Supplementary material

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

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Content

SM1. Building stock scenario narratives

We develop three building scenarios representing the building stock evolution and associated energy demand under different socioeconomics 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 ground our building narratives and scenario settings 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 (Table 1).

Table 1 Overview of the qualitative indicators for the building stock narratives.

Element	SSP1	SSP2	SSP3
Basic elements			
Population	Low	Medium	High
GDP	High	Medium	Low
Gini			
Urbanization	High	Medium	Low
Housing			
Housing size	GN: low GS: high	GN: medium GS: medium	GN: medium GS: low
Slum population	High	Medium	Low
AC access	High	Medium	Low
Access to clean fuels	High	Medium	Low
Energy efficiency level	High	Medium	Low
Space heating/cooling activity level	Low	Medium	GN: high GS: low
Energy demand for space heating and cooling	GN: low GN: relatively high	Medium	GN: high GS: relatively low

Note: GN = global North; GS = global South.

SM1.1. *SSP1*

The global SSP1 has its central features in the commitment towards sustainable development goals, increasing environmental awareness, and a gradual move to less resource-intensive lifestyles (O'Neill et al. 2017). SSP1 is characterized by relatively high projected GDP, low inequality, high urbanization and relatively low energy demand, resulting in low challenges to both adaptation and mitigation (Riahi et al. 2017). In the building sector, housing size starts declining in most regions of the global north, driven by increasing urbanization and consequent prevalence of MFH, and by increased awareness of environmental burdens of large housing size. Exceptions are the Former Soviet Union and Western Europe regions, where floorspace per capita continues to grow sustained by a more substantial GDP growth in the first half of the century. In the global south, GDP growth and poverty eradication actions result in a decrease in slum population and progressive increase in housing size, approaching decent housing standards of durability and sufficient floorspace per capita. Energy efficiency of buildings and renovation rates increase driven by policy, high technological advancement and increased environmental awareness. Populations shift to more efficient use of energy and less energy-intensive lifestyles. The global south experiences improved access to thermal comfort and a gradual shift towards cleaner fuels. As a result, space heating and cooling energy demand is relatively low for the global north, while it keeps on increasing in the global south.

SM1.2. ***SSP2***

The global SSP2 is a scenario consistent with observed historical patterns (O'Neill et al. 2017). Challenges for mitigation and adaptation are medium. The continuation of current trends entails medium level of GDP growth, inequality, urbanization and energy demand (Riahi et al. 2017). Similarly, the building stock evolution follows current trends. Housing size growth trends continue both in the global north and south, along with moderate eradication of slum settlements. Moderate increase in energy efficiency is expected, especially in the global north, consistent with current trends. Renovation rates and investment cost for energy improvements are medium, while intensity of operation for heating and cooling is not changing significantly for the global north and moderately increasing in the global south. Energy demand levels resulting from such trends are therefore in between SSP1 and SSP3.

SM1.3. ***SSP3***

The global SSP3 is a scenario of regional rivalry, international fragmentation and reversal of globalization trends (O'Neill et al. 2017). In SSP3, GDP growth and urbanization are low, while challenges to both mitigation and adaptation are high (Riahi et al. 2017). In the building sector the differences between global north and south, as well as between different income classes increase, following increase in across- and intra-country inequality. Housing size increases at a slower pace compared to SSP2 and the divide between global north and south remains large. Slum settlements persist and, whilst the share of slum population decreases, absolute numbers increase under higher population growth. Energy efficiency of buildings increases only marginally, and renovation rates remain low. At the same time, intensity of operation increases in the global north and for higher income classes in the global south. Conversely, low-income populations in the global south continue experiencing lower access to thermal comfort in many regions.

SM2. Input data and projections

SM2.1. *Region definition*

We use the eleven MESSAGE model regions[1] and further aggregate to 6 macro-regions for result reporting in the main text (Table 2).

Table 2 Region definition.

Reporting region	MESSAGE 11 regions	
WEU+EEU	WEU	Western Europe
	EEU	Central and Eastern Europe
NAM	NAM	North America
Other GN	FSU	Former Soviet Union
	PAO	Pacific OECD
CPA	CPA	Centrally Planned Asia
SAS	SAS	South Asia
Other GS	AFR	Sub-Saharan Africa
	LAC	Latin America and the Caribbean
	MEA	Middle East and North Africa
	PAS	Other Pacific Asia

SM2.2. *Survey data sources*

We report in Table 3 the list of survey microdata used for the estimation of specific parameters, such as share of housing types, housing characteristics, and floorspace.

[1] For the complete list of countries in each region, please refer to the following webpage: https://iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html

Table 3 Microdata overview.

Region	Country name	Country code	Survey name	Date	Source	Web Address
AFR	Angola	AGO	Inquérito Integrado sobre o Bem-Estar da População (IBEP)	2008-09	República de Angola – Instituto Nacional de Estatistica	https://andine.ine.gov.ao/nada4/index.php/catalog/11/study-description
	Ethiopia	ETH	Multi-Tier Framework Survey (MTF)	2017	World Bank	https://datacatalog.worldbank.org/dataset/ethiopia-multi-tier-framework-mtf-survey-2018
	Ghana	GHA	Ghana Living Standards Survey (GLSS)	2012-13	Ghana Statistical Service	https://www2.statsghana.gov.gh/nada/index.php/catalog/72
	South Africa	ZAF	Living Conditions Survey	2014-15	Statistics South Africa (producer); DataFirst (distributor)	https://www.datafirst.uct.ac.za/dataportal/index.php/catalog/608
CPA	China	CHN	Chinese Residential Energy Consumption Survey (CRECS)	2014	Renmin University of China – Department of Energy Economics	Not available
EEU	Poland	POL	Eurostat, EU Statistics on Income and Living Conditions (EU-SILC)	2015	Eurostat	https://ec.europa.eu/eurostat/web/microdata/european-union-statistics-on-income-and-living-conditions
	Serbia	SRB	Multiple Indicator Cluster Surveys (MICS)	2014	Unicef	https://mics.unicef.org/surveys
FSU	Russia	RUS	Russia Longitudinal Monitoring Survey of Higher School of Economics (RLMS-HSE)	2015	HSE University	https://www.hse.ru/en/rlms/downloads
	Belarus	BLR	Multiple Indicator Cluster Surveys (MICS)	2012	Unicef	https://mics.unicef.org/surveys
LAC	Brazil	BRA	Pesquisa de Orçamentos Familiares (POF)	2008-09	Instituto Brasileiro de Geografia e Estatistica	https://www.ibge.gov.br/estatisticas/multidominio/ciencia-tecnologiae-inovacao/9050-pesquisa-de-orcamentos-familiares.html?=&t=microdados
	Chile	CHL	Encuesta de Presupuestos Familiares (EPF)	2016-17	Instituto Nacional de Estadísticas - Chile	https://www.ine.cl/estadisticas/sociales/ingresos-y-gastos/encuesta-de-presupuestos-familiares
	Guatemala	GTM	Encuesta Nacional de Condiciones de Vida (ENCOVI)	2014	Instituto Nacional de Estadísticas - Guatemala	https://www.ine.gob.gt/estadisticasine/index.php/usuario/encovi

	Mexico	MEX	Ingresos y Gastos de los Hogares (ENIGH)	2016	Instituto Nacional de Estadística y Geografía- Mexico	https://www.inegi.org.mx/programas/enigh/nc/2016/
MEA	Iraq	IRQ	Iraq Household Socio-Economic Survey (IHSES)	2012	Economic Research Forum	http://www.erfdataportal.com/index.php/catalog/108
	Morocco	MAR	Morocco Household and Youth Survey (MHYS)	2009	World Bank	ttps://microdata.worldbank.org/index.php/catalog/1546
NAM	USA	USA	Residential Energy Consumption Survey (RECS)	2015	U.S. Energy Information Administration	https://www.eia.gov/consumption/residential/data/2015/
PAO	Japan	JPN	Housing and Land Survey*	2018	Statistics Bureau of Japan	https://www.stat.go.jp/english/data/jyutaku/index.html
PAS	Indonesia	IDN	Indonesia Family Life Survey	2014	RAND Corporation	https://www.rand.org/well-being/social-and-behavioral-policy/data/FLS/IFLS/download.html
	South Korea	KOR	Home Energy Standing Survey (HESS)	2017	Korea Energy Statistical Information System	http://www.kesis.net/sub/sub_0001.jsp?M_MENU_ID=M_M_001&S_MENU_ID=S_M_008
SAS	India	IND	National Sample Survey (NSS) - Household Consumer Expenditure	2000-01	National Sample Survey Office - M/o Statistics and Programme Implementation,Government of India	http://microdata.gov.in/nada43/index.php/catalog/91
WEU	France	FRA	Enquête Budget de famille	2010-11	Institut national de la statistique et des études économiques	https://www.insee.fr/fr/metadonnees/source/serie/s1194
	Italy	ITA	Household Budget Survey	2013	Istituto Nazionale di Statistica	https://www.istat.it/en/archivio/193939

Note: *Statistical tables used instead of microdata.

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SM2.3. *Demographics and socio-economics*

SM2.3.1. *Population and urbanization*

We use different datasets for historical population and population future projections. Historical annual population records from 1960 to the base year are available from the World Bank (WDI). For population between 1820 and 1960 we use the Maddison Project Database (MPD) (Bolt et al. 2018) at the country level and interpolate data for missing years (availability is country-dependent). For future SSP scenarios, we use population projections at the country level from the SSP database (KC and Lutz 2017), available on a five year timestep. Figure 1 reports their regional aggregation. For urbanization projections we use national data from the SSP database (Jiang and O'Neill 2017) on a five year timestep. We reconstruct past urbanization trajectories by using data from the CLIO-INFRA project (Fink-Jensen 2015) and use linear interpolation to bridge data gaps (availability is country-dependent).

SM2.3.2. *Household size*

For the base year, we estimate household size at the country level based on the United Nations data (UN 2019). The most recent record was used for each country as available. Missing values were filled by using regional averages. Past trends were reconstructed by using data for 1970 available at the level of 24 world regions (UN-HABITAT 1970). Regional averages are reported in Table 4. We linearly interpolate data between 1970 and the base year assuming no changes before 1970. Lacking data on future household size projections we keep values constant.

Table 4 Household size. Average by region.

Region	**Household size** (n. members)	
	1970	**2015**
AFR	4.9	4.9
CPA	5.4	4.3
EEU	3.7	2.7
FSU	3.9	3.7
LAC	4.9	3.7
MEA	5.4	5.1
NAM	3.7	2.5
PAO	3.8	2.5
PAS	5.4	4.2
SAS	5.3	5.6
WEU	3.5	2.5

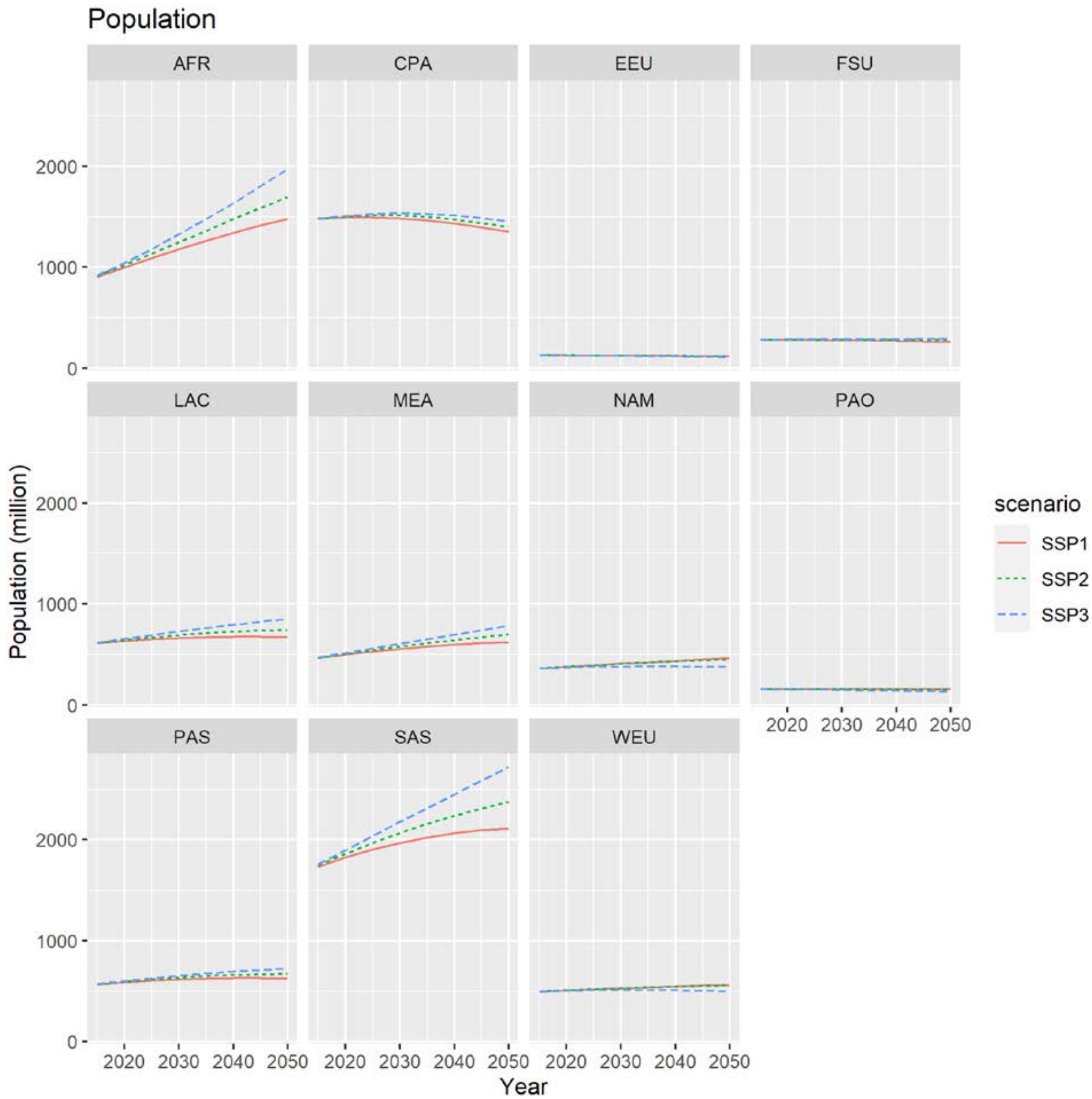


Figure 1 Population projections.

