Global scenarios of residential heating and cooling energy demand and CO_2 emissions

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Abstract

Buildings account for 36% of global final energy demand and are key to mitigating climate change. Assessing the evolution of the global building stock and its energy demand is critical to support mitigation strategies. However, most global studies lack granularity and overlook heterogeneity in the building sector, limiting the evaluation of demand transformation scenarios. We develop global residential building scenarios along the shared socio-economic pathways (SSPs) 1–3 and assess the evolution of building stock, energy demand, and CO_2 emissions for space heating and cooling with MESSAGEix-Buildings, a modelling framework soft-linked to an integrated assessment framework. MESSAGEix-Buildings combines bottom-up modelling of energy demand, stock turnover, and discrete choice modelling for energy efficiency decisions, and accounts for heterogeneity in geographical contexts, socio-economics, and buildings characteristics.

Global CO_2 emissions for space heating are projected to decrease between 34.4 (SSP3) and 52.5% (SSP1) by 2050 under energy efficiency improvements and electrification. Space cooling demand starkly rises in developing countries, with CO_2 emissions increasing globally by 58.2 (SSP1) to 85.2% (SSP3) by 2050. Scenarios substantially differ in the uptake of energy efficient new construction and renovations, generally higher for single-family homes, and in space cooling patterns across income levels and locations, with most of the demand in the global south driven by medium- and high-income urban households. This study contributes an advancement in the granularity of building sector knowledge to be assessed in integration with other sources of emissions in the context of global climate change mitigation and sustainable development.

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1 Introduction

Accounting for 36% of the global final energy demand and 39% of energy and process-related CO_2 emissions (IEA 2019a), buildings play a major role in climate change mitigation (Cabeza and Ürge-Vorsatz 2020). While considerable effort has been made towards energy efficiency improvements, the energy demand of buildings is still growing driven by increased demand for floorspace and thermal comfort (IEA 2019b). Unprecedented increase in buildings energy demand is expected in developing countries, along with rapid expansion of the building stock driven by growing incomes. Yet, there is an important opportunity in limiting future energy demand, while extending access to shelter and thermal comfort in developing countries, by promoting construction of energy efficient buildings, as the building stock is set to double by 2050 (IEA 2019a). In the developed world, energy mitigation potential largely relies on the renovation of older and inefficient buildings, which will still constitute the majority of the building stock in these regions by mid-century (Urge-Vorsatz et al. 2020).

The Paris Agreement set ambitious targets to limit global warming, calling for climate mitigation action involving portfolios of energy supply and demand-side measures (IPCC 2018; Mundaca et al. 2019). Global climate mitigation research and scenarios largely focus on supply-side solutions (Creutzig et al. 2018; Grubler et al. 2018). Drastic reductions in energy demand could play a critical role in carbon mitigation pathways, limiting the reliance on uncertain and contested negative emission technologies (Mundaca et al. 2019; Cabeza and Ürge-Vorsatz 2020). However, a better understanding on demand-side solutions is missing (Creutzig et al. 2018). In particular, assessing the evolution of the global building stock and associated energy demand under different socio-economic futures is crucial for developing successful strategies towards meeting stringent climate targets. However, most global studies lack granularity and overlook heterogeneity in the building sector, limiting the evaluation of demand transformation scenarios.

We develop a set of global residential building scenarios along the shared socio-economic pathways SSP1-3 narratives (O'Neill et al. 2017; Riahi et al. 2017) and assess the evolution of the building stock and associated energy demand and CO_2 emissions for space heating and cooling. We try to overcome limitations in previous global studies by developing a modeling framework, named MESSAGEix-Buildings, that includes modules for the assessment of energy demand, building stock turnover, and energy efficiency decisions under future scenarios, while incorporating a high level of granularity. We attempt to surmount data availability issues, by using survey data from a series of countries representative of different world regions. The model is soft-linked with the integrated assessment model (IAM) MESSAGEix-GLOBIOM (Huppmann et al. 2019), receiving inputs on energy prices and CO_2 emission factors, and accounting for the evolution of the energy system under different scenarios. IAMs are typically used for full-economy assessment of global mitigation pathways. Yet, despite often detailed process-based representations of the energy supply and land use sectors, final energy from the building sector remains comparatively unexplored. This study contributes an advancement in the granularity of building sector knowledge to be assessed in integration with other sources of emissions in the context of global climate change mitigation.

In the following sections, we discuss the state of the art on building stock energy demand modeling at the global level (Section 2), and provide an overview of the MESSAGEix-Buildings modeling framework and its global implementation (Section 3). We describe the scenario

narratives, settings, and assumptions (Section 4), and present results on the evolution of the global building stock and projections of energy demand, and CO_2 emission (Section 5). We finally discuss the implications of the results (Section 6) and we conclude (Section 7).

2 Literature review

Beside the annual IEA World Energy Outlook reports (IEA 2020), only few recent studies have focused on developing building energy demand models and scenarios at the global level in the context of climate change mitigation (Isaac and van Vuuren 2009; GEA 2012; Ürge-Vorsatz et al. 2012; Harvey 2014; Güneralp et al. 2017; Levesque et al. 2018; Knobloch et al. 2019; Edelenbosch et al. 2021), see also Supplementary Material, section SM4. Due to the complexity of the building sector and its heterogeneity across regions, as well as data availability issues, several limitations are recurrent. Most global studies lack granularity on geographical and socio-economic aspects, as well as on building stock characteristics. Existing studies often rely on strong exogenous assumptions, while overlooking the dynamics of building stock turnover, energy efficiency improvements and uptake of renovations and low energy new buildings. Recent advancements in global buildings studies have included improved representation of different building types, locations and climates (Ürge-Vorsatz et al. 2012), floorspace demand (Levesque et al. 2018), stock turnover dynamics (Edelenbosch et al. 2021), behavioral change, and efficient technology (Levesque et al. 2019). Although slum populations account for one billion people worldwide (UN 2020), informal settlements in developing countries are rarely considered in global building studies (Ürge-Vorsatz et al. 2012). Alternative socio-economic pathways are considered only by few studies (Levesque et al. 2018; van Ruijven et al. 2019), with many studies focusing on single socio-economic scenarios.

