} - T_{bal,m} \right)^{+} \tag{3}$$

The final energy demands for space heating (E_h) and cooling (E_c) are subsequently calculated based on the VDD results, by using building-specific coefficients for daily operation time fractions for heating ($f_{op,\,h}$) and cooling ($f_{op,\,c}$), share of heated ($f_{fl.,\,h}$) and cooled ($f_{fl.,\,c}$) floor area, and efficiency of the heating (η_h) and cooling (η_h) systems:

$$E_h = \sum\nolimits_{m=1}^{12} \frac{(H_{tr} + H_{ve}) \cdot f_{op,h} \cdot f_{fl,h} \cdot VDD_{h,m}}{\eta_h} \tag{4}$$

$$E_c = \sum\nolimits_{m=1}^{12} \frac{(H_{tr} + H_{ve}) \cdot f_{op,c} \cdot f_{fl,c} \cdot VDD_{c,m}}{\eta_c} \tag{5}$$

We refer the reader to previous publications (Mastrucci et al. 2019, 2021) for the detailed description of model parameters. The calculations are run over a spatial grid at 0.5° grid resolution (approximately 50 km at the equator) for the entire globe, using a set of more than 500 building archetypes representative of different regions, urban and rural locations, housing types and energy efficiency levels. Results are aggregated by location (urban/rural), country and climatic zone for the different archetypes and energy intensities per unit of floorspace are passed over to the STURM model. In this study, current climate conditions underly all model runs and climate change impacts are not included.

2.2 Energy efficiency decision modelling

The STURM model can assess investment decisions on energy efficiency improvements in new constructions, renovations and heating fuel shifts in the residential sector via dedicated discrete choice models (Giraudet et al. 2012). A life-cycle cost approach is used to compare different options and to endogenously calculate market shares based on investment costs C_{inv}, operational costs C_{op}, and intangible costs C_{int} of alternative technologies, as well as renovation rates. The following equation is used to calculate the life cycle costs (LCC_j) of a given option j for new construction or renovation:

$$LCC_j = C_{inv,j} + C_{op,j} + C_{int,j} \tag{6}$$

We then calculate the market share (MS) for each option j based on the LCC of all possible options k and the exogenous heterogeneity parameter ν using the following equation:

$$MS_j = \frac{LCC_j^{-\nu}}{\sum_k LCC_k^{-\nu}} \tag{7}$$

Operational costs are calculated based on the energy demands from the STURM model and the energy price trajectories from the MESSAGEix-GLOBIOM IAM. The intangible costs represent non-monetizable technology-specific barriers towards investments. Discount rates differ across regions and household types, depending on the housing type and tenure, to represent different degree of predisposition to investment, e.g. lower for renting and multi-family homes to account for principal-agent problems (Ástmarsson et al. 2013). Constraints relative to the applicability of specific new construction and renovation options, and bounds to renovation rates, are set at the regional level.

2.3 Stock turnover modelling

The STURM model accounts for the stock turnover of buildings using dynamic material flow analysis (MFA) (Sandberg et al. 2016). The model has population as key driver of housing demand, and consequent stock requirements, over time using “dwelling unit” as main unit of calculation. Outputs from the model include timeseries of housing stock, demolitions, and new constructions. The model runs calculations by region, location (urban and rural), and housing type, making use of exogenous population, urbanization, and housing type projections.

At every timestep, the model calculates the number of housing units in the stock based on population, urbanization, household size, and housing type projections. Demolitions are estimated via a set of lifetime probability distributions by building type in different regions. New constructions are subsequently calculated by considering the number of housing units to replace due to demolitions and the new additions to the stock driven by population increase. Renovation rates and market shares of different options for new construction, renovations, and fuel shifts (calculated using dedicated discrete choice models, see previous section) are applied to existing and new housing units to determine the updated composition of the housing stock. Per-capita floorspace and energy intensity coefficients, estimated with the CHILLED model, are used to calculate total floorspace and energy demands for space heating and cooling by region, location, housing type and heating energy carrier. Finally, CO_2 emissions are calculated by applying emission factors from consistent MESSAGEix-GLOBIOM scenario runs to final energy demands by energy carrier. We include both direct emission from fossil fuel combustion in buildings and indirect emissions from electricity and district heating. In this study, results are aggregated from the 61 native model regions to Global North and Global South and to six world regions: European Union (EU27), USA, other Global North Regions (other GN), China, India, other Global South regions (other GS).We further generate country-level results, displayed as world maps, by applying population-based downscaling from the 61 model regions.

3 Scenario setup

3.1 Scenarios overview

Our set of scenarios combines demand-side policies for buildings, including relevant policy instruments for their implementation, and climate policies (Table 1). The starting point is the shared socio-economic pathway SSP2 "middle of the road" (O'Neill et al. 2017), assumed as baseline for demographics and socio-economics. The *Avoid-Shift-Improve* framework (Creutzig et al. 2021, 2022) provides comprehensive assessment of sectoral demand-side policies, reflecting opportunities for socio-cultural, infrastructural, and technological change. In a similar fashion, we frame policies and their strategical combinations into activity reductions and activity shifts in the *Activity* (ACT) scenario, electrification and fuel shifts in the *Electrification* (ELE) scenario, technology and energy efficiency improvements in the *Technology* (TEC) scenario (Kriegler et al. 2023). We combine all investigated demand-side measures under the *Combined* (ALL) scenario and contrast them against a *Reference* (REF) scenario assuming continuation of current policies and regulation.