SM2.3.3. *GDP and inequality*

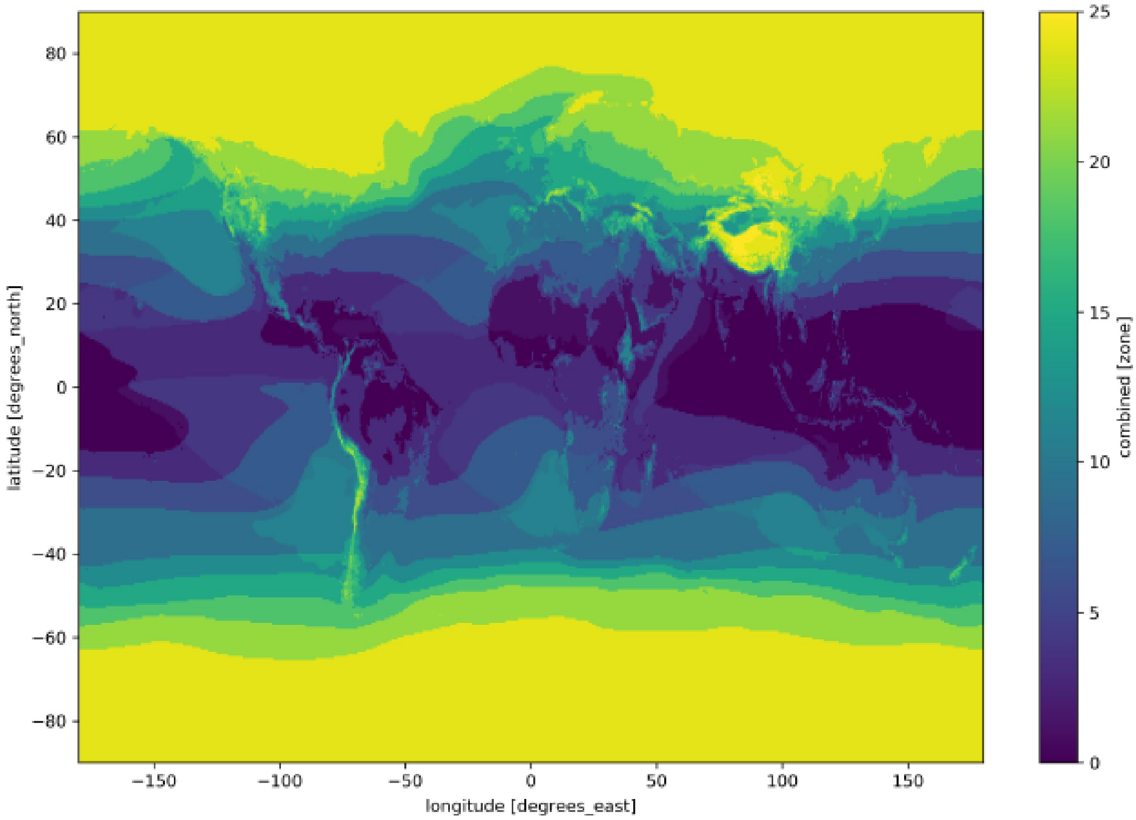
We use national GDP projections for future scenarios from the OECD dataset in the SSP database (Dellink et al. 2017). We use country level inequality (Gini) projections from the SSP database [8]. Income distributions for urban and rural are calculated based on GDP and Gini data using an empirical relationship between urban and rural income estimated from survey microdata and assuming lognormal distribution (Poblete-Cazenave et al.; van Ruijven et al. 2011). We then calculate the average income level by tertile on a country and urban/rural basis.

SM2.4. ***Climatic data***

We use the observed historical weather datasets, EWEMBI (EartH2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP), with global coverage and at daily time step between 1979 and 2013. EWEMBI combines observed global climate data variables from a number of sources, consistently downscaled and bias-corrected for use in climate impacts assessments (Lange 2016). EWEMBI was produced for ISIMIP round 2 onwards.

We use daily data of 30 years (1980-2009) to capture the full variability of the recent climate. In this implementation data is aggregated to monthly means, whilst making use of the daily temperature data to calculate number of days per month requiring cooling, D_m (Eq 4). The framework is predominantly implemented in Python using xarray (Hoyer and Hamman 2017) and Dask (Rocklin 2015), to enable parallelized processing of big multidimensional datasets. Monthly horizontal solar irradiation (from EWEMBI) was processed using the R package "solaR" (Perpiñán 2012) to calculate vertical solar irradiation for different expositions on the 0.5° grid.

Climatic data include daily outdoor mean surface air temperatures (at 2m) (variable name *tas*) and solar irradiation (long- and short-wave) (variable name *rlds, rsds)* on a spatial grid at resolution 0.5 degree (~50km at the equator) from the global EWEMBI dataset (Lange 2019). We used the ASHRAE classification (Walsh et al. 2017) to define climatic zones boundaries using the gridded data for the period 1980-2009. The ASHRAE classification combines monthly air and precipitation determine 26 zones according to the temperature, cooling and heating degree days and humidity of the climate. We report in Figure 2 a world map with the different climatic zones according to the ASHRAE definition.



0	Zone_0A	Extremely hot Humid	14	Zone_4C	Mixed Marine
1	Zone_0B	Extremely hot Dry	15	Zone_5A	Cool Humid
2	Zone_0C	Extremely hot Marine	16	Zone_5B	Cool Dry
3	Zone_1A	Very hot Humid	17	Zone_5C	Cool Marine
4	Zone_1B	Very hot Dry	18	Zone_6A	Cold Humid
5	Zone_1C	Very hot Marine	19	Zone_6B	Cold Dry
6	Zone_2A	Hot Humid	20	Zone_6C	Cold Marine
7	Zone_2B	Hot Dry	21	Zone_7A	Very cold Humid
8	Zone_2C	Hot Marine	22	Zone_7B	Very cold Dry
9	Zone_3A	Warm Humid	23	Zone_7C	Very cold Marine
10	Zone_3B	Warm Dry	24	Zone_8A	Subarctic/arctic Humid
11	Zone_3C	Warm Marine	25	Zone_8B	Subarctic/arctic Dry
12	Zone_4A	Mixed Humid	26	Zone_8C	Subarctic/arctic Marine
13	Zone_4B	Mixed Dry			

Figure 2 Map of climatic zones.

SM2.5. ***Housing data***

SM2.5.1. *Housing types*

We consider two housing types for permanent construction: single-family (SFH) and multi-family homes (MFH). Table 5 below reports the share of housing type by region and location, estimated based on survey data in Table 3. After analysis of the available data, for each region we selected a set of representative countries based on the comparison with data available from literature, and considerations on the country weight in terms of population. We use proxies from other regions where data is missing or imperfect.

Table 5 Share of single-family homes (SFH) and multi-family homes (MFH) by region and location.

Region	**Location**	**Share SFH** (%)	**Share MFH** (%)	**Data sources** (country code)
AFR	Rural	97	3	AGO, ETH, GHA, ZAF
	Urban	89	11	
CPA	Rural	43	57	CHN* (urban), KOR** (rural)
	Urban	10	91	
EEU	Rural	79	21	POL
	Urban	29	71	
FSU	Rural	79	21	POL**
	Urban	29	71	
LAC	Rural	99	1	BRA, CHL, GTM, MEX
	Urban	88	12	
MEA	Rural	93	7	IRQ, MAR
	Urban	85	15	
NAM	Rural	97	3	USA
	Urban	69	31	
PAO	Rural	97	3	JPN* (urban), USA** (rural)
	Urban	54	46	
PAS	Rural	87	13	IDN, KOR
	Urban	78	22	
SAS	Rural	96	4	IND
	Urban	70	30	
WEU	Rural	96	4	FRA, ITA
	Urban	47	53	

Notes: *Data available without distinction urban/rural. **Country from another region used as proxy in case of missing or imperfect data. Underlined data sources selected as representative for the region. Country codes refer to the data sources reported in Table 2.

SM2.5.2. *Housing tenure*

Similar to the case of housing type, we estimate regional housing tenure based on the survey data in Table 3 and selected representative countries. Results by region and location are reported in Table 6.

Table 6 Share of single-family homes (SFH) and multi-family homes (MFH) by region and location.

Region	**Location**	**Renting** (%)	**Owning** (%)	**Data sources** (country code)
AFR	Rural	2	98	AGO, ETH, GHA, ZAF
	Urban	30	70	
CPA	Rural	3	97	IDN**
	Urban	18	82	
EEU	Rural	3	97	POL, SRB
	Urban	9	91	
FSU	Rural	4	96	RUS, BLR
	Urban	5	95	
LAC	Rural	3	97	BRA, CHL, GTM, MEX
	Urban	18	82	
MEA	Rural	3	97	IRQ, MAR
	Urban	17	83	
NAM	Rural	14	86	USA
	Urban	41	59	
PAO	Rural	14	86	JPN* (urban), USA** (rural)
	Urban	37	63	
PAS	Rural	3	97	IDN
	Urban	18	82	
SAS	Rural	3	97	IDN**
	Urban	18	82	
WEU	Rural	12	88	FRA (urban), ITA (rural)
	Urban	37	63	

Notes: * Data available without distinction urban/rural. ** Country from another region used as proxy in case of missing or imperfect data. Underlined data sources selected as representative for the region. Country codes refer to the data sources reported in Table 2

SM2.5.3. *Slums*

Slums formation and development depends on complex dynamics and a series of factors (Roy et al. 2014). We investigated the relationship between the share of urban population living in slums and a set of potential explanatory variables. Using national slum 2014 data from UN-HABITAT available through the World Bank (World Bank 2020), we run linear regression in R. Results showed a good correlation with the log of per-capita GDP (Dellink et al. 2017), as shown in Table 7 and Figure 3.

Table 7 Regression analysis for urban population living in slums.

	Share of urban population living in slums
log(GDP/cap)	-0.183***
	(0.019)
Constant	1.986***
	(0.160)
Observations	79
R2	0.548
Adjusted R2	0.542
Residual Std. Error	0.157 (df = 77)
F Statistic	93.321*** (df = 1; 77)
Note:	*p**p***p<0.01

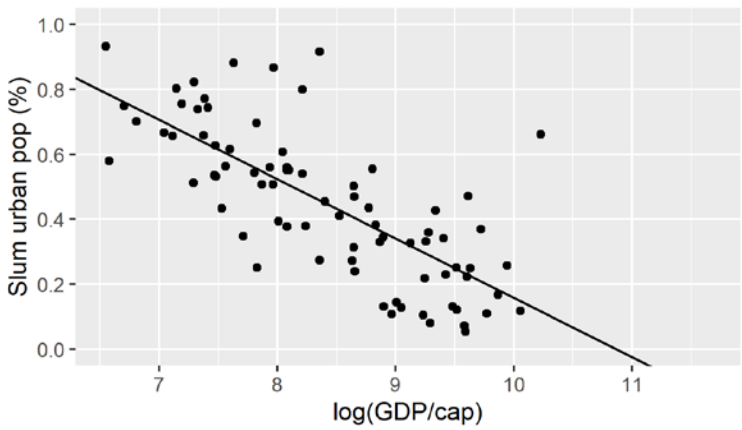


Figure 3 Linear regression for the share of urban population living in slums versus log(GDP/cap). Dots represent observations (countries).

We use the estimated regression coefficients to predict future slum population at national level, assuming that the presence of slums is limited to urban areas and to the global South. We then disaggregate national predictions to urban income tertiles, starting from filling the lower tertile and continuing to the middle (slum share higher than 1/3) and upper tertile (slum share higher than 2/3). Slum projections at regional level are shown in Figure 4.

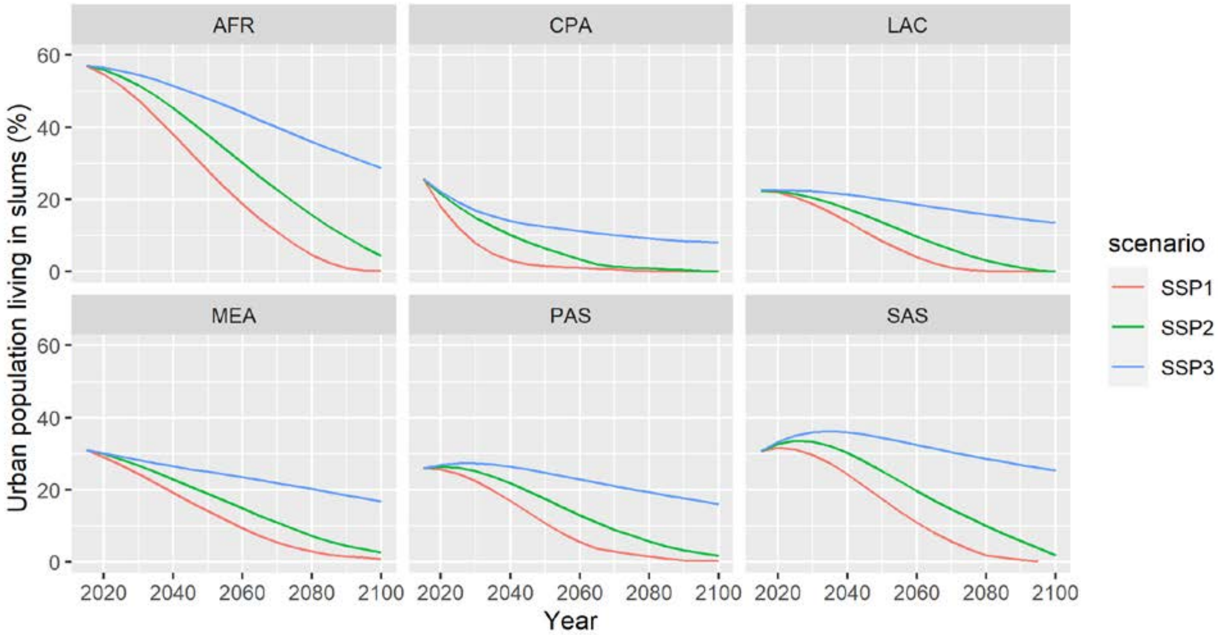


Figure 4 Slum projections at regional level.

SM2.5.4. *Floorspace*

We assume a logistic function describing the future per-capita floorspace evolution towards a saturation level. The function is described by the following equation:

$$F = \frac{S}{1 + e^{-k(x-x_0)}}$$

Where F represents the floorspace per capita, S the floorspace saturation value, k the logistic growth rate, and $x_0 = 0$ the midpoint value.

We report in Tables 7-8 the basic input parameters for floorspace projections. Saturation levels are region-specific and set on the basis of estimates in literature (Fishman et al.; Harvey 2014), while growth speed varies across regions and scenarios depending on scenario assumptions. In SSP2-3 per-capita floorspace increases for most regions, though at different pace. In SSP1 values converge towards 41.6m2/cap (current value for the global North) (Fishman et al.), resulting in more modest increase in the global North and CPA, and higher increase in other global South regions where gaps in decent living are filled more rapidly. Regional averages are shown in Figure

5. Results are then downscaled to different housing types and locations using region-specific relationships built based on survey data (Table 3). Downscaled results are reported in Figures 6-8 for SSP1-3.

Table 8 Floorspace saturation.