While quantitative studies on the global building stock have been limited, several studies focus on building scenarios at national or regional level. In contrast to global studies, regional studies are often characterized by higher granularity in representing the building stock and detailed accounting of a number of dynamics. Existing studies have improved the detail in household heterogeneity to better assess underlying trends of energy use, especially for developing countries (van Ruijven et al. 2011; Daioglou et al. 2012; Eom et al. 2012). Building stock turnover dynamics have been represented in a number of national and regional studies by using material flow analysis (Pauliuk et al. 2013; Sandberg et al. 2016, 2017; Huo et al. 2019). The dynamics of building renovation and energy efficiency choices have also been addressed using bottom-up simulation and discrete choice models (Giraudet et al. 2012; Knobloch et al. 2019). Agent-based models allow for representing a richer set of behavioral dynamics (Liang et al. 2019; Niamir et al. 2019; Nägeli et al. 2020), though their application at global level can be challenging due to lack of available data for calibration (Knobloch et al. 2019). Some of these dynamics have been implemented at the global level in studies focusing on specific aspects of buildings, in particular the decision on space heating systems (Knobloch et al. 2019), or building stock turnover (Deetman et al. 2020). However, integration of such features remains limited to specific applications, while the potential for more granularity and simultaneous representation of broader buildings and renovation dynamics remains largely unexplored.
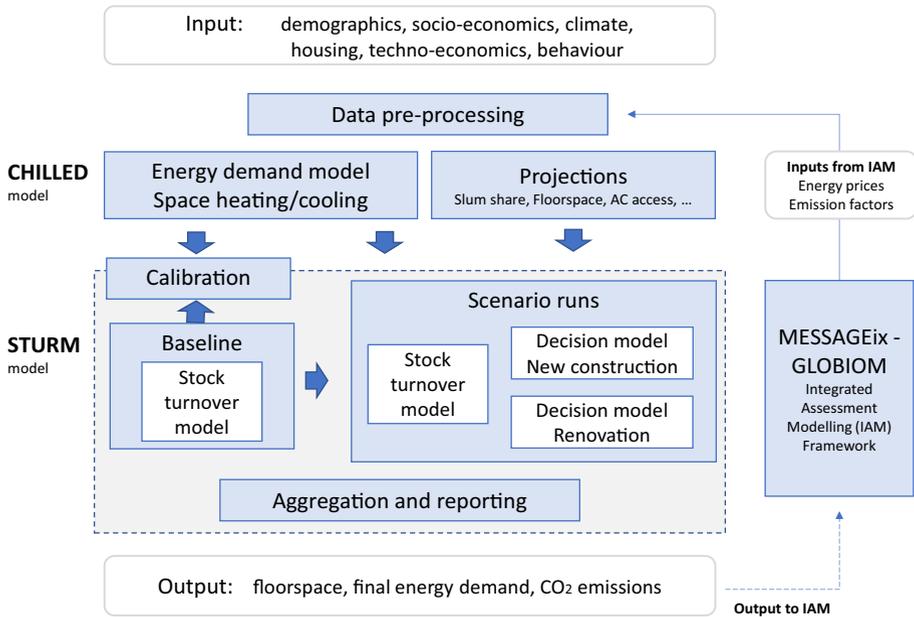
Fig. 1 Modelling framework and workflow overview.

3 Methods

3.1 Framework overview

MESSAGEix-Buildings is a framework for modeling the energy demand in the building sector under different socio-economic, technology, climate, and policy scenarios. In this study, we use two interlinked modules within MESSAGEix-Buildings: CHILLED (Cooling and Heating gLobaL Energy Demand model), a bottom-up engineering model to estimate space heating and cooling energy demand (Section 3.2); and STURM (Stock TURnover Model of global buildings), a stock turnover model based on dynamic material flow analysis (MFA) and discrete choice models to assess new constructions, demolitions and renovation activities, and energy efficiency decisions (Section 3.3). The framework is flexible in temporal and spatial resolution and allows for highly granular representation of the residential sector, including key household dimensions (location, income, and tenure) and building characteristics (housing type, energy efficiency standard, and fuel use). A soft-linkage was established with the IAM MESSAGEix-GLOBIOM (Huppmann et al. 2019), a modeling framework for the comprehensive assessment of energy-environment-economy systems extensively used for developing energy scenarios and identifying socio-economic and technological response strategies to major energy challenges.

The basic workflow is shown in Fig. 1. First, we collect and pre-process input data, including basic demographics and socio-economics projections, and building-related data. Second, we generate additional projections for intermediate variables, including floorspace, share of slum population, and access to air-conditioning (AC). Third, the space heating and cooling energy demand intensity per unit floor space is calculated in CHILLED

for all existing and future building cohorts (building types and energy efficiency levels). Fourth, the building stock configuration for the base year is reconstructed by running the stock turnover model over the past, and the results calibrated against measured data. Fifth, we run STURM along future scenarios to project building stock characteristics and energy demand. Finally, results, including building stock characteristics, floorspace, energy demand, and CO_2 emissions, are aggregated and reported.

3.2 Energy demand model

The space heating and cooling demand calculations are run using the CHILLED model presented in (Mastrucci et al. 2019), to which we refer readers for further details. The model is based on variable degree days (VDD) (Al-Homoud 2001). VDD methods differ from traditional degree days in that they analytically calculate, instead of assuming arbitrarily fixed, balance temperatures. Thus, the balance temperature is defined as the outdoor temperature at which neither heating, nor cooling is required (Claridge et al. 1987; Al-Homoud 2001). The analytical calculations in VDD allow for a more accurate representation of actual balance temperatures of buildings, depending on the level of thermal insulation of the building envelope, internal and solar heat gains, and other occupant behavior-related parameters. The balance temperature $T_{\text{bal},m}$ (°C) is calculated on a monthly (m) basis using the following equation:

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

where T_{sp} (°C) is the desired indoor set point temperature, $g_{\text{sol,m}}$ (W) is the heat flow from solar heat sources for the month m, g_{int} (W) is the heat flow from internal heat sources, H_{tr} (W/°C) is the heat transfer coefficient by transmission and H_{ve} (W/°C) is the heat transfer coefficient by ventilation. We refer the reader to previous work by Mastrucci et al. (Mastrucci et al. 2019) for the details on the calculation of the coefficients $g_{\text{sol},m}$, g_{int}, H_{tr}, and H_{ve}. The monthly variable heating ($\text{VDD}_{\text{h,m}}$) and cooling degree days ($\text{VDD}_{c,m}$) are calculated as follows:

$$\text{VDD}_{h,m} = \sum_{d=1}^{dm} \left(T_{\text{bal},m} - \overline{T}_{\text{out},d} \right)^+ \qquad (2)$$

$$\text{VDD}_{c,m} = \sum_{d=1}^{dm} \left(\overline{T}_{out,d} - T_{\text{bal},m} \right)^+ \qquad (3)$$

where $T_{\text{out},d}$ is the average daily outdoor temperature, $T_{\text{bal},m}$ the balance temperature, and d_m the number of days in the month (only positive values are accounted). The annual final energy for heating (E_h) and cooling (E_c) is calculated as follows:

$$E_h = \sum_{m=1}^{12} \frac{\left(H_{tr} + H_{ve} \right) \cdot f_{op,h} \cdot f_{fl,h} \cdot \text{VDD}_{h,m}}{\eta_h} \qquad (4)$$

$$E_c = \sum_{m=1}^{12} \frac{\left(H_{tr} + H_{ve} \right) \cdot f_{op,c} \cdot f_{fl,c} \cdot \text{VDD}_{c,m}}{\eta_c} \qquad (5)$$

where $f_{op,h}$ and $f_{op,c}$ are the daily operation time fractions for heating and cooling respectively, $f_{fl,h}$ and $f_{fl,c}$ the heated and cooled floor area, and η_h and η_c the efficiency of the heating and cooling systems. The equations are run over a spatial grid at 0.5° grid resolution (approximately 50 km at the equator) at the global level for a set of representative building archetypes with characteristics and thermal properties varying by region, housing type, and energy efficiency cohort. Results, by archetype, are population weighted; aggregated by location, country, and climatic zone; and associated with the respective geographical and housing categories in the STURM model.

3.3 Building stock turnover model

The model STURM combines a stock turnover model using MFA (Sandberg et al. 2016) and discrete choice models for energy efficiency decisions (Giraudet et al. 2012), to estimate the evolution of the building stock and building activities, including new constructions, renovations, and demolitions. The model is partly stock-driven, as housing demand is driven by population and therefore by the stock requirements, and partly activity-driven, as new construction and renovation decisions are determined using dedicated discrete choice models. Being the current distribution of building vintage cohorts unknown for many world regions, we initially run the stock turnover model over the past and use the base year results for model calibration (see Supplementary Material, sections SM3.1-SM3.2). We then run the stock turnover and decision models jointly for future scenarios. Detailed model description and equations are available in the Supplementary Material, section SM3.1.