We assess the effect of stringent climate policies in line with the 1.5 ºC target (1.5C scenario) contrasted with a baseline scenario with continuation of national policies until 2030 and no stringent climate policies (NPi scenario), based on existing scenarios from the MESSAGEix-GLOBIOM IAM (Riahi et al. 2021; Richters et al. 2024).

3.2 Model implementation of scenarios

Demand-side policies for buildings are represented with specific model implementations and dynamics (see the Supplementary Information 1, section 2, for complete information). Activity reductions mostly concern exogenous model parameters. Scenarios are modelled by adjusting the relevant model parameters and exogenous projections, i.e. per-capita floorspace, share of multi-family housing, and set-point temperature. Electrification and fuel shifts are represented by introducing constraints in the relevant discrete choice models, i.e. on minimum electrification rates and uptake of fossil fuels-based heating systems in new constructions and renovations. Model constraints are also used to model technology and energy efficiency improvements, i.e. on minimum energy efficiency standards for new constructions and renovations, and minimum renovation rates.

Climate policies and energy supply-side transformations are modelled with the help of the soft-linkage with the MESSAGEix-GLOBIOM IAM. Energy price signals and CO_2 emission factors for electricity and district heating are determined based on a consistent set of scenario runs (Riahi et al. 2021; Richters et al. 2024) in MESSAGEix-GLOBIOM and

Table 1 Overview of policy scenarios

Policy focus	Policy scenario	Description	Policy instruments
Demand-side	Reference (REF)	Continuation of current demand-side policies.	Current policy instruments with current stringencies.
	Activity (ACT)	- Reduce per-cap floorspace by 5% by 2050. - Shift to multi-family housing. - Switch to more conservative temperature set-points, reaching − 1 °C for heating and + 1 °C for cooling by 2030 compared to 2020.	Policies limiting floorspace in new construction, policies limiting new construction of single-family housing, information and awareness raising campaigns with voluntary behaviour change.
	Electrification and fuel shifts (ELE)	- Increase electrification rate in existing buildings. - Limitations on the uptake of fossil fuel-based heating systems in new construction and renovations. - Phase-down coal and traditional biomass in individual heating systems.	Fuel mandates, subsidies, and incentives, building codes, neighbourhood-based approaches.
	Technology (TEC)	- Mandatory *advanced* renovation (Global North only) and *advanced* new construction (all regions) as from 2030, including building shells and technical systems. *Advanced* corresponds to passive building standard for new construction in the Global North and energy savings for renovation of at least 40%. - Increase in yearly renovation rates up to 3% in the Global North and 1.5% in the Global South.	Building codes and regulations, subsidies and incentives, energy performance certification.
	Combined (ALL)	Combination of all demand-side policies above.	Combination of the policy instruments above.
Climate policies	No stringent climate policy (NPi)	Continuation of current national policies until 2030; no additional stringent climate policies.	Current policy instruments.
	Climate policy (1.5C)	National policies until 2030; climate policies in line with the 1.5 °C targets; cumulative CO_2 emissions (2020–2100) 600 $GtCO_2$.	Carbon taxes, supply-side oriented policies.

fed into the STURM model (Supplementary Information 1, section 3). The effects on the model results are twofold. First, energy prices influence household investment decisions on energy efficiency, e.g. under higher prices, advanced energy efficiency options are favoured in the LCC calculations, and therefore energy demands for space heating and cooling. Second, scenario-consistent emission factors determine the resulting CO_2 emission projections.

4 Results

4.1 Building stock evolution

The sectoral demand-side policies drive major changes both in the future composition of the global housing stock and the mix of energy carriers for space heating (Fig. 1). In the refer-