Region	**Floorspace saturation** (m²/cap)		
	SSP1	**SSP2**	**SSP3**
AFR	41.6	40	40
CPA	41.6	55	55
EEU	41.6	45	45
FSU	41.6	45	45
LAC	41.6	40	40
MEA	41.6	40	40
NAM	41.6	60	60
PAO	41.6	55	55
PAS	41.6	40	40
SAS	41.6	40	40
WEU	41.6	45	45

Table 9 Floorspace growth rate.

Region	**Growth rate (year saturation is reached)**		
	SSP1	**SSP2**	**SSP3**
Global North	80 (2316)*	30 (2153)	60 (2291)
Global South	20 (2107)	30 (2153)	60 (2291)

Note: *Except EEU and FSU: same values as Global South

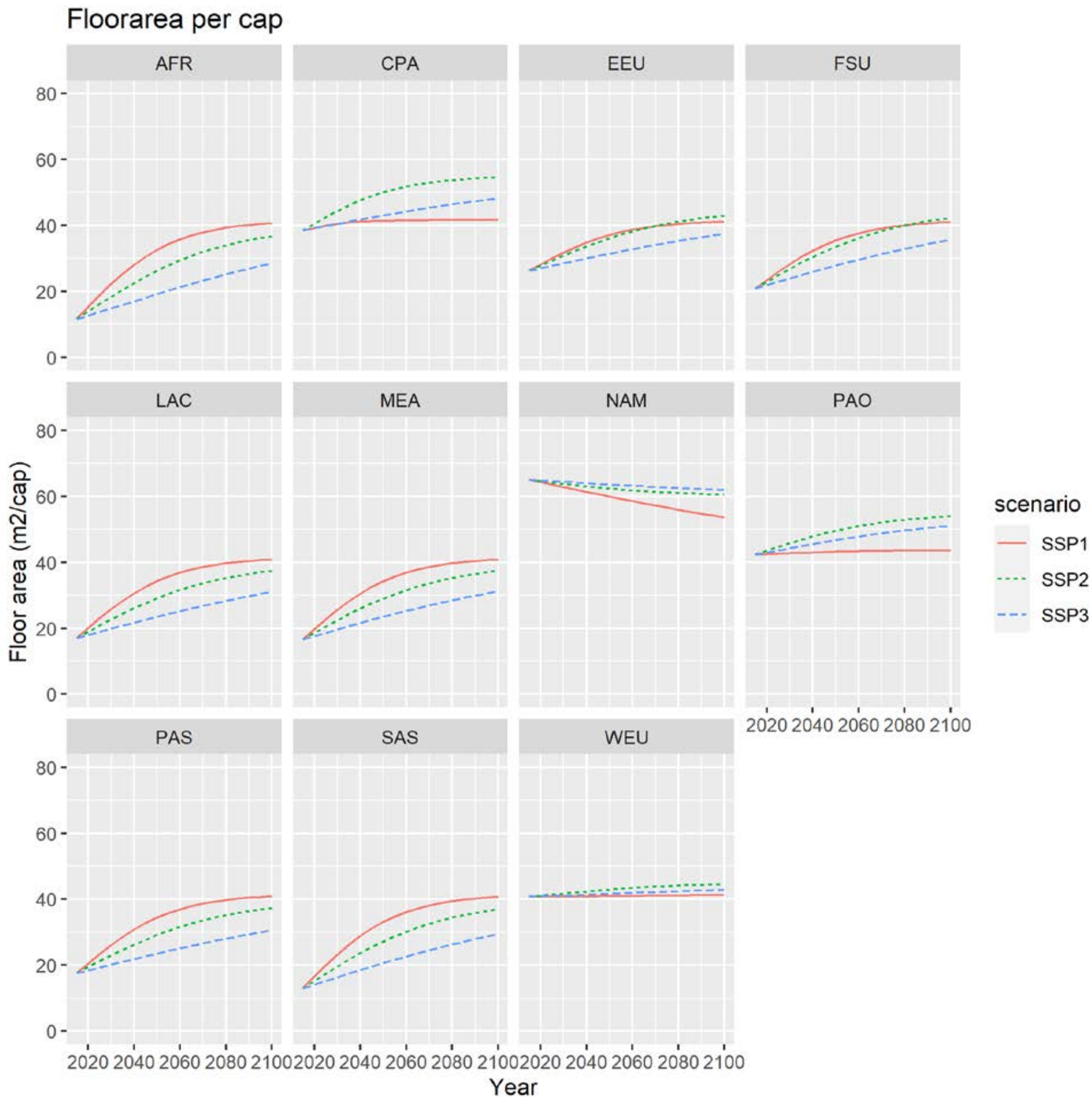


Figure 5 Floorspace projections: regional averages.

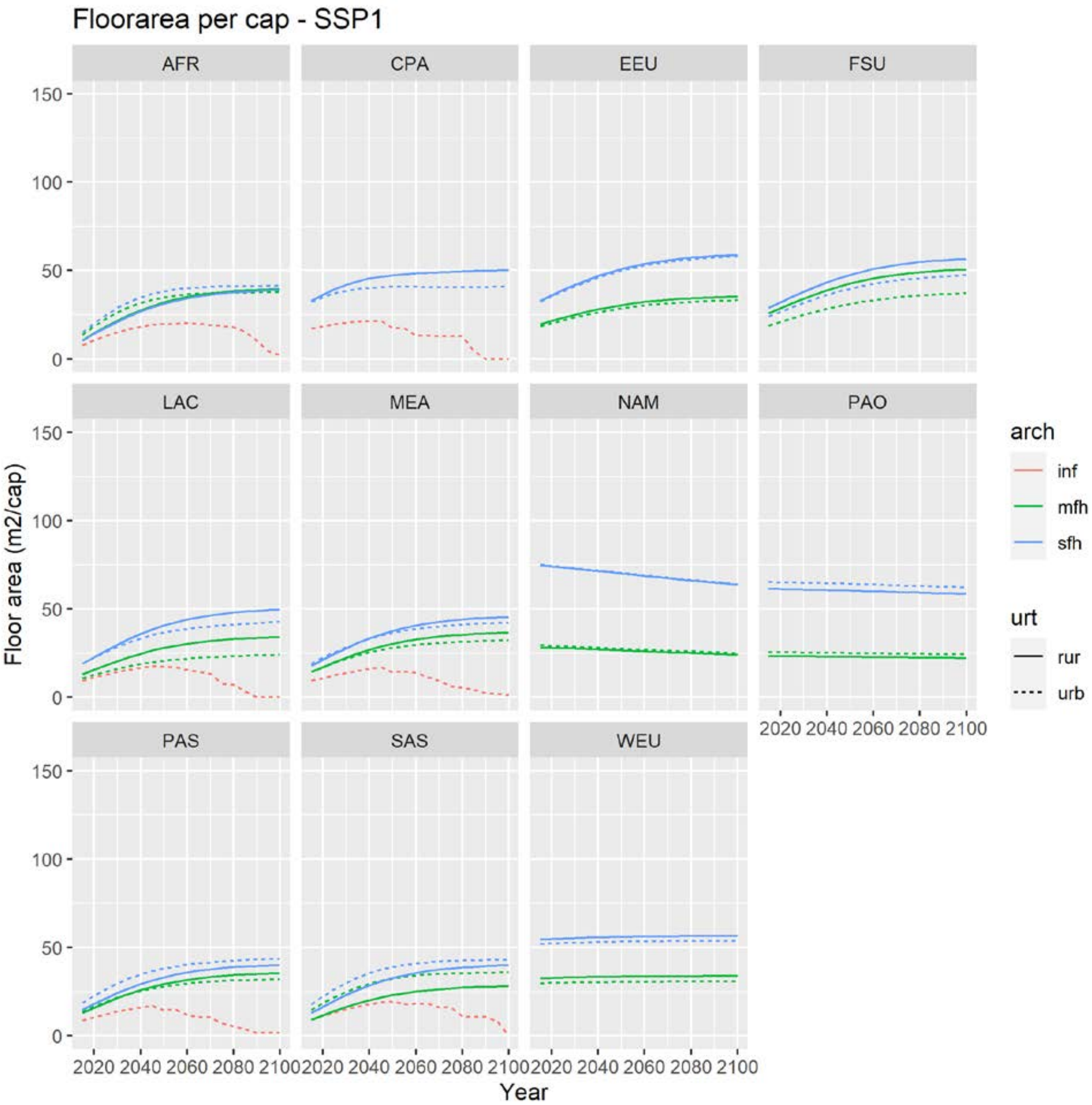


Figure 6 Floorspace projections by region, location and housing type in SSP1. Location: rural (rur), urban (rur). Housing types: slum (inf), multi-family housing (mfh), single family housing (sfh).

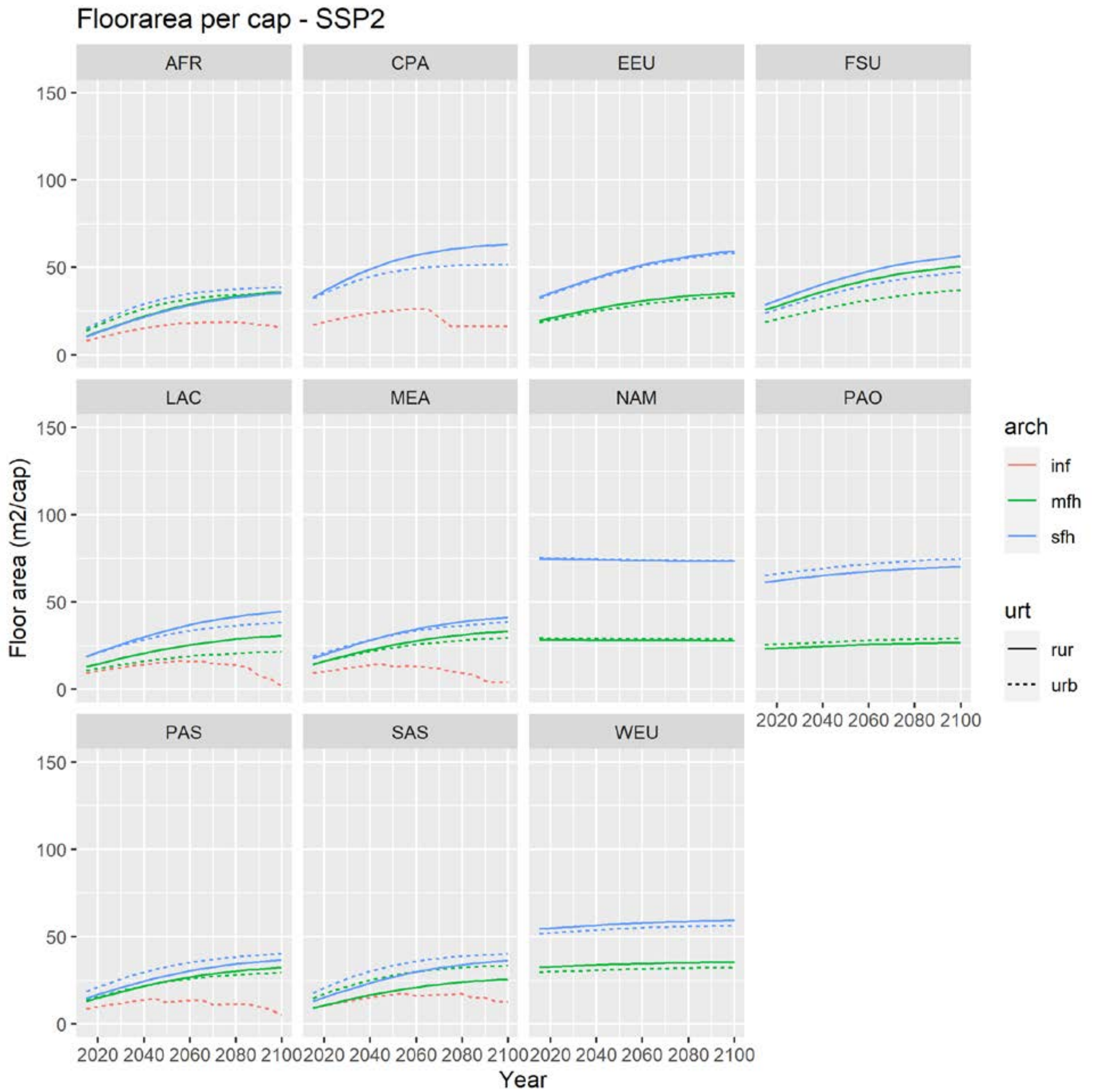


Figure 7 Floorspace projections by region, location and housing type in SSP2. Location: rural (rur), urban (rur). Housing types: slum (inf), multi-family housing (mfh), single family housing (sfh).

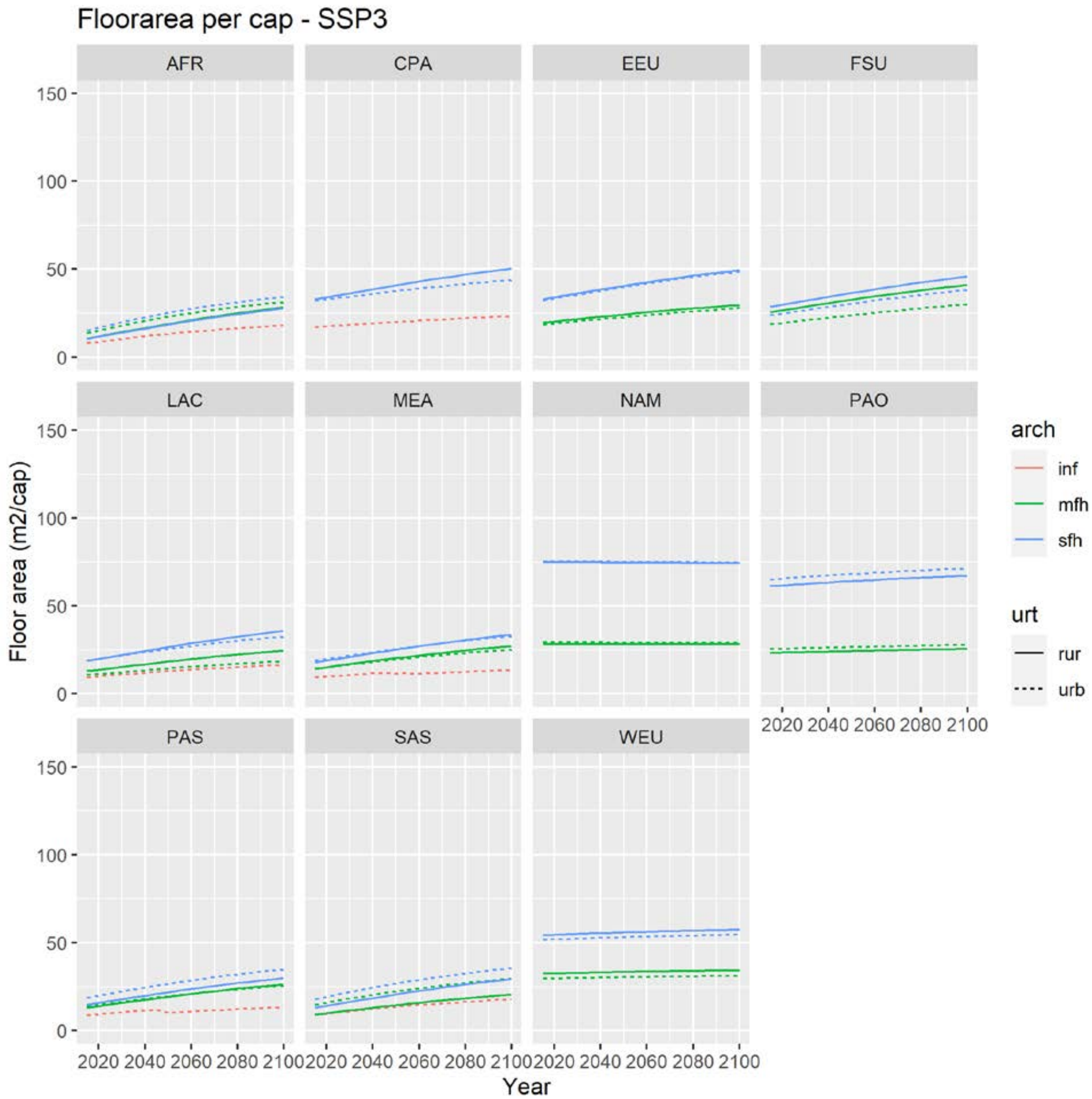


Figure 8 Floorspace projections by region, location and housing type in SSP3. Location: rural (rur), urban (rur). Housing types: slum (inf), multi-family housing (mfh), single family housing (sfh).