In the scenario runs, energy efficiency decisions on new constructions and renovations are assessed via discrete choice models based on previous studies (Giraudet et al. 2012). Decisions on the uptake of a given option (j) in new construction (new) and transitions from initial (i) to final (f) condition in renovation (ren) for building shell, heating systems, and heating fuels are estimated based on life cycle costs (LCC) considerations:

$$\text{LCC}_{\text{new},j} = C_{\text{inv},j} + C_{op,j} + C_{\text{int},j} \tag{6}$$

$$\text{LCC}_{\text{ren},i \to f} = C_{\text{inv},i \to f} + C_{op,f} + C_{\text{int},i \to f} \tag{7}$$

where C_{inv} are the investment costs, C_{op} the operational costs, and C_{int} the intangible costs associated with option j. Operational costs depend on both energy prices and energy demand associated with specific building shell and fuel options. The market share (MS) for each option is then calculated by comparing the LCC of all possible k options using the following equation:

$$MS_{\text{new},j} = \frac{\text{LCC}_{\text{new},j}^{-\nu}}{\sum_k \text{LCC}_{\text{new},k}^{-\nu}} \tag{8}$$

$$MS_{\text{ren},i \to f} = \frac{\text{LCC}_{\text{ren},i \to f}^{-\nu}}{\sum_k \text{LCC}_{\text{ren},i \to k}^{-\nu}} \tag{9}$$

where ν is the heterogeneity parameter, set exogenously to 8 (Giraudet et al. 2012). For renovation, an option for no energy efficiency improvements (no renovation) is also included. Energy renovation rates are therefore endogenously calculated, based on thenumber of

renovation actions in the stock. A set of constraints related to the feasibility of specific new construction and renovation solutions, as well as bounds to renovation rates, can be set at regional level. A discount rate is applied to operational costs and varies across regions, buildings, and household types to express different predispositions to investment.

After new construction and renovation decisions are assessed, the configuration of the housing stock is updated and total floorspace calculated by building cohort, by multiplying the number of housing units by the household size and per-capita floorspace. Finally, energy intensities from the energy demand module (Section 3.2) and emission factors are associated to different building cohorts and fuels, and total final energy demands, and CO_2 emissions are calculated at the stock level. Results can be aggregated at different target levels for reporting.

3.4 Global implementation

We explicitly represent in the model a series of dimensions to account for geographical, socio-economic, and housing stock heterogeneity (Table 1). Each dimension is linked to a series of model parameters (Table 2). The model is highly rich in granularity and represents different geographical contexts (countries, regions, climatic zones), locations (urban/rural), socio-economics (income classes, tenure), housing and heating/cooling systems (housing types, energy efficiency cohorts, fuel types), and associated dynamics. We distinguish standard housing (formal), including single-family houses (SFH) and multi-family houses (MFH), from slum (informal) housing to track access to decent housing. Energy efficiency levels are represented by a series of building cohorts. We differentiate existing non-renovated buildings based on their vintage, corresponding to different levels of insulation and energy efficiency of heating systems. Similar to existing studies (GEA 2012; Ürge-Vorsatz et al. 2012), we distinguish "standard" and "advanced" renovated and new buildings depending to their energy performance[1] (see Supplementary Material, section SM2.6.2–2.6.3). Housing types and energy efficiency cohorts are mapped to heating fuels and jointly determine the energy efficiency of the heating system. As an example, buildings using electricity for heating are associated either with electric heaters or heat pumps based on their energy efficiency level, assuming that the latter are not suitable in combination with poorly insulated building shells. While decisions on energy efficiency improvements and heating fuels are endogenous and reflect different household behaviors, we consider district heating exogenously, to reflect actions on infrastructures normally not decided at an individual household level.

We run simulations at the level of 174 countries plus climatic zones, and feed the model with rich input data at the most granular level to represent geographic heterogeneity. For data not available at the national level, we use data at a more aggregate level, using the definition of the eleven regions in global IAM MESSAGEix-GLOBIOM. For convenience, in this paper, we report results by six macro-regions (see Supplementary Material, section SM2.1 for detailed region definition): Europe (WEU + EEU), North America (NAM),

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[1] "Standard" energy efficiency level represents the current construction practice, "advanced" represents improved performance. Advanced new buildings have thermal insulation level of the building shell meeting the passive standard in the global north, and level similar to European current practice in the global south. Energy savings levels for renovation range between 10 (SSP3) and 30% (SSP1) for standard, and between 30 (SSP3) and 50% (SSP1) for advanced renovation.

other global north (other GN), Centrally Planned Asia (CPA), South Asia (SAS), and other global south (other GS).

Scenario runs cover the period 2015 to 2050, with a time step of 5 years. As data on the distribution of building vintage is available only for limited regions, mostly in the global north, we run the turnover model starting from 1820 to recreate the stock configuration for the base year in all regions. Building stock results are then validated in the base year for the regions with available data, showing a good agreement (see Supplementary Material, section SM3.3).

4 Scenarios

We develop three building scenarios representing different socio-economics aligned with the SSP framework. The SSPs represent alternative futures of societal development (O'Neill et al. 2017), widely used for integrated assessment of global environmental change. We focus on SSP1, SSP2, and SSP3 to represent respectively low, medium, and high challenges to climate mitigation and adaptation. We subsequently translate the qualitative narratives into assumptions and input settings for the model.

4.1 Building stock narratives

The global SSP1 is characterized by commitment towards sustainable development goals, increasing environmental awareness, and a gradual move to less resource-intensive lifestyles (O'Neill et al. 2017) with low challenges to both adaptation and mitigation (Riahi et al. 2017). Housing size declines in most regions of the global north, while increasing in the global south under rising income levels, improved access to decent housing, and slums eradication. Energy efficiency of buildings and renovation rates increase driven by policy, high technological advancement, and increased environmental awareness. Space heating and cooling energy demand is relatively low for the global north, while it keeps on increasing in the global south under improved access to thermal comfort.

The global SSP2 is a scenario consistent with observed historical patterns (O'Neill et al. 2017) with medium challenges to mitigation and adaptation (Riahi et al. 2017).

Table 1 Model dimensions in the global implementation

Dimension	Values
Country	174 countries
Region	11 regions (aggregated to 6 regions for reporting)
Location	Rural, urban
Climatic zone	20 climatic zones
Income class	Low, middle, high (tertiles)
Tenure	Owning, Renting
Housing type	Single-family house (SFH), Multi-family house (MFH), slum (informal)
Energy efficiency cohort	Existing buildings: before 1945, 1946–1990, 1991–2015 New buildings: standard, advanced Renovated buildings: standard, advanced
Energy carrier (Heating fuel)	Biomass (solid), coal, district heating, electricity, gas, oil