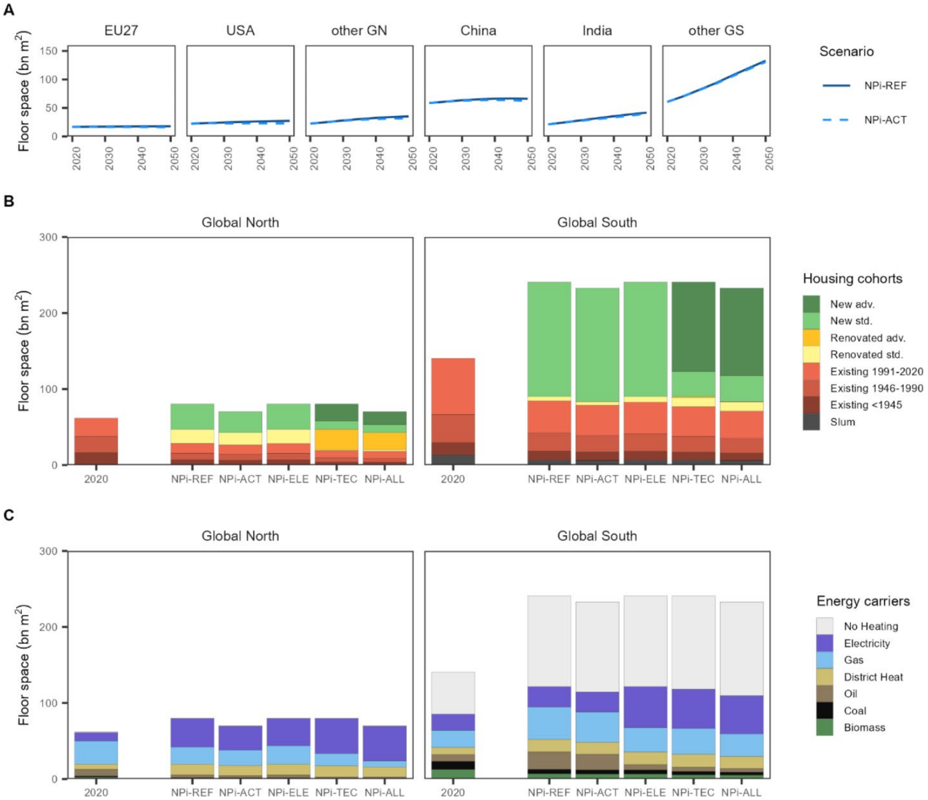

Fig. 1 **A** Housing floorspace projections in the reference (NPi-REF) and activity reduction (NPi-ACT) scenarios for different world regions: European Union (EU27), USA, other Global North Regions (other GN), China, India, other Global South regions (other GS). **B** Housing stock floorspace breakdown by building energy efficiency cohort in 2020 (base year) and in 2050 for different demand-side policies (see Table 1) without stringent climate policies (NPi). Standard (std) indicates current new construction and renovation practices. Advanced (adv.) indicates passive building standard for new construction in the Global North and energy savings of at least 40% for renovation of existing buildings. **C** Housing stock breakdown by energy carriers for space heating in 2020 (base year) and in 2050 for different demand-side policies (see Table 1) without stringent climate policies (NPi)

ence scenario (NPi-REF), in the Global North, more than half of the existing housing stock of 2020 is still standing in 2050 (59% of total floorspace), though a part of it is renovated under current policies. Conversely, in the Global South, a stark increase in total floorspace is driven by population growth and increase in average affluence. As a result, the housing stock in 2050 is mostly composed of new buildings (63% of total floorspace). The NPi-ACT scenario has a 6% lower total global floorspace compared to the NPi-REF, but no substantial difference in the mix of energy carriers. The NPi-ELE scenario entails a major shift in energy carriers for space heating, including significant increase in electrification and phase-out of fossil fuels, especially in the Global South. The NPi-TEC scenario is characterized by advanced technology solutions leading to higher shares of *advanced* new construction and renovations by 2050. In the Global North, acceleration of the deep renovation rates results in higher share of renovated buildings, and larger electrification due to the uptake of heat-pumps combined with higher insulation standards. The NPi-ALL scenario combines all considered demand-side policies, resulting in both lower floorspace levels, and higher penetration of electric systems and advanced new construction and renovation. Natural gas and other fossil fuels are reduced in the Global South and almost completely phased-out in the Global North, as a result of high electrification levels.

4.2 Final energy demand projections

The final energy demand for space heating and cooling differs across the investigated scenarios in different world regions (Fig. 2), resulting from the interplay of activity drivers, buildings stock dynamics, and energy efficiency improvements (see Supplementary Information 1, section 4 for detailed results). In the reference scenario (NPi-REF), the energy demand for space heating decreases in the European Union and in the USA driven by energy efficiency improvements under current policies. Energy efficiency improvements are partly offset in other Global North regions due to increasing floorspace. In China, the energy demand for space heating peaks around 2040 and then starts declining under energy efficiency improvements from continuation of current policies, offsetting the floorspace growth. Other regions of the Global South have relatively lower but steadily increasing demand for space heating. Overall, the energy demand for space heating decrease by 11% in the Global North and increases by 36% in the Global South between 2020 and 2050. Changes in energy demand differ across locations and housing groups, with the largest increase in urban areas (see Supplementary Information 1, section 4.1).

The developed demand-side scenarios reflect different potentials to reduce energy demand for space heating, the most effective being NPi-TEC (− 44%), followed by NPi-ACT (− 26%) and then NPi-ELE (− 13%) compared to NPi-REF in 2050. The combination of all demand-side policies (NPi-ALL) has the largest energy demand reduction potential

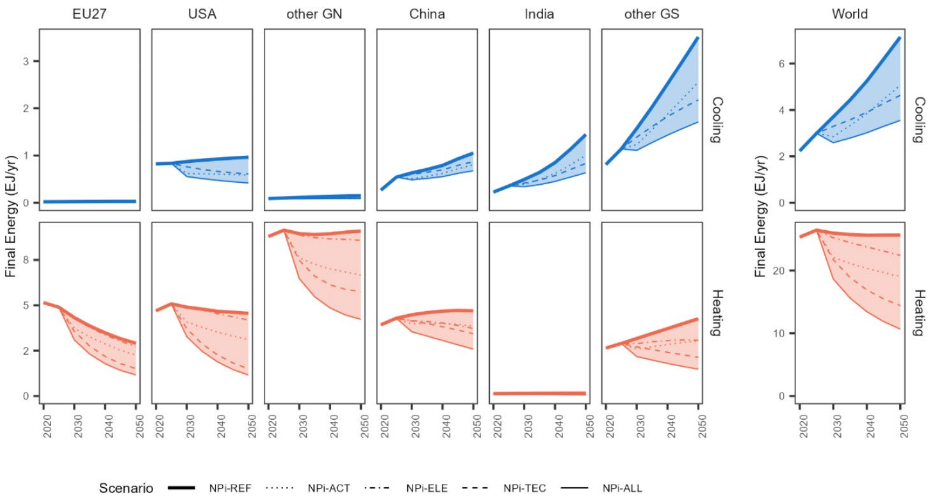

Fig. 2 Projections of final energy demand for space heating and cooling for different demand-side policies (see Table 1 for full definition of scenarios) without stringent climate policies (NPi) in different world regions: European Union (EU27), USA, other Global North Regions (other GN), China, India, other Global South regions (other GS)