SM2.5.5. *Access to air conditioning*

We use the AC adoption model developed by McNeil & Letschert (Mcneil and Letschert 2010) as applied by Isaac & Vuuren (Isaac and van Vuuren 2009) and in a previous study (Mastrucci et al. 2019b). The dependence of AC adoption to climate conditions is represented by a maximum saturation level dependent on a given Cooling Degree Days (CDD) threshold. This was determined by fitting regional AC ownership against CDD in the USA, assuming here ownership is not constrained by income levels. The saturation level AC_{MaxSat} is given by:

$$AC_{MaxSat} = 1 - 0.949e^{-.00187*CDD}$$

A standard S-curve describes the relationship between AC adoption rate and income:

$$AC_{Adopt} = \frac{1}{(1 + e^{4.152}e^{-.237*\frac{Inc}{1000}})}$$

Where *Inc* is per capita GDP in purchasing power parity (PPP) dollars. We calculate standard CDD at the temperature of 18.3◦C on spatial gridded data (see section SMSM2.4) and aggregate results by country and climatic zone, weighted on population.

We apply this AC adoption model to different climatic zones and households differentiated by income level to account for heterogeneity across regions and households. We compared predictions for the base year against AC access data collected from the surveys in Table 3 and from previous studies (Mastrucci et al. 2019a). The comparison revealed deviations for some of the regions. We reconciled national AC access projections with empirical data for the base year, where available, by using monotonic splines interpolation. Results aggregated at the regional level are reported in Figure 9.

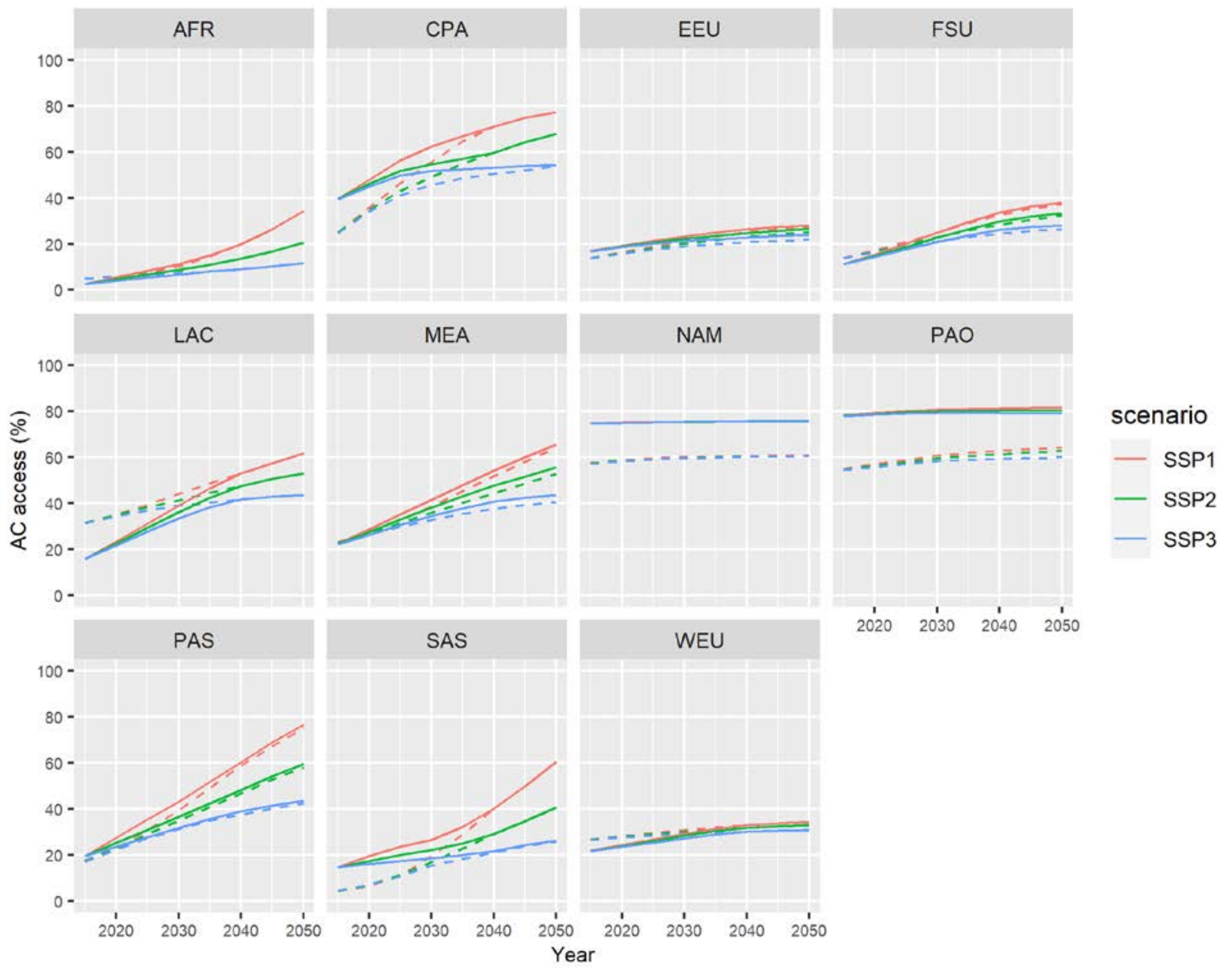


Figure 9 Air-conditioning access projections by region for SSP1-3. Dashed lines represent original model projections. Continuous lines projections corrected using empirical data for the base year.

SM2.5.6. *District heating*

Share of urban housing units served by district heating was estimated based on data from existing studies and databases (Harvey et al. 2014; International Energy Agency 2019) and reported in Table 10. We keep the share of urban housing units served by district heating as fixed over time, with the total number changing depending on urbanization and population growth.

Table 10 Share of urban housing units served by district heating by region, where available.

Region	District heating (%)
CPA	32
EEU	30
FSU	84
NAM	0
PAO	7
WEU	7

SM2.6. *Techno-economics*

SM2.6.1. *Building lifetime distribution*

Stock-driven approaches for building turnover require assumptions on the lifetime of buildings. We adapted Weibull distribution parameters from existing studies (Deetman et al. 2020) to represent buildings in different regions and, when available, different housing types, as reported in Table 11.

Table 11 Weibull parameters for building lifetime distributions.

Region	Single-family homes SFH		Multi-family homes MFH	
	Shape	Scale	Shape	Scale
AFR	1.97	67.34	1.97	67.34
CPA	2	33.85	2	31.03
EEU	2.5	150	2.5	150
FSU	2.5	73.26	2.5	53.6
LAC	1.97	68.24	1.97	68.24
MEA	1.97	67.34	1.97	67.34
NAM	4.16	150	4.16	150
PAO	1.97	94	1.97	94
PAS	1.88	41.23	1.9	43.95
SAS	1.97	67.34	1.97	67.34
WEU	2.95	150	2.95	150

SM2.6.2. *Building thermal properties*

We use an archetype approach to represent building characteristics and thermal properties by region, housing type and energy efficiency level in the energy demand calculation. Building geometry is differentiated by housing type and defined based on previous studies (Mastrucci and Rao 2017; Mastrucci et al. 2019b) (Table 12). We define U-values by region, vintage and energy efficiency level of buildings, based on existing literature, databases and standards (Feist et al. 2007; Mastrucci et al. 2019b; EU Building Stock Observatory 2020; Edelenbosch et al. 2021) and report average values in Table 13. U-values for new buildings of standard type are based on current building practice. Advanced new buildings have U-values meeting the passive standard (Feist et al. 2007) in the global North, and U-values similar to current practice in EU in the global South. U-values for roofs, used in the calculation of solar heat gains through opaque elements (Mastrucci et al. 2019b), are reported in Table 14. All other parameters related to building thermal properties are from previous work (Mastrucci et al. 2019b). For building renovation, we assume different final building characteristics and energy saving levels by renovation type and SSP scenario (Table 15), based on the range of energy savings identifying light renovation (standard) and medium renovation (advanced) in the European context (Esser et al. 2019).

Table 12 Area of building envelope components per unit of floorspace area.

Housing type	**Walls area** (m^2/m^2)	**Roof area** (m^2/m^2)	**Windows area** (m^2/m^2)	**Envelope area** (m^2/m^2)
Single-family homes (SFH)	1.575	1.000	0.125	3.700
Multi-family homes (MFH)	0.985	0.250	0.125	1.610

Table 13 Average U-values by region and energy efficiency level.

Region	**U-values** (W/m^2K)				
	Existing before 1945	**Existing before 1945**	**Existing before 1945**	**New standard**	**New advanced**
AFR	3.48	3.48	3.26	3.03	0.59
CPA	3.15	2.40	1.65	1.53	0.59
EEU	1.63	1.54	0.96	0.71	0.30
FSU	1.63	1.54	0.96	0.71	0.30
LAC	3.15	2.89	2.68	2.65	0.59
MEA	3.53	3.18	2.64	2.50	0.59
NAM	2.45	1.79	1.48	2.50	0.30
PAO	2.42	1.86	1.04	0.94	0.30
PAS	3.48	3.48	3.26	3.03	0.59
SAS	3.48	3.48	3.26	3.03	0.59
WEU	2.35	1.62	0.81	0.59	0.30

Table 14 Roof U-values by region and energy efficiency level.

Region	**U-values** (W/m^{2}K)				
	Existing before 1945	**Existing before 1945**	**Existing before 1945**	**New standard**	**New advanced**
AFR	3.30	3.30	3.06	2.70	0.23
CPA	2.00	1.30	0.76	0.70	0.23
EEU	1.60	1.10	0.45	0.23	0.10
FSU	1.60	1.10	0.45	0.23	0.10
LAC	2.00	1.90	1.64	1.60	0.23
MEA	3.30	2.50	1.20	1.00	0.23
NAM	1.50	0.60	0.36	0.34	0.10
PAO	1.86	1.18	0.47	0.35	0.10
PAS	3.30	3.30	3.06	2.70	0.23
SAS	3.30	3.30	3.06	2.70	0.23
WEU	1.98	1.19	0.46	0.28	0.10

Table 15 Energy savings level for different type of renovation by scenario.

Scenario	**Energy savings** (%)	
	Standard renovation	Advanced renovation
SSP1	30	50
SSP2	20	40
SSP3	10	30

SM2.6.3. *Heating and cooling systems*

We set the energy efficiency coefficients of heating and cooling systems based on existing literature (IEA 2018; Levesque et al. 2018; Knobloch et al. 2019) and report their values for the base year in Table 16 for heating, and Table 17 for cooling systems. Energy efficiency coefficients for heating systems vary with the energy efficiency level of buildings, assuming that advanced new and renovated buildings are equipped with high-efficiency systems and can use a limited set of fuels (district heating, electricity, gas, and solid biomass). Two options are available for electric heating, namely direct and heat pump. We assume direct heating applies to existing buildings, and standard new constructions and renovations in the global South, and heat pumps to all other cases. We assume the use of traditional solid biomass and associated heating systems with lower efficiency for the global South, except for advanced standard construction. The efficiency of heating and cooling systems increases towards target values set for 2100 based on previous studies (Levesque et al. 2018; Knobloch et al. 2019). Target values for 2100 are reported in Table 18. 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. For the portion of the stock not served by district heating (section SM2.5.6), we determine the share of housing stock using different heating fuels in the base year based on data from IEA (International Energy Agency 2019) and existing literature (Harvey et al. 2014). Both data sources provided fuel shares on final energy for space heating. We use the final energy efficiency coefficients above to estimate the share of housing units using different heating fuels based on the available data, and reporting results by region (Table 19). We assume that solid biomass is used for the most part in rural areas, except for regions of the global South with lower income levels.

Table 16 Energy efficiency coefficients of heating systems in the base year.

	Energy efficiency coefficient (-)		
	Existing buildings	**Standard new and renovated buildings**	**Advanced new and renovated buildings**
Global North			
Coal	0.75	0.75	-
District heating	0.98*	0.98	0.98
Electricity – heat pump	2.5	2.5	2.7
Electricity – direct	1	1	-
Gas	0.75	0.75	0.9
Oil	0.75	0.75	-
Solid biomass	0.7	0.7	0.85
Global South			
Coal	0.75	0.75	-
District heating*	0.98	0.98	0.98
Electricity - heat pump	2.5	2.5	2.5
Electricity - direct	1	1	-
Gas	0.75	0.75	0.9
Oil	0.75	0.75	-
Solid biomass	0.4	0.4	0.7

Note: A value of 0.8 was used for existing buildings in CPA and FSU to account for lower efficiency of district heating networks (Jiang et al. 2017; Yu et al. 2018; Romanov et al. 2020).

Table 17 Energy efficiency coefficients of cooling systems in the base year.

Region	**Energy efficiency coefficient** (-)
AFR	2.7
CPA	3.2
EEU	3
FSU	3
LAC	2.9
MEA	2.9
NAM	3
PAO	3
PAS	2.9
SAS	2.9
WEU	3

Table 18 Target energy efficiency coefficients of new heating and cooling systems by 2100.