Table 2 Model parameters overview

Category	Parameter	Unit	Resolution	Main data sources*	Detailed description (supplementary material section)
Demographics and socio-economics	Population	Million	Country	Database (Riahi et al. 2017)	SM2.3.1
	Urbanization	%	Country	Database (Riahi et al. 2017)	SM2.3.1
	Household size	Number of members	Country	Database (UN 2019)	SM2.3.2
	GDP	$2005PPP/cap	Country	Database (Riahi et al. 2017)	SM2.3.3
	Inequality	-	Country	Database (Riahi et al. 2017)	SM2.3.3
Climate	Surface air temperatures	°C	0.5° Spatial grid	EWEMBI Database (Lange 2019)	SM2.4
	Solar irradiation (long- & short-wave)	W/m^2	0.5° Spatial grid	EWEMBI Database (Lange 2019)	SM2.4
Housing	Share of housing types	%	Region, location	Survey data	SM2.5.1
	Share of renting/owning	%	Region, location	Survey data	SM2.5.2
	Share of slums	%	Country, location, income class	Database (World Bank 2020)	SM2.5.3
	Floorspace per-capita	m^2/cap	Country, location, housing type	Survey data, literature (Fishman et al.; Harvey 2014)	SM2.5.4
	AC access	%	Country, location, climatic zone, income class	Survey data, literature (McNeil and Letschert 2008; Isaac and van Vuuren 2009)	SM2.5.5
	Share district heating	%	Region, location	Literature (Harvey et al. 2014)	SM2.5.6

Table 2 (continued)

Category	Parameter	Unit	Resolution	Main data sources*	Detailed description (supplementary material section)
Techno-economics	Building lifetime	Years	Region, housing type	Literature (Deetman et al. 2020)	SM2.6.1
	U-values	W/m²K	Region, housing type, energy efficiency cohort	Literature (Edelenbosch et al. 2021)	SM2.6.2
	Heating/cooling system efficiency	-	Energy source, energy efficiency cohort	Literature (IEA 2018; Levesque et al. 2018; Knobloch et al. 2019)	SM2.6.3
	Emission factors	tCO₂/TJ	Region, energy carrier	Output from MESSAGEix-GLOBIOM (McCollum et al. 2018)	SM2.6.4
	Energy prices	$	Region, energy carrier	Output from MESSAGEix-GLOBIOM (McCollum et al. 2018)	SM2.6.5
	Investment costs	$	Region, energy efficiency cohort, heating fuel	Literature (Giraudet et al. 2012; Fleiter et al. 2016; Esser et al. 2019; Mastrucci and Rao 2019)	SM2.6.6
	Intangible costs	$	Region, energy efficiency cohort, heating fuel	Literature (Giraudet et al. 2012)	SM2.6.7
	Discount rates	%	Region, housing type, tenure	Literature (Poblete-Cazenave et al. 2021; Giraudet et al. 2012)	SM2.6.8

Table 2 (continued)

Category	Parameter	Unit	Resolution	Main data sources*	Detailed description (supplementary material section)
Behavior	Set point heating/cooling	°C	Fixed	Survey data, literature (Jones et al. 2015)	SM2.7
	Hours operation heating/cooling	Hours	Region, climatic zone	Output of the energy demand calibration	SM2.7
	Share of heated/cooled floor-space	%	Region	Output of the energy demand calibration	SM2.7

* A complete overview of the survey data used in this study is available in the Supplementary Material, section SM2.2. Complete data sources are reported in the Supplementary Material, at the sections indicated in the table

Housing size growth trends continue both in the global north and south. Moderate increase in energy efficiency is expected, along with medium renovation rates. Energy demand levels are therefore in between SSP1 and SSP3.

The global SSP3 is a scenario of regional rivalry, international fragmentation, and reversal of globalization trends (O'Neill et al. 2017) with high challenges to both mitigation and adaptation (Riahi et al. 2017). Housing size increases at a slower pace compared to SSP2 and the divide between global north and south remains large, with persistence of slum settlements. Energy efficiency of buildings increases only marginally, and renovation rates remain low. Intensity of space heating and cooling operation increases in the global north and for higher income classes in the global south, while low-income populations in the global south continue experiencing lower access to thermal comfort and clean fuels. We refer the reader to the Supplementary Material, section SM1, for complete narrative descriptions.

4.2 Scenario settings, data inputs, and projections

The developed SSP building narratives were translated into quantitative assumptions for the model. Table 2 reports an overview of the main model parameters and data sources. Detailed descriptions of input data and projections are available in the Supplementary Material, section SM2.

4.2.1 Demographics, socio-economics, and climate

We use the SSP1-3 country-level projections for population, urbanization, economic growth, and income inequality from the SSP database (Riahi et al. 2017). We estimate income distributions based on GDP and Gini and attribute an average income level by income tertiles across households.

Climatic data include daily outdoor mean surface air temperatures, precipitation and solar irradiation (long- and short-wave) on a spatial grid at resolution 0.5 degree (~50 km at the equator) from the global EWEMBI dataset (Lange 2019) (see Supplementary Material, section SM2.4). We use the ASHRAE classification to define climatic zones boundaries using the gridded data for the period 1980–2009 (ANSI/ASHRAE 2013). This assessment represents only recent climatic conditions, but not changes in future climate.

4.2.2 Housing

Housing projections include the share of slum urban population, per-capita floorspace, and AC access (Fig. 2). Other parameters, such as housing vintage and energy efficiency levels, are model results. We estimate the share of SFH and MFH for the base year by region, based on survey data. Lacking more specific information, we keep the shares constant into the future by urban and rural areas. Thus, different urbanization rates lead to different stock composition, with higher urbanization typically corresponding to higher share of MFH.

Slums formation and development depend on complex dynamics and a series of factors (Roy et al. 2014). We found an empirical relation between slum urban population and per-capita GDP based on data for multiple countries (see Supplementary Material,

section SM2.5.3) and use it for extrapolations in future scenarios in the global south (no slums are assumed for rural areas and for the global north). While the share of urban slum population declines with income growth both in SSP1-2, though at different speed, it stays largely constant or increases in SSP3.

Per-capita floorspace projections were generated by first identifying scenario-specific regional trends, and then downscaling results to different housing types and locations. Similar to other studies (Hong et al. 2016), we assume a logistic function describing the future per-capita floorspace evolution towards a saturation level (Fishman et al 2020.; Harvey 2014), with region- and scenario-specific growth speed (see Supplementary Material, section SM2.5.4). In SSP2-3 per-capita floorspace increases for most regions, though at different pace. In SSP1 values converge towards 41.6m^2/cap (current value for the global north) (Fishman et al. 2020), resulting in constant or declining floorspace in the global north, and higher increase in other GS regions. Results are downscaled to different housing types and locations using region-specific relationships built based on survey data, e.g., per-capita floorspace is typically larger for rural compared to urban households, and for SFH compared to MFH and slums.

AC adoption is estimated through the model in (McNeil and Letschert 2008; Isaac and van Vuuren 2009), driven by climate and income level. We apply the model to different countries, locations, climatic zones, and income levels, for improved accounting of heterogeneity.

4.2.3 Techno-economics

We set building lifetime and survival curves by housing type and region based on existing studies (Deetman et al. 2020) and keep these constant over time and across scenarios. *U*-values depend on building efficiency level and vintage and vary by region. The efficiency of heating and cooling systems increases towards target values based on previous studies (Levesque et al. 2018; Knobloch et al. 2019). For heat pumps and AC, target values are scenario-dependent, higher in SSP1 and lower in SSP3, in line with the different scenario assumptions on technological development. Regional emission factors and energy prices for different fuels are based on the outputs of the IAM MESSAGEix-GLOBIOM (McCollum et al. 2018), soft-linked to MESSAGEix-Buildings. Investment costs for new construction, renovation, and heating systems are from literature (Fleiter et al. 2016; Esser et al. 2019). Similar to previous studies (Connolly et al. 2014), we consider decreasing investment costs for heat pumps in SSP1-2, but not for other heating technologies considered to be mature. All investment costs are fixed in SSP3, following the assumption of slow technological innovations. Discount rates are set differently across different regions, household, and housing types to represent different attitudes towards investments, and barriers to efficiency improvement decisions due asymmetric information and split incentives (Poblete-Cazenave et al. 2021; Giraudet et al. 2012). Intangible costs are applied to represent barriers towards energy efficiency improvements (Giraudet et al. 2012).