for space heating, but less than the sum of each of them (− 58%) due to the high level of policy reinforcement rather than additionality. Overall, reductions in energy demand are higher for single-family housing, due to higher floorspace and energy intensity, as well as higher uptake of energy efficiency improvements compared to multi-family housing, that are more affected by the principal-agent problem (Giraudet et al. 2012) and other barriers (see Supplementary Information 1, section 4.1).

The energy demand for space cooling is projected to triple globally between 2020 and 2050 in the NPi-REF scenario, driven by growing access to air-conditioning and larger floorspace in the Global South. The largest growth is projected for India and other regions, such as South-East Asia, Middle East Asia, and Sub-Saharan Africa, with severe climatic conditions and rapidly increasing population and service levels. Such growth in cooling demand is prevailing over energy efficiency improvements, resulting in severely increasing final energy in the reference scenario. China is among the top countries for cooling energy demand due to high levels of air-conditioning penetration, especially in urban areas. In the Global North, the energy demand for cooling is lower compared to the Global South, due to different climatic conditions. However, in the USA, the energy demand for space cooling is substantial due to almost full penetration of air-conditioning. Similar to space heating, the combination of demand-side policies (NPi-ALL scenario) can significantly mitigate the global energy demand for space cooling by 50% in 2050 compared to the NPi-REF scenario, with high saving potential both in the Global South (− 50%) and in the Global North (− 61%). For space cooling, the global energy savings delivered in the NPi-ACT (− 29%) and NPi-TEC (− 35%) scenarios are comparable, highlighting the more critical role of behavioural factors. The energy demand and reduction potentials for cooling strongly differ across socio-economic groups in different regions. The potential to reduce cooling demand is larger for higher income groups with broader access to air-conditioning and thus responsible for high energy demand for cooling, in particular in India and other Global South Regions (see Supplementary Information 1, section 4.2).

4.3 Global decarbonization pathways

We explore here the combined effect of demand-side policies and climate policies consistent with the 1.5 °C target towards residential space heating and cooling decarbonization (Fig. 3; Table 2). In the reference scenario (NPi-REF), global final energy demands for space heating and cooling reach 32.8 EJ/yr by 2050 (+ 19% compared to 2020). Global CO_2 emissions increase under growing demand and peak around 2045 before going back to 2.03 $GtCO_2$/yr, levels similar to 2020, due to progressive electrification and supply-side decarbonization. Demand-side policies drive major energy demand reduction for heating and cooling, up to 57% in the NPi-ALL scenario relative to the reference NPi-REF scenario in 2050 (Fig. 3, A). Climate policies, through higher energy prices, only drive down energy demand by 10% in the 1.5C-REF scenario relative to the NPi-REF scenario in 2050 and combined with demand-side policies (1.5C-ALL), add only marginal energy demand reductions to NPi-ALL, reaching 59% reductions.

The major effect of the stringent climate policies is on CO_2 emission reductions (Fig. 3, B), through the decarbonization of district heating and the electricity supply. CO_2 emission reductions amount to 74% in the 1.5C-REF scenario relative to the NPi-REF scenario in 2050, while the combination of all demand-side policies alone cause only 57% CO_2 miti-

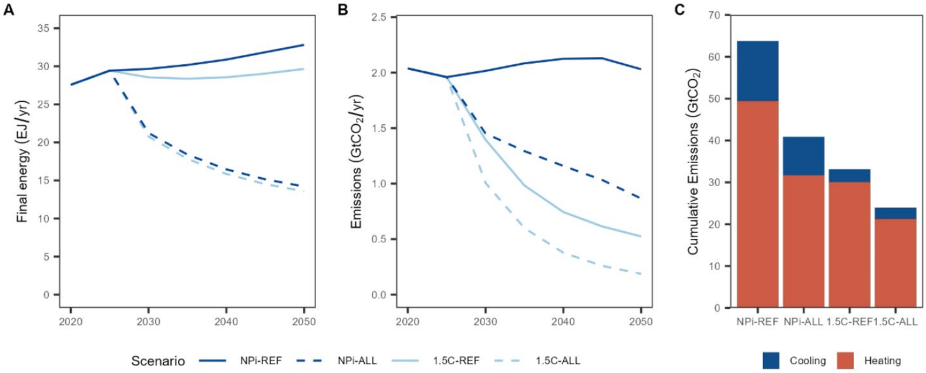

Fig. 3 **A** Global final energy demand for space heating and cooling for different combinations of demand-side (REF and ALL) and climate policy (NPi and 1.5C) scenarios. **B** Global CO2 emissions for space heating and cooling for different combinations of demand-side (REF and ALL) and climate policy (NPi and 1.5C) scenarios. **C** Global cumulative emissions between 2020 and 2050 for space heating and cooling in different scenarios. See Table 1 for scenarios definition