	Energy efficiency coefficient (-)		
	SSP1	**SSP2**	**SSP3**
Heating systems			
Coal	0.75	0.75	0.75
District heating	0.98	0.98	0.98
Electricity - heat pump	6	5	3.875
Electricity - direct	1	1	1
Gas	0.9	0.9	0.9
Oil	0.86	0.86	0.86
Solid biomass	0.85	0.85	0.85
Cooling systems			
Air-conditioning	6	5	3.875

Table 19 Share of housing units by heating fuel for individual heating systems in the base year (individual heating systems only, district heating excluded).

Region	**Location**	**Coal** (%)	**Electricity** (%)	**Gas** (%)	**Oil** (%)	**Solid Biomass** (%)
AFR	Rural	24	14	0	20	43
	Urban	24	14	0	20	43
CPA	Rural	53	23	0	0	24
	Urban	39	61	0	0	0
EEU	Rural	19	7	22	3	50
	Urban	38	14	43	5	0
FSU	Rural	7	7	51	13	22
	Urban	9	9	66	16	0
LAC	Rural	0	16	14	51	19
	Urban	1	20	17	63	0
MEA	Rural	0	16	34	48	2
	Urban	0	17	34	49	0
NAM	Rural	0	10	43	10	36
	Urban	0	15	68	16	0
PAO	Rural	3	12	34	36	14
	Urban	3	14	40	42	0
PAS	Rural	0	12	0	0	88
	Urban	0	12	0	0	88
SAS	Rural	0	12	0	0	88
	Urban	0	12	0	0	88
WEU	Rural	3	9	32	13	43
	Urban	5	16	56	23	0

SM2.6.4. *Emission factors*

We calculate emission factors based on the results of the Integrated Assessment Modelling framework MESSAGEix-GLOBIOM (McCollum et al. 2018). We consider scenario runs with National Policies until 2030 (NPi) (McCollum et al. 2018). For each year in the time series, we calculate the emission factors by region and separately for electricity (Figure 10) and district heating (Figure 11) as the ratio between total emissions and secondary energy. Similarly to the MESSAGEix-GLOBIOM framework[2], emission factors of fossil fuels are based on the 1996 version of the IPCC guidelines for national greenhouse gas inventories (IPCC 1996) and biomass is considered as carbon neutral in the energy system (Table 20).

Table 20 Emission factors of fossil fuels and biomass.

Fuel	**Emission factor** (tCO_2/TJ)
Coal	94.6
Gas	56.1
Oil	73.3
Biomass	-

[2] For more details on the accounting of emission from energy in MESSAGEix-GLOBIOM, we refer the reader to: https://docs.messageix.org/projects/global/en/latest/emissions/message/index.html

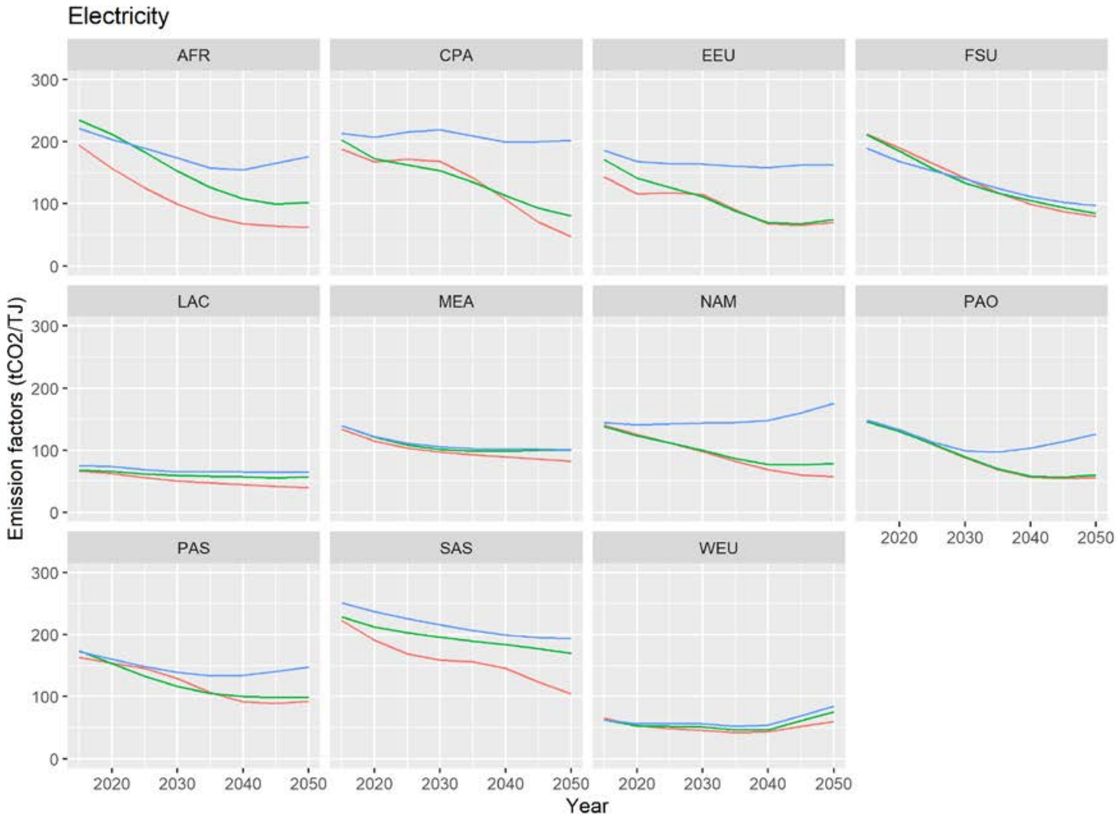


Figure 10 Emission factors for electricity.

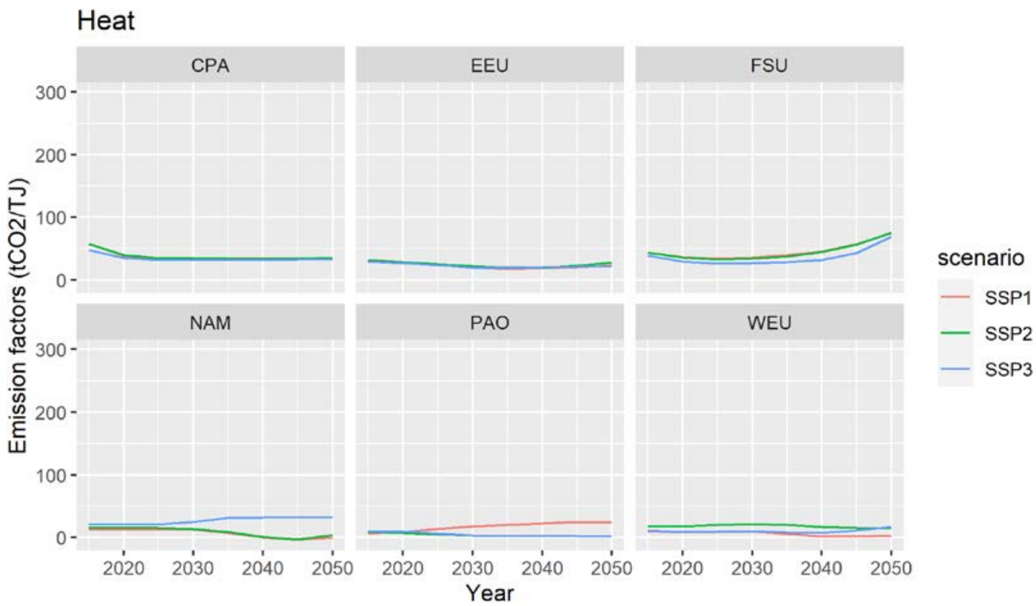


Figure 11 Emission factors for district heating, where available.

SM2.6.5. *Energy prices*

We report below the regional energy price data for different fuels in SSP1-3 (Figures 12-14). Energy prices are based on the output of MESSAGEix-GLOBIOM (McCollum et al. 2018).

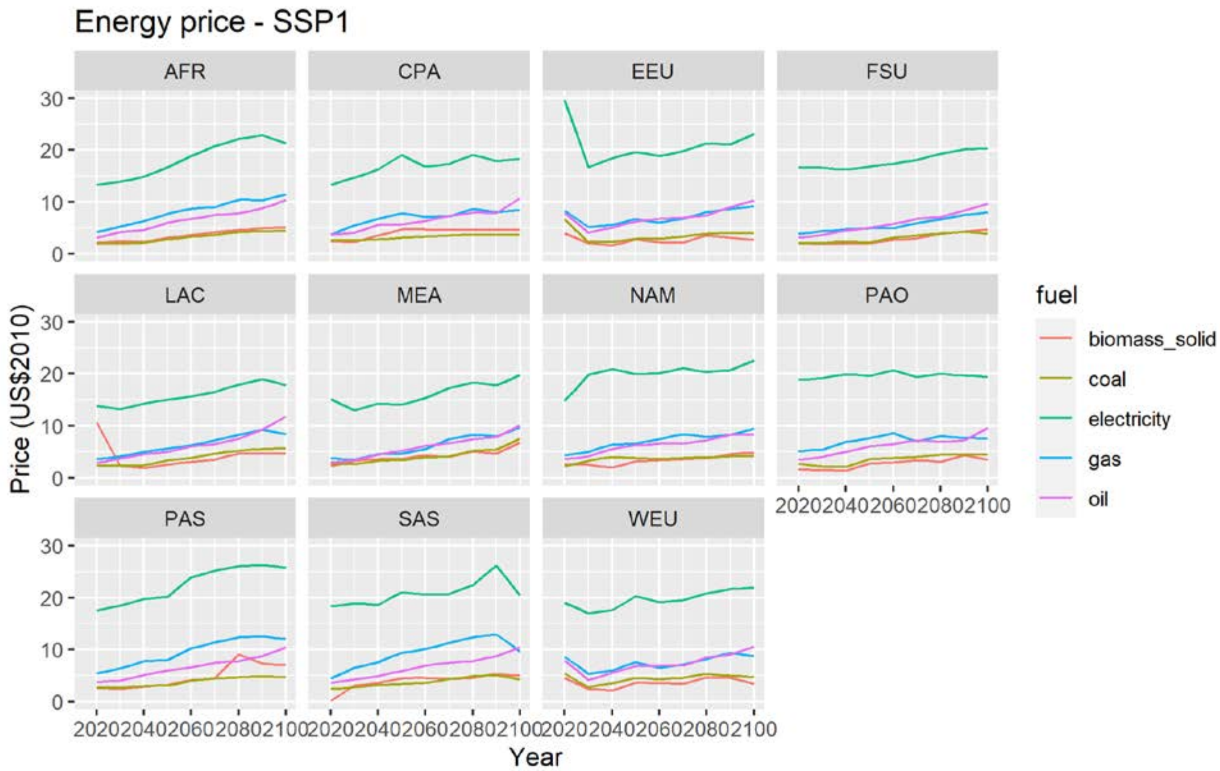


Figure 12 Energy prices for different fuels in SSP1.

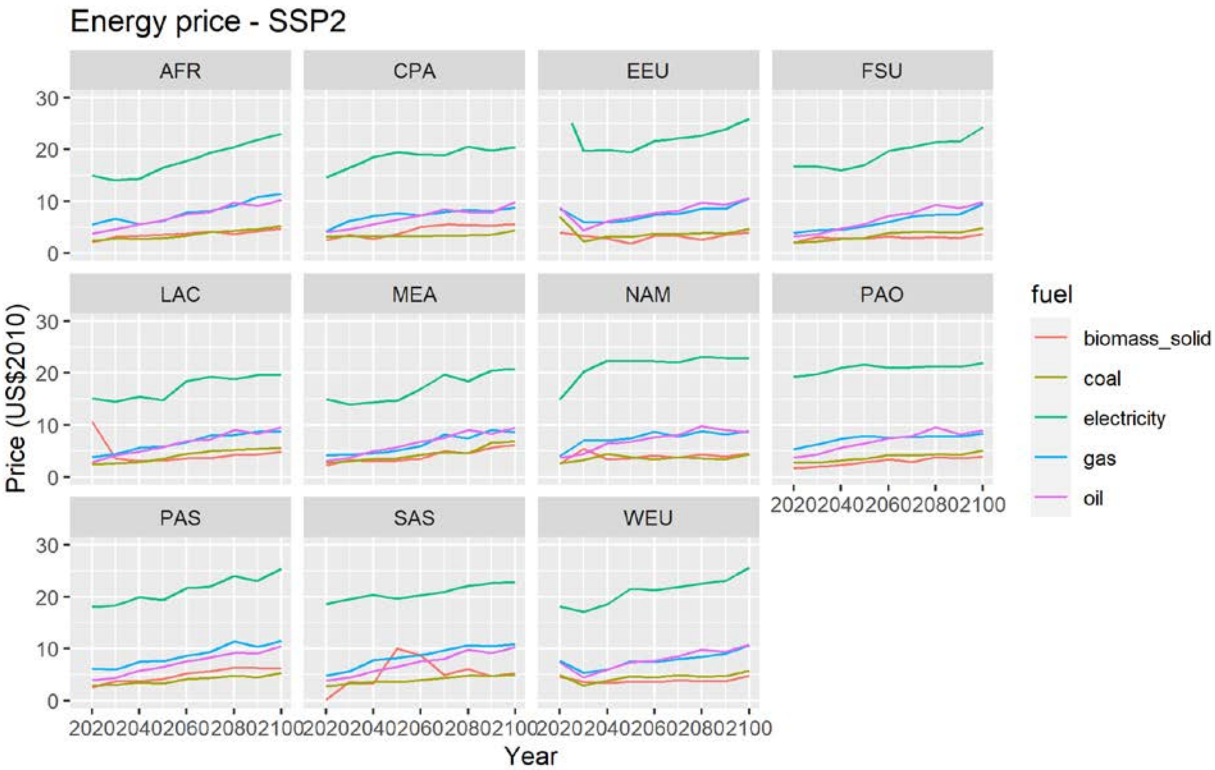


Figure 13 Energy prices for different fuels in SSP2.