4.2.4 Behavior

Behavioral aspects accounted by the model are indoor set point temperatures, daily hours of operation and share of conditioned space. Values for heating and cooling set point temperatures are respectively 21 °C and 23 °C based on survey and literature data (Jones et al.
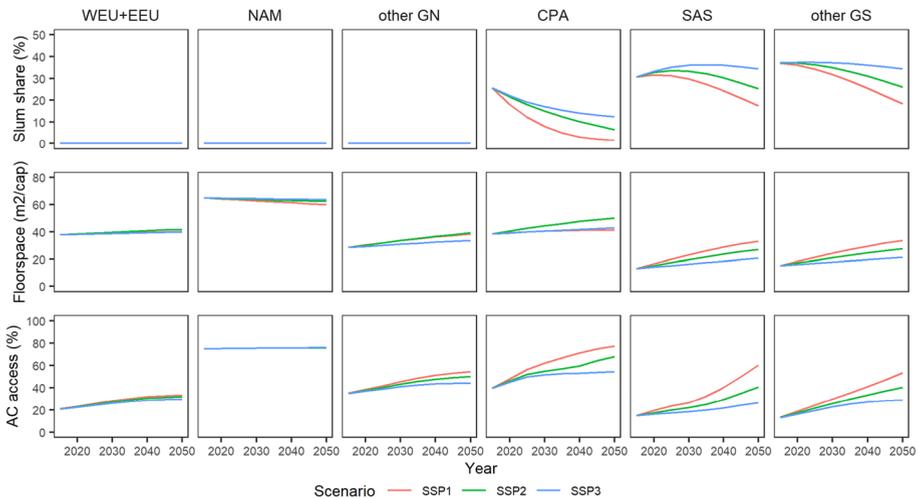
Fig. 2 Projection of share of urban population living in slums, floorspace per-capita, and access to air-conditioning in different world regions for SSP1-3

2015). While there is large uncertainty on behavior in different contexts and household types, we calibrate the model by tuning daily hours of operation and share of conditioned floorspace area to reproduce observed energy demand levels in the base year (see Supplementary Material, section SM3.1). We run additional sensitivity analysis on set point temperatures to show the effect on energy demand and report the results in the supplementary material (section SM3.6.2).

5 Results

5.1 Building stock dynamics

5.1.1 Building stock composition

Fig. 3 illustrates the evolution of the global housing stock across different SSPs, both in terms of energy efficiency cohorts (Fig. 3 top panel) and heating fuels (Fig. 3 bottom panel). In SSP1, high renovation rates enable a progressive upgrade of existing buildings, leading to 40% of the initial stock renovated by 2050 in Europe, around one-third of which are compliant with advanced renovation standard. Newly built housing represents 43% of the total stock in 2050, mostly with advanced energy efficiency as a result of enforced building codes. In SSP3, a substantial part of the building stock (35%) is still not renovated by 2050, as consequence of low renovation rates, and renovations are mostly of standard type. SSP2 is in between the two other scenarios (see Supplementary Material, section SM3.4 for detailed results on new construction and renovation rates).

The global south shows different trends across the SSPs. Slum settlements gradually disappear in CPA under SSP1, while they persist in other regions and SSPs, though
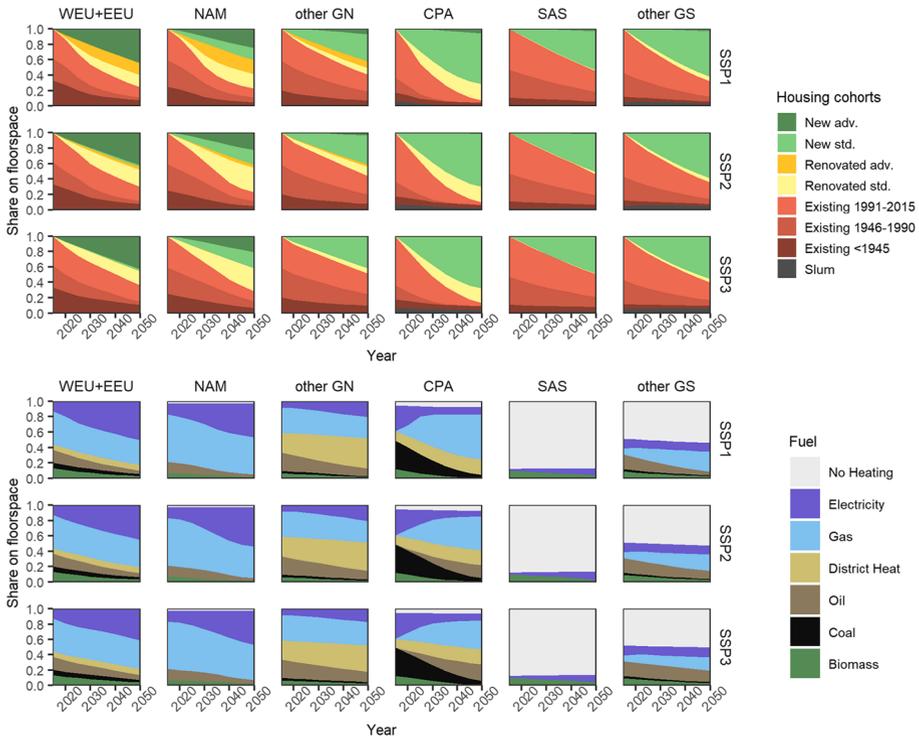
Fig. 3 Distribution of energy efficiency cohorts (above) and heating fuels (below) in the housing stock of different world regions for SSP1-3

by a smaller amount in SSP1. In CPA, a large portion of the existing housing stock is either renovated or replaced by 2050, with high turnover rates leading to a housing stock dominated by new constructions. In other GS regions, the existing stock largely remains non-renovated in SSP2-3 and new constructions rapidly penetrate under population growth and faster replacement of the existing stock.

Renovation rates differ not only across scenarios and regions, but also across housing types and over time. We report in Fig. 4 illustrative results for the NAM region, showing that renovation rates initially speed up under increasing energy prices and decreasing investment costs, reaching a peak between 2025 and 2030, and then slow down as the fraction of non-renovated buildings shrinks due to both renovation and turnover. Renovation rates are lower for MFH compared to SFH, as result of asymmetric information and split incentives barriers (Palm and Reindl 2018).