Table 2 Final energy and total (direct and indirect) CO_2 emission reduction potential in 2050 compared to the NPi-REF reference scenario

Scenario	Final energy reduction potential in 2050 (%)			CO_2 emission reduction potential in 2050 (%)		
	Global	Global North	Global South	Global	Global North	Global South
NPi-ACT	27	28	25	27	29	25
NPi-ELE	10	6	15	11	7	14
NPi-TEC	42	46	37	43	51	36
NPi-ALL	**57**	**60**	**53**	**57**	**64**	**52**
1.5C-REF	**10**	**16**	**2**	**74**	**70**	**78**
1.5C-ALL	**59**	**62**	**54**	**91**	**91**	**91**

gation (NPi-ALL). Only the combination of all demand-side policies and climate policies (1.5C-ALL) leads to emission levels closer to zero in 2050 (0.19 $GtCO_2$/yr), with 91% reductions compared to the NPI-REF scenario in 2050.

The investigated scenarios result in substantially different cumulative CO_2 emissions for space heating and cooling in the period 2020–2050 (Fig. 3, C). The demand-side policies in the NPi-ALL scenario reduce cumulative emissions by 36% compared to the NPi-REF scenario. Under stringent climate policies (1.5C-REF), cumulative emissions are lowered by 48%. Implementing demand-side policies in combination with stringent climate policies (1.5C-ALL) further reduces cumulative emissions by 14%, realizing a total reduction of 62% relative to the NPi-REF scenario.

4.4 Regional and sectoral decarbonization

The analysis of CO_2 emissions by region, end-use and emission type – direct from fossil fuel burning in buildings and indirect from district heating and electricity supply – provides further important insights on the mitigation pathways (Fig. 4). In most Global North regions (Fig. 4, A), significant reductions in CO_2 emissions are expected already in the NPi-REF scenario, up to − 30% compared to 2020 (see Supplementary Information 1, sec-

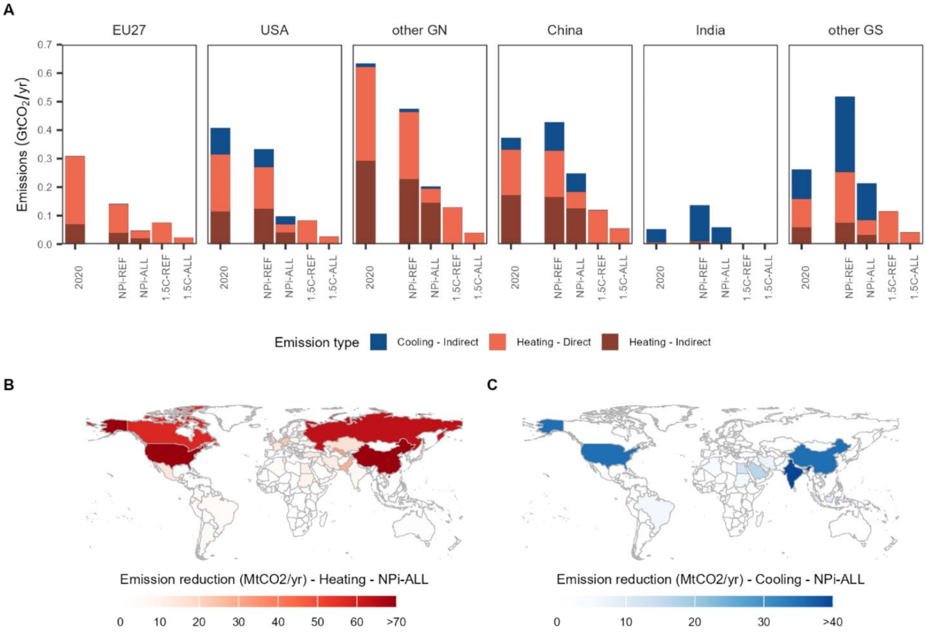

Fig. 4 **A** CO_2 emissions for space heating and cooling in different world regions in 2020 (base year) and in 2050 for different combinations of demand-side (REF and ALL) and climate policy (NPi and 1.5C) scenarios. See Table 1 for scenarios definition. World regions: European Union (EU27), USA, other Global North Regions (other GN), China, India, other Global South regions (other GS). **B** Map of CO2 emission reductions for space heating in the NPi-ALL scenario relative to the NPi-REF scenario in 2050. **C** Map of CO2 emission reductions for space cooling in the NPi-ALL scenario relative to the NPi-REF scenario in 2050

tion 4.3 for country-level results). This is due to reduced direct emissions for space heating driven by increase in energy efficiency and partial supply system decarbonization under current policies, particularly in the European Union, and to some extent in the USA and other regions. In the NPi-ALL scenario, emissions substantially drop due to the implementation of demand-side measures, up to 64%. The countries with the highest absolute emission reduction potential in the Global North include the USA, Russia, and Canada for space heating and the USA for space cooling (Fig. 4, B). While major reductions in indirect CO_2 emissions are achievable under more stringent climate scenarios (1.5C-REF), only the sectoral policies drive the abatement of direct emissions for space heating (1.5C-ALL), up to a total 91% reduction of direct and indirect emissions compared to the NPi-REF scenario in 2050.