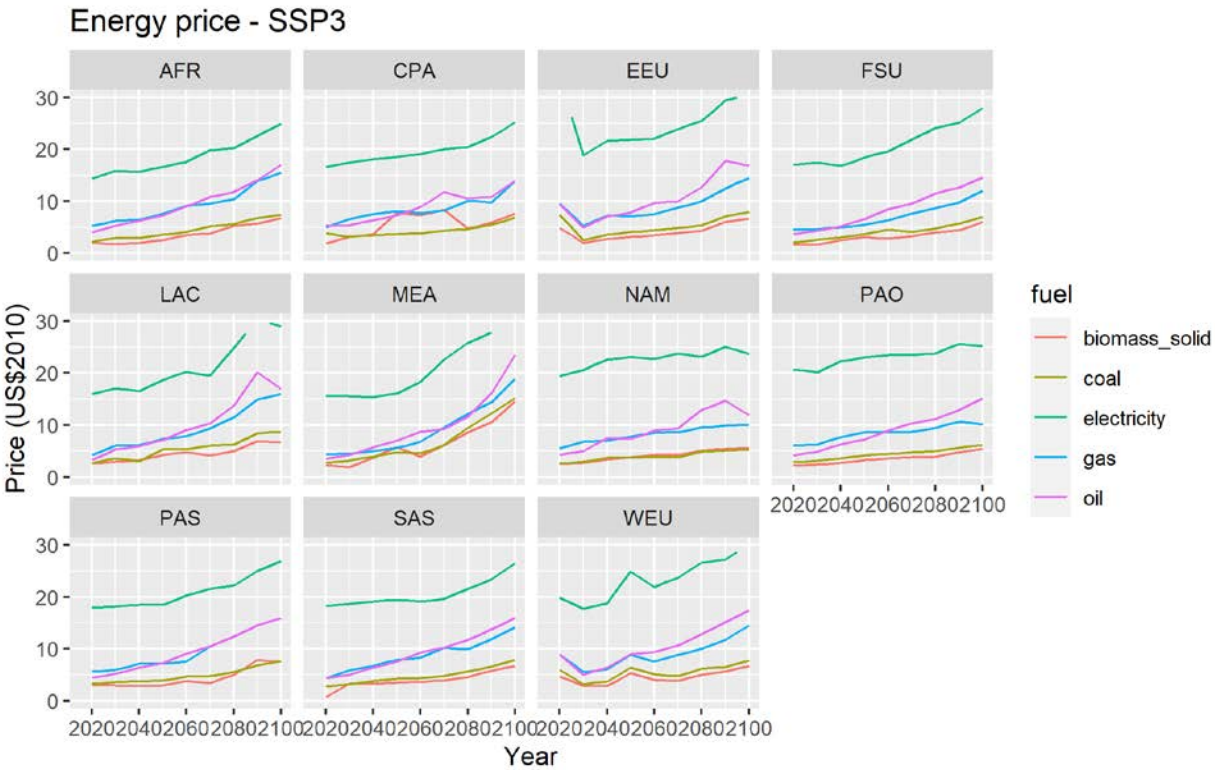


Figure 14 Energy prices for different fuels in SSP3.

SM2.6.6. *Investment costs*

Investment costs are reported in Table 21 for new construction and building shell renovation, and in Table 22 for heating systems. Investment costs for new construction, renovation and heating systems are based on literature (Giraudet et al. 2012; Fleiter et al. 2016; Esser et al. 2019; Mastrucci and Rao 2019) and adapted for global North and South regions. Similar to previous studies (Connolly et al. 2014), we consider decreasing investment costs for heat pumps but not for other heating technologies considered to be mature. Ten-year reductions for the investment costs of heat pumps are 7.5% and 5% respectively in SSP1 and SSP2. All investment costs are fixed in SSP3, following the assumption of slow technological innovations.

Table 21 Investment costs for new construction and building shell renovation.

Intervention	**Unit**	**Cost** (US$)	
		Global North	**Global South**
New - Standard	$/m2	1614.59	454.78
New - Advanced	$/m2	1937.50	591.21
Renovation - Standard	$/m2	487.17	146.93
Renovation - Advanced	$/m2	730.76	220.39

Table 22 Investment costs for heating systems in new construction and renovation.

Heating system	**Unit**	**Cost** (US$)
Electricity	$/unit	8806.42
Gas	$/unit	6528.32
Oil	$/unit	8548.59
Solid Biomass	$/unit	8732.25

SM2.6.7. *Intangible costs*

We use intangible costs to represent market barriers towards energy efficient new constructions and renovations. Intangible costs for new construction and building shell renovation, adapted from existing literature (Giraudet et al. 2012), are reported in Table 23. In addition, in SSP1 and SSP2, we also use intangible costs to limit the uptake of heating systems based on fossil fuels, and traditional biomass in the global South, in line with the switch towards cleaner technologies in these two scenarios.

Table 23 Intangible costs for new construction and building shell renovation.

		Intangible costs ($/m2)	
Intervention	**Scenario**	**Global North***	**Global South**
New - Advanced	SSP1	500	500
	SSP2	1000	1000
	SSP3	5000	NA
Renovation - Advanced	SSP1	500	5000
	SSP2	2000	NA
	SSP3	10000	NA

Note: * In WEU and EEU we assume all new buildings to be of advanced type as of 2020. NA= not available

SM2.6.8. *Discount rates*

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.; Giraudet et al. 2012). First, we set values for the global North (Table 24) based on (Giraudet et al. 2012). Values for other regions are then estimated by applying regional coefficients (Table 25) based on (Poblete-Cazenave et al.).

Table 24 Discount rates for the global North. Adapted from (Giraudet et al. 2012).

Intervention	**Housing type**	**Tenure**	**Discount rate** (%)
Renovation	Single-Family	Owning	7
		Renting	35
	Multi-Family	Owning	10
		Renting	40
New construction	Single-Family	-	7
	Multi-Family	-	10

Table 25 Regional coefficients for discount rates. Adapted from (Poblete-Cazenave et al.) .

Region	Coefficient
AFR	1.12
CPA	1.18
EEU	1.00
FSU	1.00
LAC	1.22
MEA	1.33
NAM	1.00
PAO	1.00
PAS	1.26
SAS	1.26
WEU	1.00

SM2.7. ***Behaviour***

Behaviour-related input parameters considered in this study include heating and cooling set point temperatures, operation schedules, and share of conditioned floorspace area. We assign set point temperatures based on survey and literature, and use the results of the model calibration (see section SM2.1) to set operation schedules, and share of conditioned floorspace area.

We consider a 21°C set point for heating, corresponding to the average value estimated from survey data for the USA (see Table 3), and from a survey for social housing in the UK (Jones et al. 2015), consistent with the value suggested by the World Health Organization for a comfortable indoor temperature in living rooms to prevent health issues (World Health Organization 2007). For cooling, we set a value of 23°C corresponding to average value estimated from survey data for the USA (see Table 3). Due to high uncertainty in set point temperatures, we run a sensitivity analysis (section SM2.3) to assess the impact on heating and cooling energy demand. We report in Table 26 the share of conditioned floorspace area on total, resulted from the energy demand calibration process. The daily hours of heating and cooling operation are reported respectively in Table 27 and Table 28. We assume that the daily hours of heating increase in the global South converging towards values for the global North, thought at a different speed in the three SSPs.

Table 26 Share of conditioned floorspace on total floorspace for different regions.

Region	Share of heated floorspace on total	Share of cooled floorspace on total
AFR	0.3	0.4
CPA	0.4	0.6
EEU	0.9	0.8
FSU	1.0	0.8
LAC	0.4	0.8
MEA	0.4	1.0
NAM	0.5	1.0
PAO	0.3	0.6
PAS	0.3	0.4
SAS	0.3	0.4
WEU	0.9	0.8

Table 27 Daily hours of heating operation in different climatic zones and regions.

Climatic zone	Description	Hours/day of space heating operation	
		Global North	Global South
Zone_0	Extremely hot	0	0
Zone_1	Very hot	0	0
Zone_2	Hot	1	1
Zone_3	Warm	2	2
Zone_4	Mixed	6	3
Zone_5	Cool	6	3
Zone_6	Cold	6	3
Zone_7	Very cold	6	6

Table 28 Daily hours of cooling operation in different regions.

Region	**Hours/day of space cooling operation**
AFR	4
CPA	6
EEU	8
FSU	8
LAC	6
MEA	10
NAM	10
PAO	8
PAS	4
SAS	4
WEU	8

SM3. Detailed methods and results

SM3.1. *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 section SM3.1-SM3.2). We then run the stock turnover and decision models jointly for future scenarios (Figure 15).

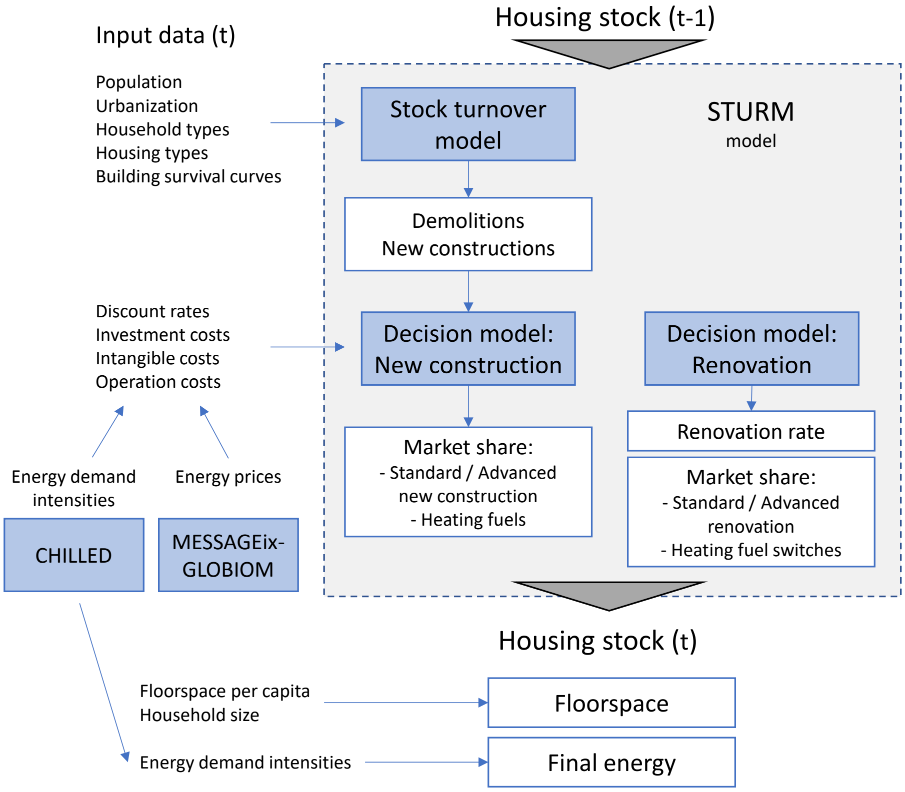


Figure 15 Scenario runs workflow. Iteration at timestep t.

The stock dimension in housing units (S) is estimated based on population (P) and household size (H) at every timestep t:

$$S_t = P_t / H_t \quad (1)$$

Housing units (S) are then apportioned to different housing and household types (h), depending on their share (s) in the stock at the timestep i:

$$S_{h,t} = S_t \cdot s_{h,t} \quad (2)$$

The number of demolitions is calculated based on survival curves specific to different building types using the convolution method in (Sandberg et al. 2016). The amount of required new construction (N) is calculated based on the stock variation $\Delta S_{h,t} = S_{h,t} - S_{h,t-1}$ and the demolitions (D) at housing type level:

$$N_{h,t} = \Delta S_{h,t} + D_{h,t} \quad (3)$$

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

$$LCC_{new,j} = C_{inv,j} + C_{op,j} + C_{int,j} \quad (4)$$

Where $C_{inv,j}$ are the investment costs, $C_{op,j}$ the operational costs, and $C_{int,j}$ 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_j) for option j is then calculated by comparing the LCC of all possible options (k) using the following equation:

$$MS_{new,j} = \frac{LCC_j^{-\nu}}{\sum_k LCC_k^{-\nu}} \quad (5)$$

Where ν is the heterogeneity parameter, set exogenously to 8 (Giraudet et al. 2012).

For renovation, the model estimates the market share for different energy efficiency improvements on building shell, heating system, and heating fuel switches, enabling transitions from an initial (i) to a final (f) configuration and energy efficiency level. An option for no energy efficiency improvements is also included. Energy renovation rates are therefore endogenously calculated, based on the share of energy renovation actions. Equations to calculate the LCC of transitioning from i to f ($LCC_{ren,i\rightarrow f}$) and the market share ($MS_{ren,i\rightarrow f}$) on all possible final solutions (k) are similar to the case of new construction:

$$LCC_{ren,i\rightarrow f} = C_{inv,i\rightarrow f} + C_{op,f} + C_{int,i\rightarrow f} \quad (6)$$

$$MS_{ren,i\to f} = \frac{LCC_{i\to f}^{-\nu}}{\sum_k LCC_{i\to k}^{-\nu}} \quad (7)$$

A set of constraints related to the feasibility of specific new construction and renovation solutions can be set at a regional or global level. The renovation rate can be bounded by upper and lower limits, so as to replicate observed renovation rates. 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, market shares are used to calculate the updated amount of housing units ($S_{h,j,t}$) by building cohort, representing specific housing and household types (h), and energy efficiency levels and fuels (j):

$$S_{h,j,t} = S_{h,j,t-1} \cdot \left(1 - \sum_{k\neq j} MS_{ren,h,j\to k,t}\right) - D_{h,j,t} + N_{h,t} \cdot MS_{new,h,j,t} + \sum_{k\neq j}\left(S_{h,k,t-1} \cdot MS_{ren,h,k\to j,t}\right) \quad (8)$$

where $MS_{ren,h,j\to k,t}$ represents the total market share for renovations from j to a different cohort k (units exiting building cohort j), $MS_{ren,h,k\to j,t}$ the total market share for renovations to j from a different category k (units entering building cohort j), and $MS_{new,h,j,i}$ the market share for new construction. Number of housing units ($S_{h,j,t}$), household size ($H_{h,t}$), and average floorspace per capita values ($F_{cap,h,t}$) are used to calculate the total floorspace by building cohort ($F_{h,j,t}$):

$$F_{h,j,t} = S_{h,j,t} \cdot H_{h,t} \cdot F_{cap,h,t} \quad (9)$$

Finally, energy intensities from the energy demand module CHILLED 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.

SM3.2. *Energy demand model calibration*

A common issue in building energy demand simulation is disagreement between calculated and measured energy consumption data. This issue is increasingly addressed by using model calibration (Fabrizio and Monetti 2015). Sensitivity analysis can support the identification of the model parameters which are the most influential on energy demand results. In previous work (Mastrucci et al. 2017, 2019a; Mastrucci and Rao 2017) we ran extensive sensitivity analysis, highlighting that behaviour-related parameters are among the most influential in energy demand simulation. Thus, in this study we focus on behaviour-related parameters to calibrate the energy demand model at global level for the base year, using a manual approach (Fabrizio and Monetti 2015) for space heating and cooling. Behaviour-related parameters in this model include set point temperatures, daily hours of operation, and share of conditioned floorspace area on total. In this process, to avoid overspecification, we keep the value fixed for one of the parameters, set point temperature, for which data is available from survey and literature, and we tune the parameters 1) daily hours of operation and 2) share of conditioned floorspace area to match observed energy demand in the base year.