5.1.2 Heating fuels

In terms of heating fuels, in the global north, the initial high share of gas reduces progressively as electrification advances, driven by the uptake of energy efficient heat pumps under reducing investment costs and increasing fossil fuel prices, especially in SSP1-2 (Fig. 3 and Fig. 4). The phase-out of coal and oil is also faster in SSP1 under
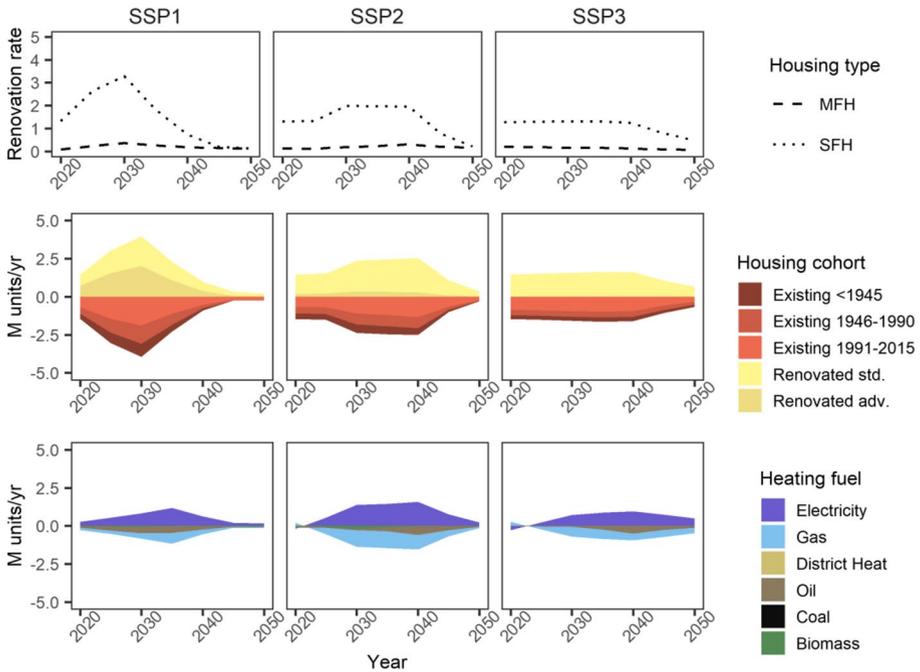
Fig. 4 Renovation rate by housing type (above), net number of housing units transitioning between different energy efficiency cohorts (center), and between different fuels (below) in the NAM region for SSP1-3. Negative values indicate that there are more housing units exiting than entering a given cohort, and vice versa for positive values

higher energy price for fossil fuels. District heating is predominant in cold regions, in particular the Russian region, and its share increases over time as urbanization advances.

In the global south, a smaller fraction of households owns heating systems, due to hotter climatic conditions, with the exception of CPA. In SAS, the initial large share of biomass in space heating is gradually replaced by electricity (direct heating and heat pumps) in SSP1-2. Other regions with colder climates, in particular CPA, see the rise of gas and a continued use of electricity, oil, and district heating. Traditional biomass and oil are progressively substituted by electricity and gas, though the speed differs significantly across SSPs, being the fastest in SSP1 and the slowest in SSP3.

5.2 Energy efficiency improvements

Changes in the apparent energy intensity for space heating and cooling are the result of the combined access to energy services, energy efficiency improvements, and behavioral changes, and largely differ across scenarios, region, housing, and household cohorts.

Energy intensities for space heating (Fig. 5, top panel) are higher for the global north and decreasing over time, as a result of more efficient new buildings, renovations, and fuel switches, especially in SSP1. Urban housing has lower energy intensity compared
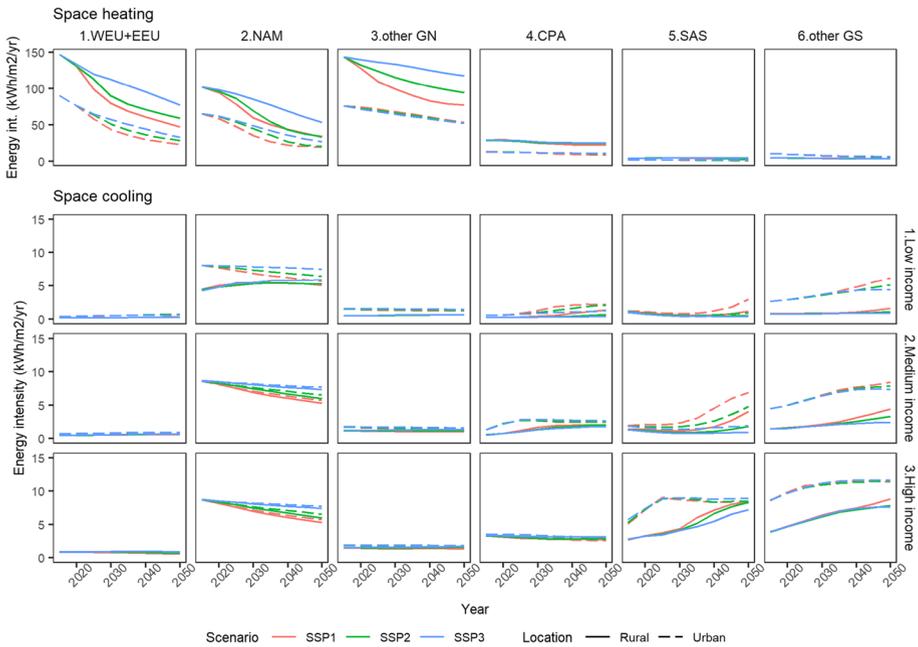
Fig. 5 Apparent energy demand intensity for space heating (above) and cooling (below) by location and income tertile (cooling only) in different world regions for SSP1-3

to rural due to different housing types (prevailing MFH with compact geometry and lower heat losses) and heating fuels (presence of district heating and lower share of solid biomass and fossil fuels). Energy demand intensity reductions are higher for rural, where the prevailing SFH have higher renovation rate and uptake of advanced new construction, leading towards convergence with urban in most regions.

The apparent energy intensities for space cooling (Fig. 5, bottom panel) are higher for developing regions, steeply increasing for SAS and other GS regions, and only partially counterbalanced by energy efficiency improvements. There is a large heterogeneity both across SSPs, locations and income levels. While energy intensities rapidly increase for urban and high-income classes, rural, and low-income households remain at very low energy intensity levels, due to limited access to AC. Differences across SSPs are evident for urban low- and mid-income classes, under unequal income growth and consequent AC adoption. In contrast, cooling energy intensities are low for most developed regions, and similar across scenarios, income levels, and locations, with the exception of NAM.

5.3 Space heating and cooling projections

While energy efficiency improvements play a critical role in energy intensities, total energy demand trajectories strongly depend also on the demand for buildings floorspace. Fig. 6A reports the projections of total floorspace, final energy demand for space heating and cooling for SSP1-3. The global north experiences a modest increase in floorspace

across all scenarios due to low population growth and stabilization or decline in floorspace per-capita. The global south shows significant differences in total floorspace across SSPs, driven by different dynamics for population, urbanization, and floorspace per-capita. Especially in SSP1, a stark increase in floorspace is projected for SAS and other developing regions, due to increasing housing size.

The energy demand for space heating is dominated by the global north regions and CPA, with the major contributors by 2050 being China, the USA, and Russia (Fig. 6.B). In the global north, space heating demand decreases rapidly in SSP1, as a result of energy renovations and new energy efficient construction (Fig. 3), and more slowly in SSP2-3. The decrease is more substantial in Europe (up to 70% in SSP1), following tight building codes. In CPA, energy demand for space heating reduces by 43% in SSP1, while reductions are modest in SSP2-3, as energy efficiency improvements are offset by growing housing size and population. In other GS regions, space heating requirements stay substantially lower, despite a moderate projected demand increase.

The energy demand for space cooling is relatively low when compared to space heating. However, space cooling is projected to rapidly increase in developing regions, characterized by warm and hot climates, with the highest increase in SSP1. This process is largely driven by higher AC adoption and larger housing size under income growth, and only partially offset by the gradual increase in energy efficiency. In the global north, cooling energy demand is relatively lower, with the exception of NAM, and projected to stay relatively constant under the opposite drivers of significant access to AC and increased energy efficiency. The global cooling energy demand will double in SSP3 and triple in SSP1 by 2050, with the major contributors being India, China, and the USA (Fig. 6.B).