In the Global South, CO_2 emissions from space heating and cooling increase by 57% by 2050 in the NPi-REF scenario (see Supplementary Information 1, section 4.3 for country-level results) and constitute more than half of global emissions. This increase is mostly driven by the tripling indirect emissions for space cooling under stark demand increase, especially in India and other developing regions. The combination of sectoral policies (NPi-ALL) leads to 52% reduction in CO_2 emissions for space heating and cooling in the Global South relative to the NPi-REF scenario in 2050. Reductions are driven by lower energy demand levels, and fossil fuel switches, resulting in lower emissions from cooling and direct emissions for heating. The top countries for absolute emission reduction potential in the

Global South include India, China, and Saudi Arabia for space cooling and China for space heating (Fig. 4, B). The decarbonization of the supply system under 1.5 °C-consistent climate policies (1.5C-REF), contributes to neutralizing indirect CO_2 emissions, while the direct emissions for heating are significantly reduced only when combining the demand-side policies (1.5C-ALL), bringing down total emissions by 91%.

5 Demand-side policies to deliver climate change mitigation

Understanding gaps between model-estimated potentials for climate change mitigation and the realized emission reductions has been under scrutiny and shown to be challenging. This section showcases real-life policy examples around the world, whose extension, more stringent implementation, combined with new initiatives could deliver the energy demand reduction potential in our modelled scenarios. The NPi-ALL scenario assumes a strengthened system of energy demand policies compared to current policies in the NPi-REF scenario. Although a wide range of public policies in the building sector are already used across both the Global South and the Global North, the NPi-REF scenario projects an increase of energy demand and activity levels (floor space, cooling and heating penetration, usage patterns, etc.). Energy efficiency policies spread dynamically across countries, reducing energy demand by nearly 50% in the Organisation for Economic Co-operation and Development (OECD) countries between 1970 and 2000 (Geller et al. 2006), and doubling energy efficiency progress during the decades preceding the 2020s (IEA 2023a), substantiating the modelled trends described in Section 4. Traditionally, sectoral technology policies aimed at supply and end-use technology, while the potential of socio-behavioural and infrastructural policies is gaining attention only recently. The uptake and stringency of energy demand policies have geared up, for example 30% more countries had building energy codes in 2020 than in 2015 (79 and 62 respectively) (UNEP 2021), with a gradual paradigm shift towards performance-based, integrated, and modular building codes (Nwadike et al. 2019). Further broadening along this line is underlying the results of the NPi-ALL scenario. Hereby, we provide examples of policies along the three demand-side policy dimensions in this study – Activity, Electrification, and Technology (see Section 2) – to exemplify how the modelled results could materialize (with more details and examples in Supplementary Information 1, section 5).

5.1 Activity level reductions and sufficiency

Policies related to activity level reductions and sufficiency are underrepresented across actual policy systems and modelling studies (Samadi et al. 2017). Yet, in the future they have a critical role in reducing the demand at the closest point to actual consumption, thus relate to a potential of 27% CO_2 emission reductions in our modelling. They are also well placed to address fair consumption of space and resources (Cabeza et al. 2022).

Activity reductions have been often achieved through policies supporting voluntary measures. The Japanese "Cool Biz" or the French "All actions matter" campaigns (OECD 2024) encouraged changing clothing behaviour in combination with more conservative room temperature set-points, and achieved significant energy savings. Given the expected rise in cooling demand in the NPi-REF scenario, adopting similar temperature campaign policies in the Global South could help limiting the overgrowth of cooling while ensuring indoor thermal comfort levels (Jareemit and Limmeechokchai 2019).

Construction moratoria (Nick 2024), while considered rather authoritative, can limit floor space demand for specific local goals, for instance addressing concerns about uncontrolled sprawl in North Macedonia (Stefanovska and Koželj 2012), or preserving green belts in Seoul, South Korea (Bengston and Youn 2006). Cluster zoning ordinances in New York and other US cities led to more compact urban development (Bengston et al. 2004). The adoption of these and other policies for urban sprawling containment already experimented in the Global North could help address rapid growth of cities of the Global South (Amponsah et al. 2022) with important implications not only for energy but also for land and resources demand.

In the Global North, reusing vacant space and limiting secondary and holiday homes could reduce floorspace demand and policies were already demonstrated in Europe, e.g. the vacancy tax in France or the 'Auto-récupéro' program in Italy (Foundation Abbé Pierre, 2016), making use of empty living space for social housing. Similar policies could be particularly impactful in regions with large vacant housing stocks, such as the EU (Fondation Abbé Pierre 2016) and China (Woodworth and Wallace 2017).

The limitation of sufficiency policies lies in the level of acceptance by their target groups (Akenji et al. 2021) and the risk of rebound effects (Sorrell et al. 2020). It is important to stress that providing adequate services, such as minimum housing as defined e.g. through decent living standards (Rao and Min 2018), must become part of successful policies, exemplified by national cooling action plans, which prioritize passive and low-cost measures over technological solutions to reduce cooling energy demand, while ensuring human well-being (Hu et al. 2023).