For the calibration, we compare model results with final energy demand 2015 data from IEA (Agency 2019) for individual countries, complemented by a second IEA dataset (International Energy Agency (IEA) 2016) for 2013, resulting in more than 30 data points covering most of world regions. We started by calculating energy demand for space heating and cooling for the base year with an initial set of values from previous work (Mastrucci et al. 2017, 2019a; Mastrucci and Rao 2017). After a first results comparison, for space heating we observed systematic overestimation of energy demand in countries with warmer climates and underestimation in colder climates, as well as differences between global North and global South. We consequently adapted the daily hours of operation for space heating by climatic zone and region (Table 27). For space cooling, we observed underestimation of energy demand for countries with higher access to AC and consequently adapted the daily hours of operation by region (Table 28). After a second round of comparison, we tuned in the share of heated and cooled floorspace area on total and repeated the operation until we reached a satisfactory matching against the country level datasets from IEA described above, with most countries within a ±10% range of deviation. We report the results of the final energy demand comparison at the country level in Figure 16 for space heating and Figure 17 for space cooling. We performed additional comparison with 2018 data for Europe (EU27) from Eurostat (Eurostat 2020), showing good agreement. Finally, we compared floorspace (Figure 18) and energy demand (Figure 19) results with an existing study by Harvey (Harvey et al. 2014), using similar region definition. Noting that results in the study by Harvey are for 2010, and our base year is 2015, the comparison showed a good agreement, with some differences in the energy demand for cooling.

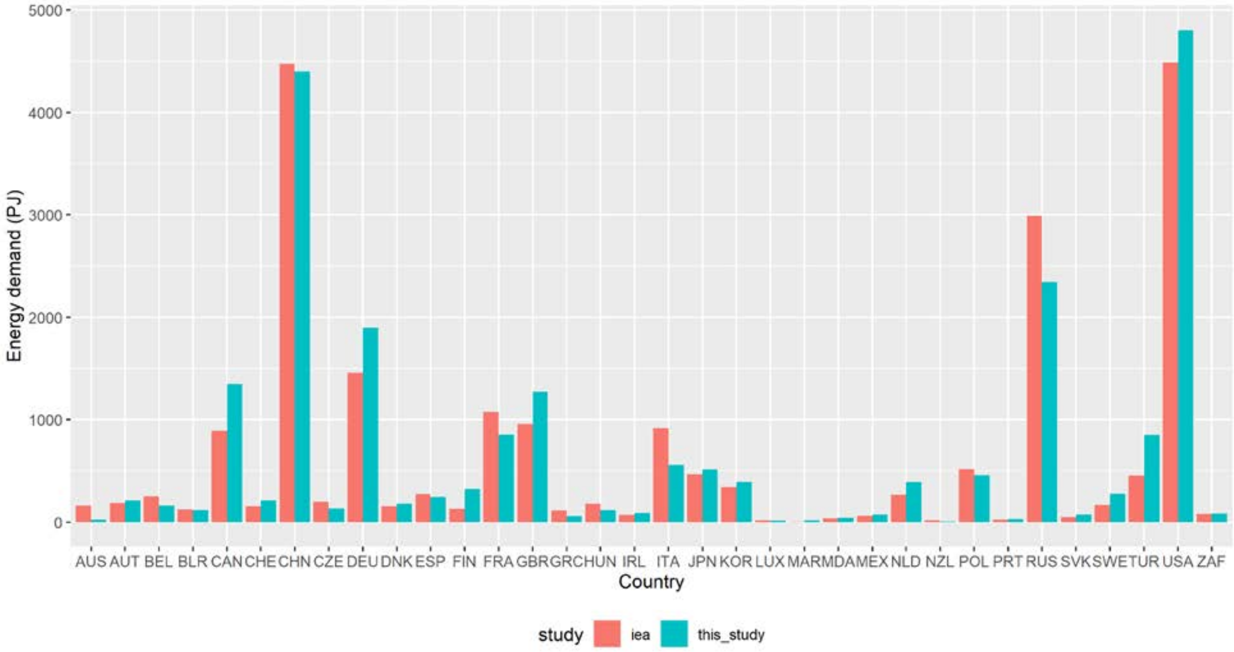


Figure 16 Comparison of final energy result for space heating in the base year with IEA data for selected countries (Agency 2019). *Note: ISO3 countries codes are reported in the x-axis.*

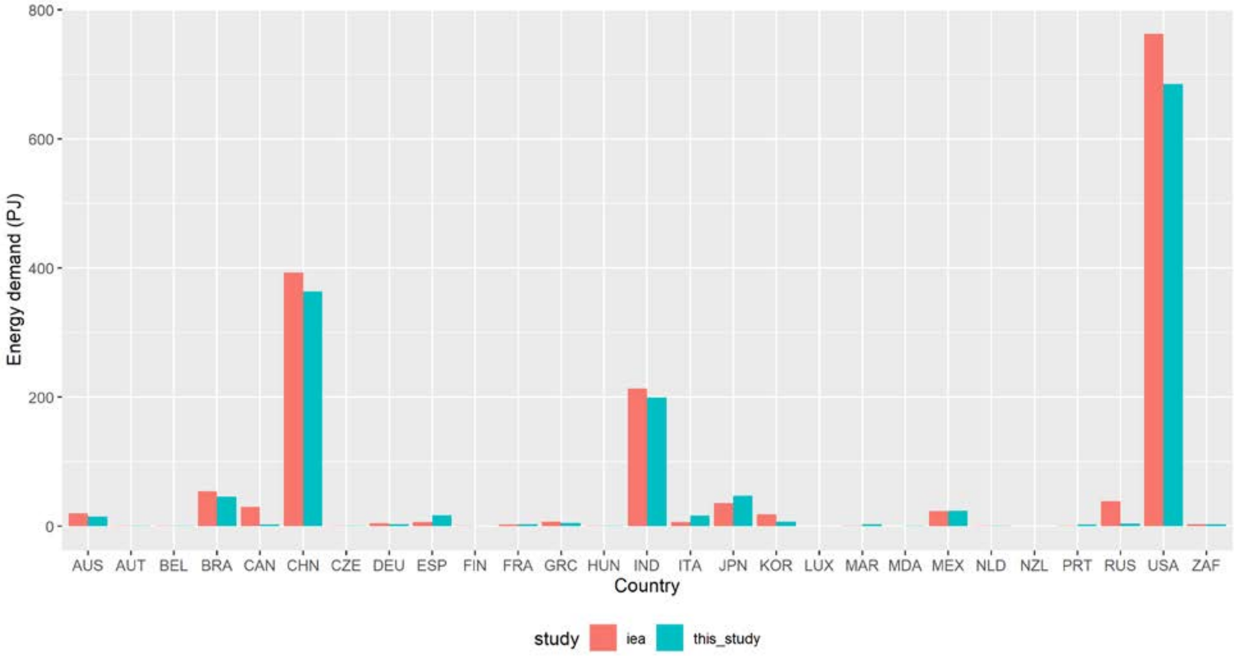


Figure 17 Comparison of final energy result for space cooling in the base year with IEA data for selected countries (Agency 2019). *Note: ISO3 countries codes are reported in the x-axis.*

Table 29 Comparison of results for the EU27 in the base year with Eurostat data for 2018 (Eurostat 2020).

End-use	**Final energy demand (EJ/yr)**	
	This study	**Eurostat**
Space heating	6.499	6.541
Space cooling	0.035	0.038

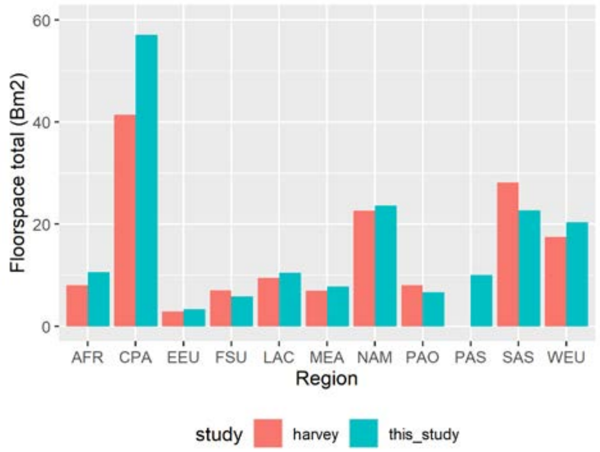


Figure 18 Comparison of floorspace results for the base year with an existing study by Harvey (Harvey et al. 2014)*. Note: in* (Harvey et al. 2014) *results for the PAS and SAS regions are aggregated (here reported under SAS).*

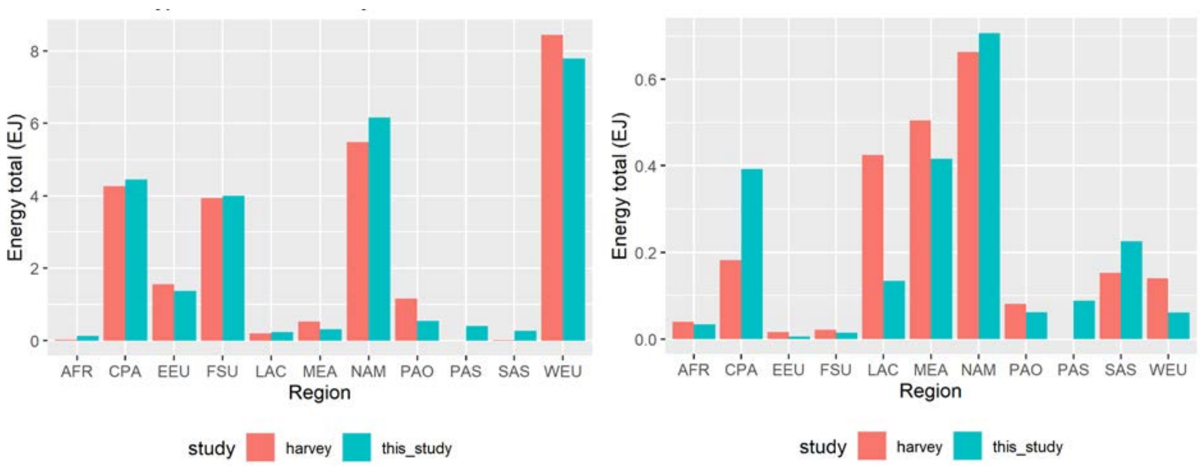


Figure 19 Comparison of final energy demand results for space heating (left) and cooling (right) for the base year with an existing study by Harvey (Harvey et al. 2014)*. Note: in* (Harvey et al. 2014) *results for the PAS and SAS regions are aggregated (here reported under SAS).*

SM3.3. ***Housing stock results validation***

We show here detailed housing stock results for a selection of countries and comparison with data from IEA (International Energy Agency 2019) for Europe (Figure 20) and other world regions (Figure 21). Results showed a good agreement with the IEA data for most of the analysed countries.

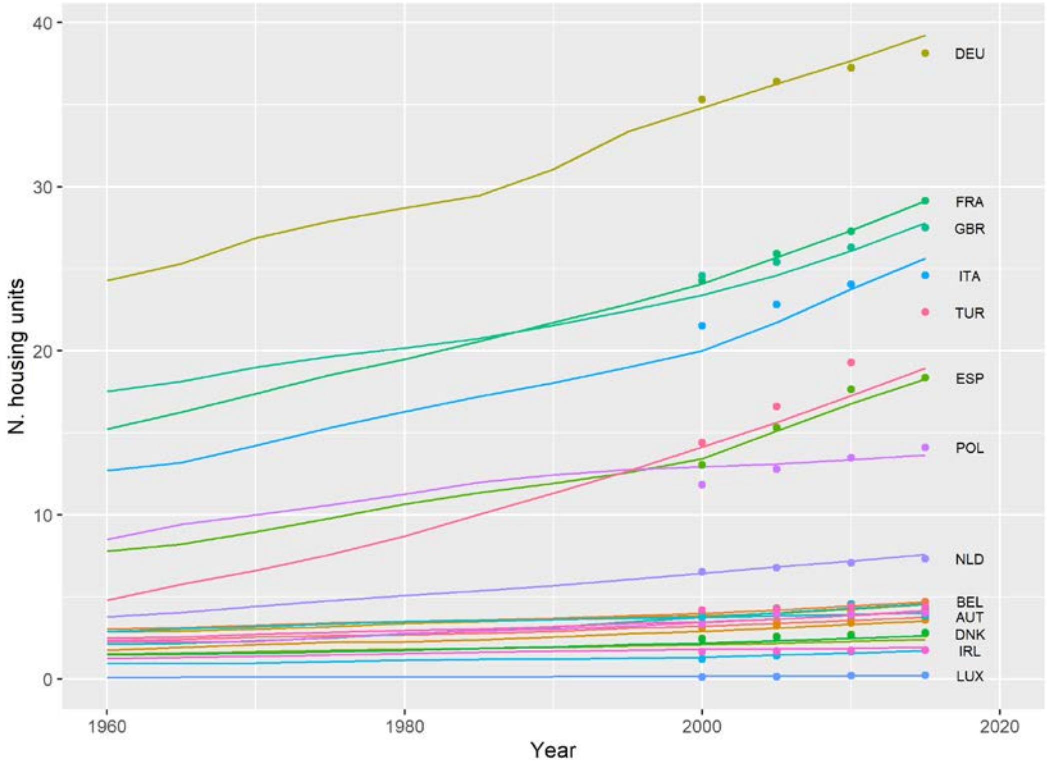


Figure 20 Housing stock results (lines) and reference values (dots) from IEA (International Energy Agency 2019) *for countries in Europe (EEU and WEU regions). Countries are identified by their ISO3 codes.*