5.4 CO_2 emission projections

Figure 7 shows CO_2 emissions in the base year and in 2050 for different SSPs, and the breakdown by housing energy efficiency cohorts (top panel), and fuels and end-uses (bottom panel). In the global north, CO_2 emission reductions by 2050 range between 55.7 (SSP1) and 30% (SSP3). Existing renovated and non-renovated buildings are responsible for most of the CO_2 emissions in 2050, with new buildings accounting for only 24–25% of total emissions. The effect of slower and less efficient renovations is evident in SSP3, where renovated buildings contribute to larger emissions and lock-in effects. Space heating is dominant in all scenarios, accounting for 92.0 (SSP1) to 81.2% (SSP3) of total CO_2 emissions. The phase-out of coal and oil results in major reductions of emissions. The contribution of electricity significantly varies depending on the decarbonization of the supply-side, being the lowest in SSP1 despite the higher penetration of electrical systems (Fig. 3, bottom panel).

In the global south, new constructions account for more than half of the CO_2 emissions in 2050 in all scenarios. Differently from the global north, total CO_2 emissions in SSP1 2050 are similar to the base year, as a result of energy efficiency improvements and decarbonization of the energy system balancing the increase in activity levels, and increase by comparable amounts in SSP2 and SSP3. CO_2 emissions for space cooling increase by a factor of 2.2 (SSP1) to 2.4 (SSP2) and become dominant in the global south, representing 53.2 (SSP3) to 61.8% (SSP1) of total CO_2 emissions in 2050. The absolute amount of future emissions for cooling is similar across SSPs, but as consequence of different driving forces: SSP1 is characterized by higher access to AC, but improved energy efficiency and decarbonized electricity; on the other hand, SSP3 has larger AC access gaps, but
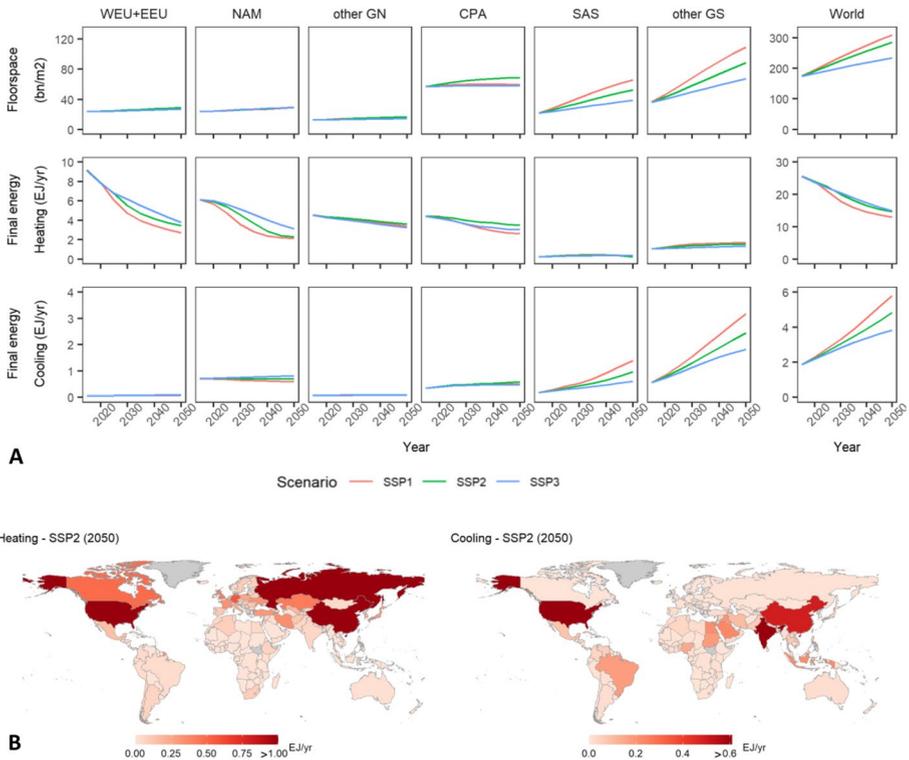
Fig. 6 Panel **A** Residential floorspace (top), energy demand for space heating (middle) and for space cooling (bottom) in different world regions for SSP1-3. Panel **B** Total residential final energy demand for space heating (left) and cooling (right) in SSP2 (2050)

lower efficiency and higher emission factors. CO_2 emissions for space heating drop almost by half in SSP1, as a result of coal and oil phase-out, and decarbonization of electricity. Conversely, in SSP3, they only reduce by 27.0%.

6 Discussion

This study has explored energy demand and emissions pathways for residential space heating and cooling under different socio-economic scenarios. In this section, we discuss the projected global trends in comparison with previous studies, the advancements on representing building stock dynamics and heterogeneity in housing and household characteristics, and the limitations of this work and further research needs.

6.1 Global space heating and cooling trends

The results of this study show that different future socio-economic pathways will have significant impact on both global space heating and cooling energy demand and CO_2 emissions. CO_2 emissions for space heating decline globally in the three scenarios, with
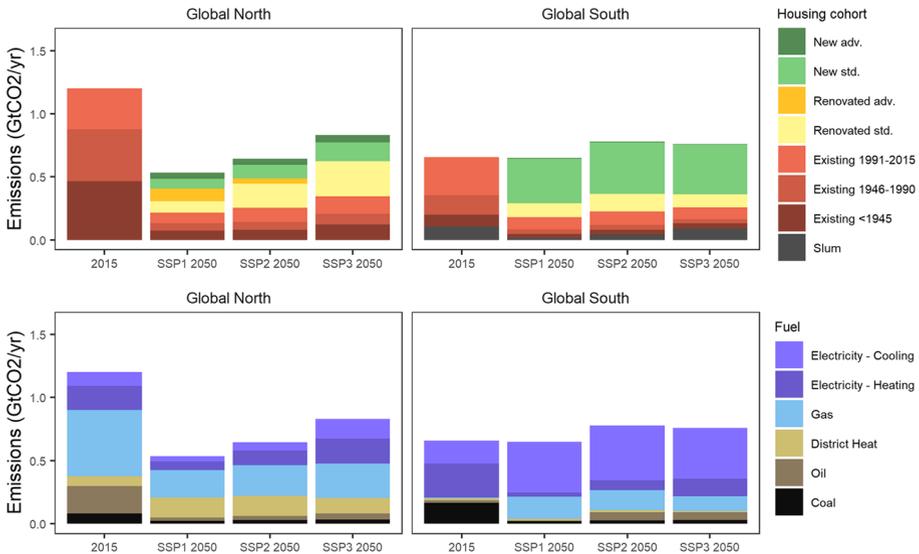
Fig. 7 CO_2 emissions in the base year (2015) and for SSP1-3 (2050) in the global north and south: breakdown by energy efficiency cohort (top panel) and fuels (bottom panel)

reductions of 34.4% in SSP3, 41.1% in SSP2, and 52.5% in SSP1 by 2050. Such reductions are mainly driven by energy efficiency improvements and electrification in the global north, with the global south contributing to a lower extent due to warmer climates. Electrification advances in the three SSPs, though at a different pace, but a substantial share of final energy and CO_2 emissions for space heating will still be from gas and other fossil fuels until 2050, even in the more optimistic SSP1, posing challenges to the decarbonization of space heating towards climate goals. In Europe, projected CO_2 emission reductions for space heating range between 70.0 in SSP1 and 53.2% in SSP3 by 2050, indicating different attainment levels towards carbon neutrality targets (Supplementary Material, section SM3.5). In SSP1, higher renovation rates, dominance of advanced renovations, and switch to electricity enable more aggressive emission reductions. Conversely, lock-ins due to slow and less efficient renovations, and persistence of gas in the mix result in larger gaps towards carbon neutrality in SSP2 and especially SSP3.