5.2 Electrification and fuel shifts

Fuel shifts on the demand-side are critical components of emission reduction policies, sometimes even contrasted to energy efficiency solutions. The impacts on CO_2 emissions are lower, because of the countereffects of growing overall demand for the service they supply. Policies related to electrification, fuel shifts, and rolling-out renewable technologies in buildings were introduced progressively since the 1950s, increasing in the 1970s, and peaking in the early 2000s, with another boost in the 2020s (IEA 2023b). Electrification of heating at the household or district level distils largely to heat pumps as the main technology pathway. By 2018 close to 50% of US new residential buildings were constructed with heat pumps (IEA 2022), 43% in Germany and 90% in Switzerland in 2019 (Weigert et al. 2022). Heat pump subsidies have become universal in the EU member states by 2022, leading to 8 $MtCO_2$ emission savings only from new installations in that year. With extension to global level, the avoided gas demand was estimated to be 80 billion m^3 in 2030 (IEA 2022), as local examples of similar grants in the Global South show.

Financial incentives, taxes and levies influence the household electricity-to-gas price ratio. In Belgium, the growth of the ratio from around 3 to 6 in 15 years partially due to high taxes, explains a shift towards biomass and gas heating (+ 18.6% and +6.0%) (Soete et al. 2024). Conversely, in Sweden taxes reduce the price differences, upholding more electric solutions (Ruffino et al. 2022). Removing perverse subsidies on fossil fuels has been advocated to expedite electrification and decarbonization effectively (Zhang and Zahoor

2025). Previous studies (Shittu et al. 2024) have shown that fuel subsidies in Malaysia are highly regressive, and only 4% of the subsidy lands with the bottom 20% of the population. They claim that the short-term stress on low-income households should be compensated instead of avoiding subsidy reform. Yet, climate effectiveness and political feasibility have been questioned by others (Chepeliev and Van Der Mensbrugghe 2020). In recent fuel shift examples, e.g. in Indonesia, Ghana, and Hungary (UNDP 2021), the combination with other deliberate information campaign, compensational measures for vulnerable households, or support for electrification was part of the success.

Mandatory regulations on fossil heating technology, such as banning of new gas, oil, and coal boilers, swaps of existing heaters, and combined with financial incentives (Braungardt et al. 2023; Torné and Trutnevyte 2024) enhance the impact of electrification policies. In the Global South, e.g. Brazil and India, measures to connect urban space heating and cooling with industrial waste heat or co-generation at a district level have been on the rise (IRENA, IEA and REN21 2018). Though policies are varied for demand electrification, our study shows a limited impact of 11% CO_2 emission reduction in the NPi-ELE scenario compared to NPi-REF in 2050. This highlights the need of combining fuel shifts with energy efficiency improvements of building shells for larger energy and emission reductions. Further to fuel shifts, the recent report of the Intergovernmental Panel on Climate Change (IPCC) estimates that renewable energy policies contribute 9% of the total potential of emission reduction (IPCC 2023).

5.3 Technology and energy efficiency improvements

Policies to improve technologies and their adoption have the longest history and can achieve CO_2 emission reductions of 43% in 2050 according to our results. Energy codes for residential buildings are used in 85 countries, but 20 per cent of mandatory codes are older than 10 years and would require critical updates (UNEP 2025). Building codes and product standards deliver the highest net savings at societal level, however their emission saving potential strongly depends on the effectiveness of enforcement (Boza-Kiss et al. 2013). In response to the Paris Agreement, building standards have become more stringent, moving towards net-zero commitments (UNEP 2025), e.g. the 2022 Zero Code for California (IEA 2022), the Brussel Capital Region PEB legislation (Boza-Kiss et al. 2022), among many others.

Low renovation rates limit wide-scale adoption of high performing buildings. While the EU directives such as the revised Energy Performance of Buildings Directive EU/2024/1275 set out renovation rate improvement targets (Dulian 2024), implementation policies are rare. Examples include the obligatory renovation of certain building types in the rental market in the Domestic Minimum Energy Efficiency Standard in the UK (BEIS 2023), and tailored information through renovation passports in Germany (Sesana and Salvalai 2018), or the combination of loans, subsides and facilitators in the form of one-stop shops around the EU (Bertoldi et al. 2021a).

Financial and fiscal instruments to support renovation and energy-efficient technologies, such as grants, subsidies, loans, taxes, levies, tax relief, and innovative instruments such feed-in tariffs and white certificates, are popular because of easiness of implementation and wide-ranging experience (Bertoldi et al. 2021b). However, program evaluations are rare and have shown that results can significantly vary, between few percents to up to 20–25%

energy consumption savings (Hondeborg et al. 2023). Financial and fiscal instruments are particularly sensitive to design, implementation scrutiny, and the local context and can cause harm in other policy areas or be susceptible for free-riders. A combination of schemes is more effective than single subsidies to increase the depth of energy efficiency improvements, in line with the results of our TEC scenarios. Grants and subsidies should be focused to overcome transaction costs, initial high costs of new technologies, and awareness raising, especially for measures with longer payback time. The use of financial instruments can be justified also for low return investments if energy efficiency aspirations are combined with energy poverty alleviation and social targets (Müller et al. 2024).In developing countries, upscaling the uptake of affordable low-energy buildings through targeted policies can contribute not only to reduce energy and GHG emissions, but also to bridge the current housing gaps and promote the sustainable development agenda (Bulkeley et al. 2014; Mastrucci and Rao 2019).

6 Discussion and conclusions

This study explored the decarbonization effect of a broad set of demand-side policies with or without ambitious climate policies for the global residential building sector, focusing on space heating and cooling. The results showed that policies centred on activity reduction, electrification and fuel shifts, and demand-side technology improvements entail the highest energy demand reduction potential when combined, up to 57% (NPi-ALL scenario) relative to the reference scenario (NPi-REF) in 2050, even in the absence of supply-side interventions and carbon taxes. Stringent climate policies, enabling the decarbonization of the electricity supply system, are critical for CO_2 emission abatement. However, this study showed that only the combination of demand-side policies and stringent climate policies (1.5C-ALL scenario) delivers CO_2 emission levels close to net-zero, with reductions up to 91% relative to the reference scenario in 2050. Reaching full carbon neutrality would require additional efforts to abate the residual direct CO_2 emissions, e.g. due to remaining use of gas and other fossil fuels for space heating.

These results are aligned with available residential global space heating and cooling projections (Chatterjee et al. 2022a; Daioglou et al. 2022; Camarasa et al. 2022), and the recent report of the IPCC on climate change mitigation (Cabeza et al. 2022). The global CO_2 emission reduction potential of our demand-side policy scenario (NPi-ALL scenario) is also comparable to the global mitigation potential of 61% average mitigation potential of the entire building sector based on aggregated results of bottom-up studies reported in the IPCC report compared to baseline scenarios.

An abundant range of policies has already contributed to demonstrate demand-side energy reductions in the real world. Increasing the adoption and enhancing the effectiveness of these policies beyond current levels would be needed to deliver the energy demand and emission reductions in our NPi-ALL scenario, leading to floorspace and activity reductions, electrification and fuel switches, and technology efficiency improvements in new and existing buildings. Examples of potential improvements include: increasing the stringency of building standards; combining new electrical technologies with fossil-related bans; providing new types of tailored information, as exemplified by renovation passports; and promoting innovative facilitation models, including one-stop-shops and financial mechanisms.

While there are many barriers and uncovered policy areas, we also found many successful examples of these policies. For most of the policies presented, we have illustrated that they need reinforcing with other policies to deliver larger change and address additional policy goals, such as reduction of inequality (Irrek and Jarcynski 2007; Givoni et al. 2010; Boza-Kiss et al. 2013).

Existing literature shows that policy-driven market transformation has pushed the costs of climate mitigation strategies in buildings to the range of conventional buildings (Ürge-Vorsatz et al. 2020). Energy efficiency investments in buildings are, however, significantly below the level required to meet mitigation targets (UNEP 2025). New highly energy-efficient buildings with costs < 100 USD per tCO_2 could realize 25% of the mitigation potential in 2050 in developing countries (Cabeza et al. 2022). Sufficiency policies focusing on activity reduction are likely to have lower costs, although robust cost assessments are largely missing, and could support the delivery of higher mitigation potential in developed countries (Cabrera Serrenho et al. 2019), along with renovation efforts. While existing cost figures are mostly based on exemplary buildings, wide-scale cost assessments are still limited, especially at the global level (Knobloch et al. 2019; Daioglou et al. 2022). Moreover, cost effectiveness of advanced buildings solution and heating and cooling systems significantly differs across literature (Cabeza et al. 2022). Existing literature shows that richer policy mixes, while being more capital-intensive, could lead to larger fuel savings for heating compared to carbon taxes only (Knobloch et al. 2019). The longer payback time of ambitious demand-side interventions could reduce their financial attractiveness. Considering the broader impacts of mitigation strategies on the economy, environment, health, and wellbeing beyond energy costs, often referred to as "co-benefits", has been widely discussed as solution to promote demand-side policies (Baniassadi et al. 2022). Yet, there are significant gaps in the assessment of co-benefits for specific sectors, technologies, and geographies (Thema et al. 2019). Previous studies have shown potential of energy efficiency policies on buildings to support economic growth, self-sufficiency, and sustainable development in developing regions, and health benefits, productivity, and avoided fuel costs in developed regions (Chatterjee et al. 2022b). More research is needed to comprehensively assess the cost-benefits of demand-side policies in global mitigation scenarios.

Future developments will focus on expanding the model to cover other energy services, e.g. cooking and appliances, and the public and commercial sectors. Climate change impacts on heating and cooling demand and temperature feedback will be further included leveraging the linkage with the MESSAGEix-GLOBIOM IAM (Byers et al. 2024). Accounting for the material dimension of buildings is critical for assessing the broader effect of mitigation policies while considering all stages of the building life cycle beyond operational energy, e.g. including the impacts of material production as effect of building activities. While our model was calibrated with available external data to ensure consistency of building stock and energy demand estimates in the base year, additional data on building stock and activities, including timeseries, would be needed. Data of this kind are scarce, especially for the Global South, and could improve the building sector projections in future developments. As a result, the representation of heterogeneities across housing and household groups is still hindered by limited data availability in several regions and will be further improved in future work. With improved data availability and empirical evidence on the effect of different policies in different contexts, the representation of heterogeneities and building dynamics can be improved to better reflect local contexts and distributional aspects. Coupling with models focusing on specific aspects, e.g. social and behavioural aspects, can contribute to overcoming current limitations in the exogenous representation of some key dimensions, e.g. behaviour and lifestyle changes.

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Benigna Boza-Kiss: Investigation, Writing – Original draft.
Bas van Ruijven: Conceptualization, Writing – Review & Editing, Validation.

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Data availability The datasets generated during the current study are available in the Supplementary Information 2.

Declarations

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

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