Energy demand and emissions for space cooling are projected to increase in all scenarios, driven by progressively larger per-capita floor space and improved access to AC in the global south, suggesting that increased activity level will prevail over energy efficiency improvement effects. CO_2 emissions for space cooling increase by 58.2% in SSP1, 72.5% in SSP2, and 85.2% in SSP3 by 2050, in absence of additional policies. These results are generally consistent with recent global studies focusing on energy demand and emissions in the residential sector. A direct comparison by SSP was possible with an existing global study (Levesque et al. 2018), showing similar declining trends for final energy demand for space heating and increasing trends for cooling. However, the growth in cooling demand for SSP1 is lower in (Levesque et al. 2018) compared to this paper, probably due to different assumptions on behavioral change. Beyond a direct SSP comparison, results by region for our SSP1 and SSP2 scenarios are in line respectively with the results for the "Moderate" and "Deep" scenarios in (Güneralp et al. 2017), with the main difference being lower space conditioning energy demand reported for the South Asia region in our study.

Additional comparison with an existing study for India (Akpinar-Ferrand and Singh 2010) reveals similar trends and magnitude in the rise of cooling demand. Finally, a comparison with a global multi-sectoral study (van Ruijven et al. 2019) shows similar trends in the reduction of natural gas and increase in electricity use for residential demand, higher in SSP1 and lower in SSP3.

6.2 Towards improved representation of building dynamics and heterogeneity

This framework advances global modeling of buildings energy demand in multiple directions. First, the accounting of building stock turnover and renovations allows tracking the stock composition and uptake of energy efficiency measures over time. Such information is key to assess the potential impact of policies targeting new construction and renovation separately, whereas most of the other global models exogenously impose average building insulation improvements at the stock level without differentiating between new and existing buildings. The building lifetime is also explicitly considered and allows evaluating the implications of different turnover rates. For instance, we show that the rapid turnover of buildings in CPA requires addressing energy efficiency primarily in new construction, whereas renovations are key in the global north due to slower building replacement rates.

Second, we explicitly model household decisions on energy efficiency improvements using dedicated decision models. Market shares for new construction technologies, energy renovation rates and fuel switches are also estimated at the margin, rather than exogenously assumed. Having such dynamics endogenous to the model, allows analyzing the effect of contextual and technological changes on the decisions of different household types. For instance, we showed that electrification and renovation rates differ across scenarios as consequence of different energy prices, investment costs, and technological advancement influencing household decisions. While we focus here on differences across socio-economic scenarios, endogenizing housing and household dynamics enables exploring a broader range of contextual conditions and policies.

Third, with our modeling framework we improve the representation of granularity and heterogeneity on key geographical, technological, and socio-economic aspects. While previous studies at global level differentiated income levels, or locations, those are rarely combined with different housing types and heating and cooling technologies, overlooking important interactions. As an example, we showed that energy demand for space cooling is expected to rise in developing countries driven mostly by high- and medium-income households in urban areas and is only partially counterbalanced by energy efficiency improvements. Improving the combined representation of households and housing heterogeneity allows for further insights on distributional aspects, which are key to inform policies on climate and sustainable development goals.

6.3 Limitations and further research

Global studies on the evolution of the building sector and its energy demand are inevitably affected by a high degree of uncertainty, related to context, inputs, models, parameters, and outcomes (Walker et al. 2003). We focus here on the uncertainty related to different socio-economic pathways by using the SSP narratives and their quantification for the building sector. Additional uncertainty analysis on key model parameters is reported in the Supplementary Material, section SM3.6. While these scenarios do not consider additional climate policy interventions, they aim at representing the challenges policies would have to target to achieve

climate goals under different socio-economic futures. Future energy demand for heating and cooling is likely to be affected by climate change (Isaac and van Vuuren 2009; Auffhammer and Mansur 2014; Hasegawa et al. 2016; van Ruijven et al. 2019). We do not consider here future changes in climate, with the aim to establish a baseline scenario. A more thorough uncertainty analysis, including different climate futures, is planned as part of future work.

The structure of this modeling framework allows future expansion towards more heterogeneities and further endogenization of household and building dynamics. However, this first implementation is simplified in some aspects due to limited information availability. For instance, while we differentiate building lifetime by region and building type, we assume no future changes along future scenarios, whereas different lifetime values might affect the penetration of new technologies and renovation rates. Similarly, we represent heterogeneity in housing types and tenure by region and location but we assume it does not vary over time. Empirical studies have shown that uptake of energy efficiency measures by households depends not only on monetary and structural dwelling factors, but also on education, personal and social norms, environmental attitude, and energy behavior (De Cian et al. 2019; Niamir et al. 2020). Similar to other studies (Giraudet et al. 2012; Knobloch et al. 2019), we attempt to capture differences across households by using specific discount rates and barriers to energy efficiency by introducing intangible costs. Behavioral changes in the use of heating and cooling are important drivers of energy demand (Levesque et al. 2019) and are only partially addressed in this study. In particular, while the projected increase in AC adoption is supported by other studies, it is not clear to what extent energy demand will increase, as low-income households might not afford running cooling equipment for extensive periods. Finally, all these aspects require studies on their own and will improve the results and insights from this model even further over the years to come.

The representation of current heterogeneity is also limited for some dimensions for which we could not identify sufficient supporting data. For instance, we assume similar heating fuels, and heating and cooling operation across income levels. Data gaps for the global south represent a major challenge that we attempted to bridge by using household survey data, when available, and adaptations from data from other regions in other cases.

In addition to bridging data gaps, future work around MESSAGEix-Buildings will address the analysis of a broader range of policy scenarios towards carbon neutrality in the building sector, improved linkage with IAM to investigate interactions with the energy system, and analysis of distributional aspects in access to decent housing and basic thermal comfort towards the sustainable development targets.

7 Conclusions

We presented a modeling framework to assess the evolution and the energy demand and CO_2 emissions of large building stocks, highly granular and detailed in representing geographical contexts, socio-economics, and buildings characteristics and dynamics. We applied the framework to the assessment of space heating and cooling demand for the global residential building sector along alternative socio-economic scenarios (SSP1-3). The results showed that global CO_2 emissions for space heating are decreasing under energy efficiency improvements and electrification, though at a different pace across the three scenarios, reaching 52.5% and 34.4% reductions respectively in SSP1 and SSP3 by mid-century. In contrast, space cooling demand steeply increases in the global south by 2050, doubling in SSP3 and tripling in SSP1, under rising income levels, housing size, and access to AC. Global CO_2 emissions for space cooling

increase in the range of 58.2 (SSP1) and 85.2% (SSP3). The high granularity of this model allowed to provide additional insights on the differences in construction and renovation dynamics and energy demand across households and housing types. As examples, the results showed different renovation rates by housing type, higher in single-family homes, and a disproportionate shift in future access and energy demand for cooling between different income levels in the global south. The modeling framework and the scenario results presented in this study can support further analysis of energy demand and carbon emission mitigation strategies for the building sector and joint assessment with other sectors in IAM, contributing to inform policies towards reaching global climate and sustainable development targets.

Data availability The manuscript has data included as electronic supplementary material.

Code availability Code can be made available upon request to the authors.

Declarations

Conflict of interest The authors declare no competing interests.

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