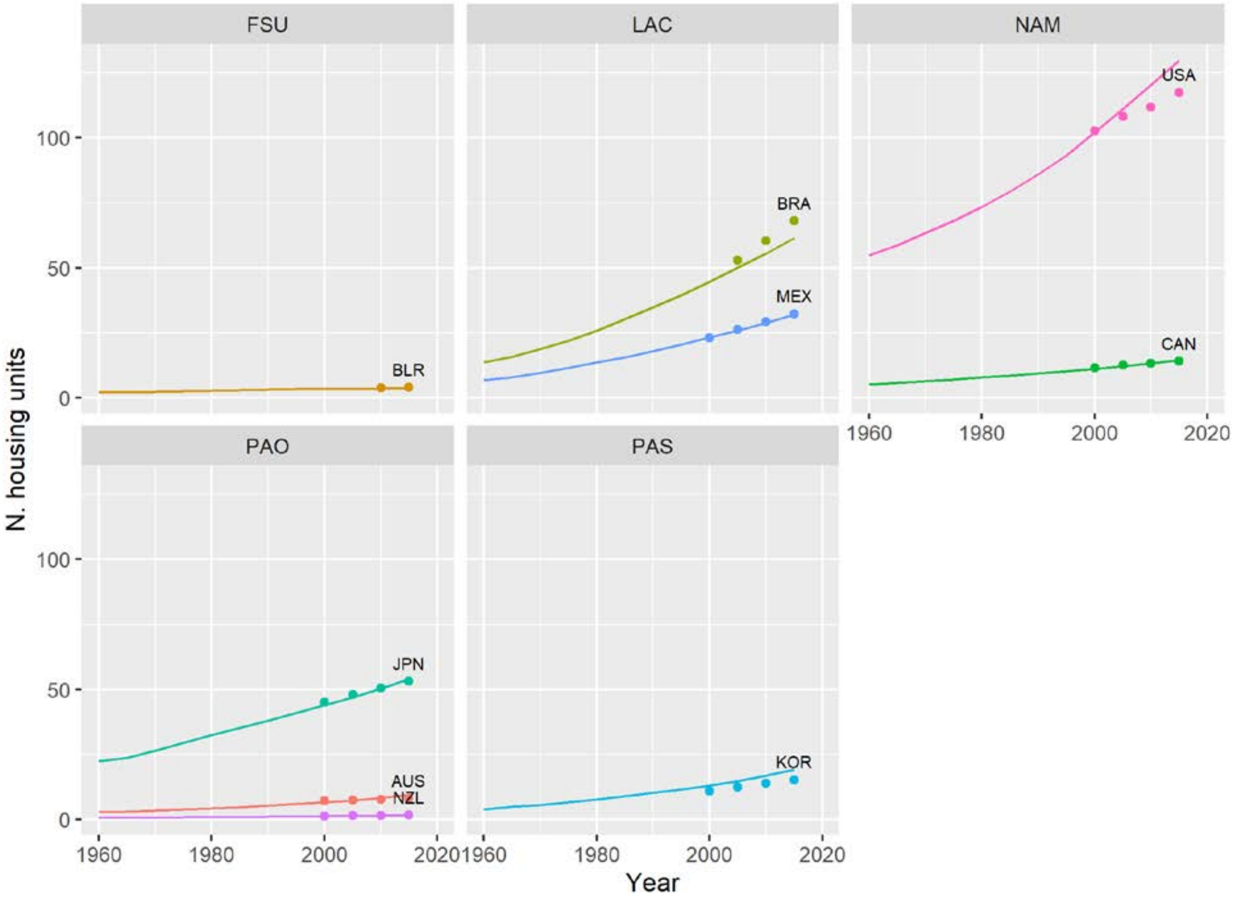


Figure 21 Housing stock results (lines) and reference values (dots) from IEA (International Energy Agency 2019) *for other world regions. Countries are identified by their ISO3 codes.*

SM3.4. ***Detailed new construction and renovation results***

Renovations and new constructions decisions play an important role in improving the energy efficiency of the building stock. In this section we report detailed results on new construction and renovation decisions for different regions, housing and household types.

The uptake of advanced new constructions (Figure 22) is higher in the global North, supported by building codes and standards, and increasing over time as investment costs decrease, energy efficient standards improve, and energy prices increase. In the global South, heating needs are relatively lower and building codes only partially enforced, determining a lower uptake of advanced new constructions. In SSP2 and especially SSP3, barriers towards energy efficiency improvements and imperfect application of building codes, represented by higher intangible costs, result in lower uptake of energy efficient solutions. Results suggest higher uptake of more advanced solutions for SFH, compared to MFH, due to their higher energy intensity and consequent higher potential for energy savings.

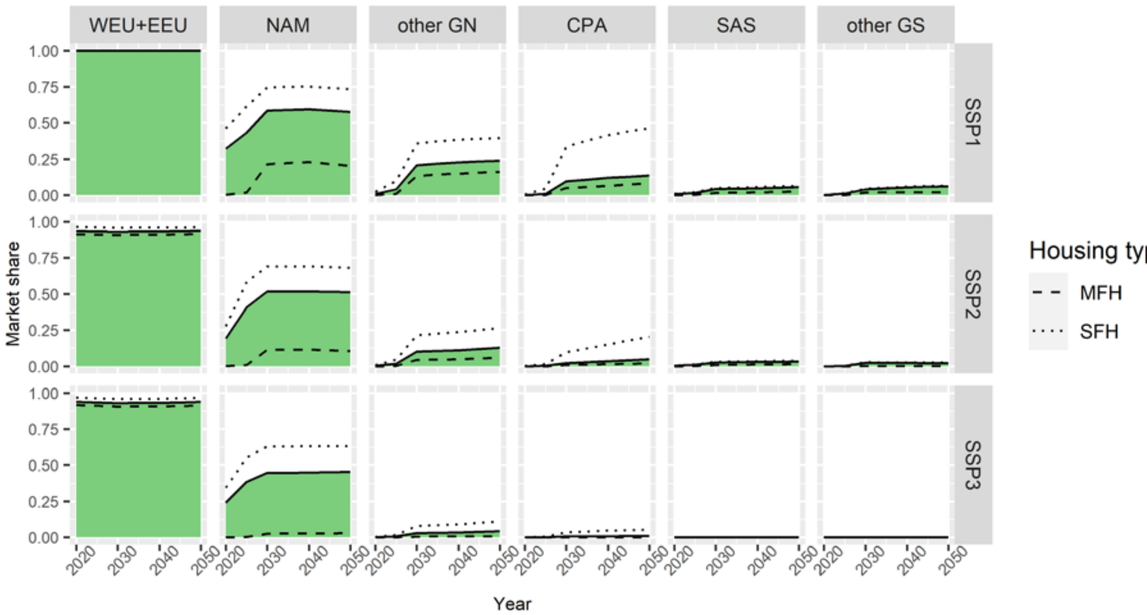


Figure 22 Market share of "advanced" new constructions by housing type in different world regions for SSP1-3.

Renovation trends differ across different SSPs and world regions (Figure 23). In SSP1, renovation rates initially speed up under increasing energy prices and decreasing investment costs, reach a peak between 2025 and 2030, and then slow down as the fraction of non-renovated buildings is shrinking due to both renovation and turnover. In SSP2, the pace of renovations is slower, in line with current trends, and the renovation peak reached later. In SSP3, renovation rates stay constant or decline over time as efficiency improvements are slower and investment costs being unchanged. Renovation rates are higher in Europe, NAM and CPA, with the latter rapidly declining due to faster building turnover dynamics. Other world regions mostly experience low renovation rates due to prevailing buildings demolitions and reconstruction over renovation and lower heating needs not justifying the initial investment for energy efficiency improvements.

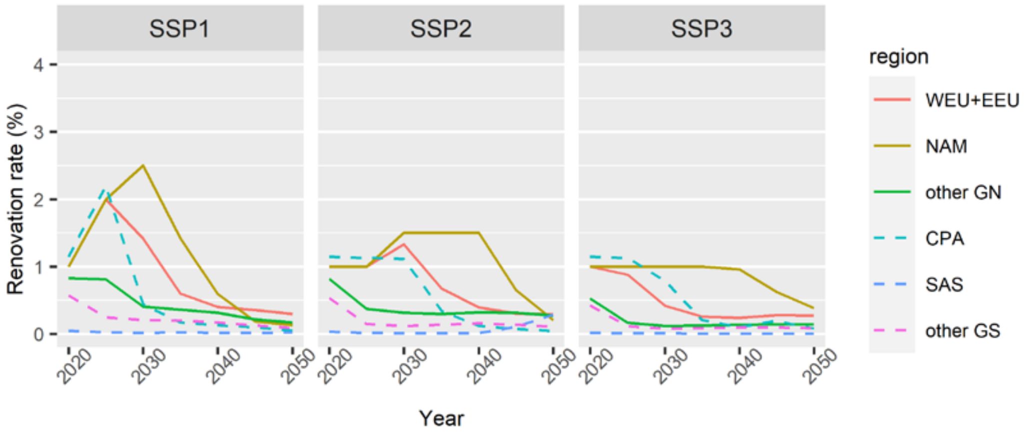


Figure 23 Renovation rates in different world regions for SSP1-3.

SM3.5. ***Detailed CO2 emission results***

Figure 24 shows regional CO2 emission projections by housing cohort and heating fuel.

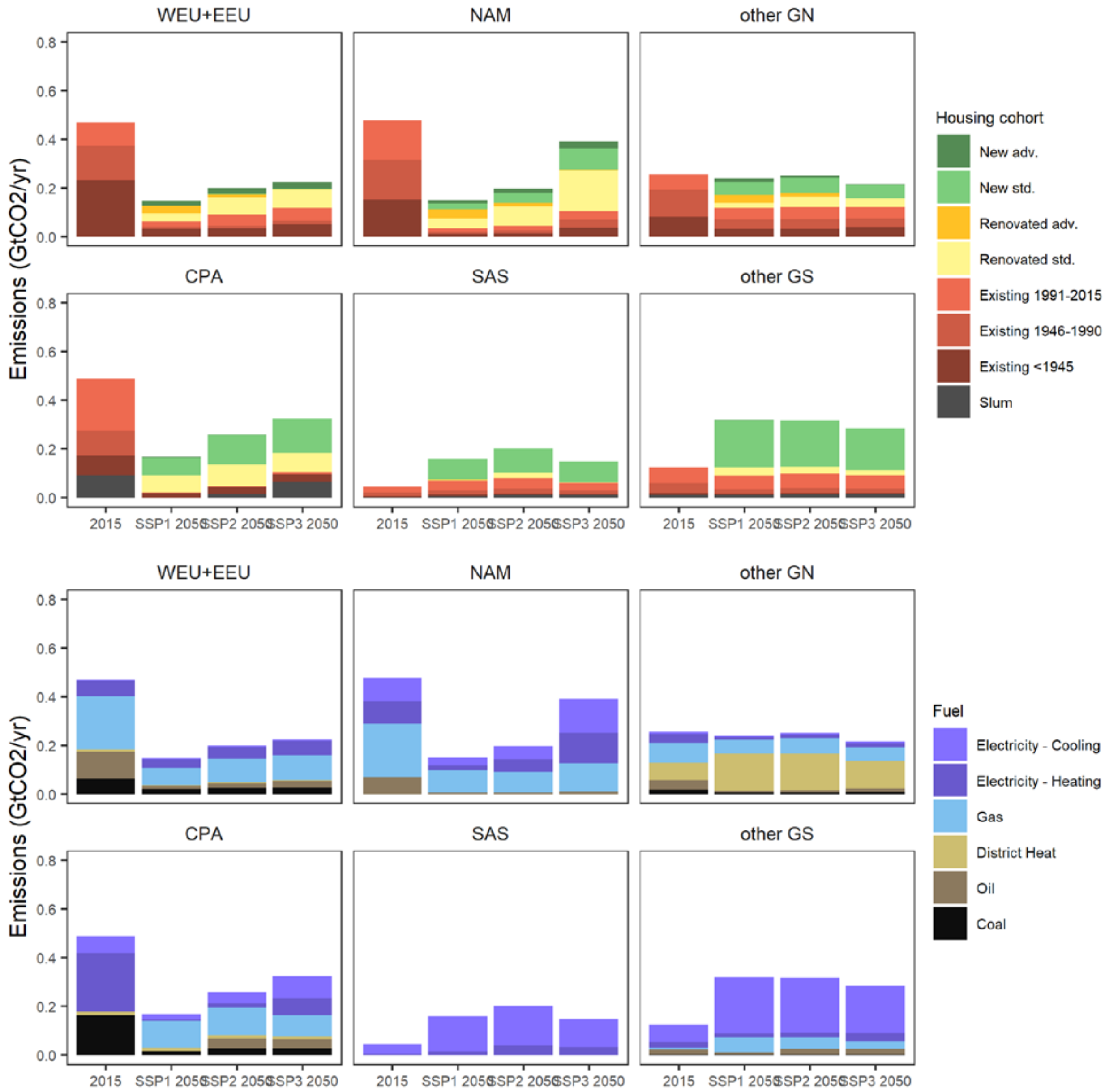


Figure 24 CO_2 emissions in the base year (2015) and for SSP1-3 (2050) by region: breakdown by housing cohort (top panel) and energy carrier (bottom panel).

SM3.6. ***Uncertainty and sensitivity analysis***

SM3.6.1. *Uncertainty analysis*

We account for future uncertainty by considering a set of socio-economic scenarios (SSP1-3), covering a range of different demographics, socio-economic and technology developments. In this section we show how key scenario-dependent input parameters (GDP, energy prices and costs) and related model outputs differ across the SSPs.

GDP is directly linked to slum population and AC access in the model. Figure 25 shows the distribution of national values of GDP, share of slum population on total, and AC access across the SSPs. Higher values of GDP in SSP1 are associated with lower share of slum population and higher access to AC, and vice versa in SSP3.

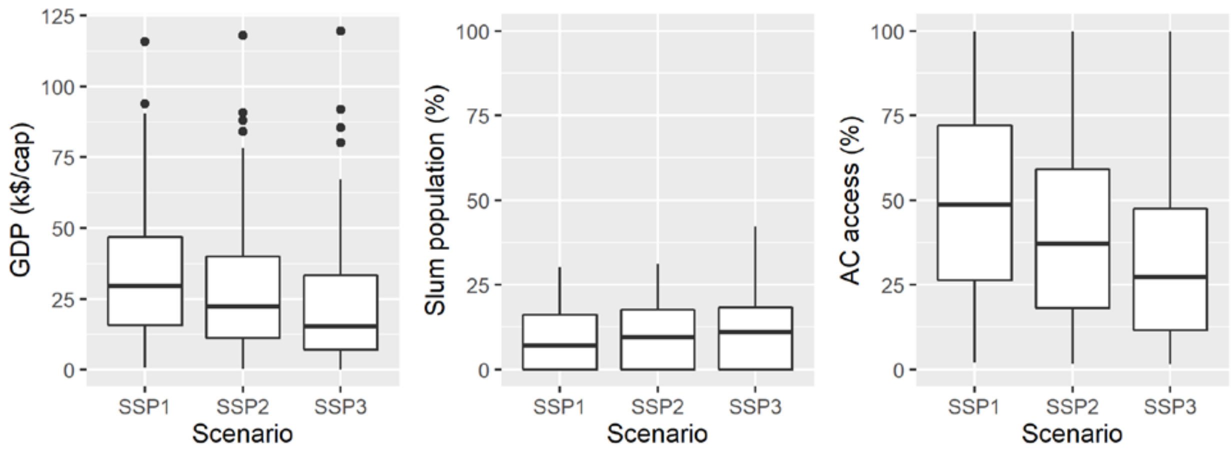


Figure 25 Distribution of national values of GDP, share of slum population on total, and AC access for SSP1-3 in 2050.

Figure 26 and Figure 27 show the relations between investment costs for heat pumps and market share of electricity respectively for new construction and renovation decisions. While heat-pump costs are constant in SSP3, they decrease in SSP2 and SSP1 (see section SM2.6.6). Lower investment costs correspond to higher market share of electricity compared to other fossil fuels. Differences in market shares are larger in regions with higher heating requirements.

The relation between final energy intensity for space heating and average energy price, weighted on the share of energy carriers, is stronger for regions with colder climates, and weaker for regions with low space heating requirements (Figure 28). While trends are similar across SSPs, similar level of energy prices generally corresponds to lower energy intensities in SSP1, due to differences in technology developments and uptake of energy efficiency measures.

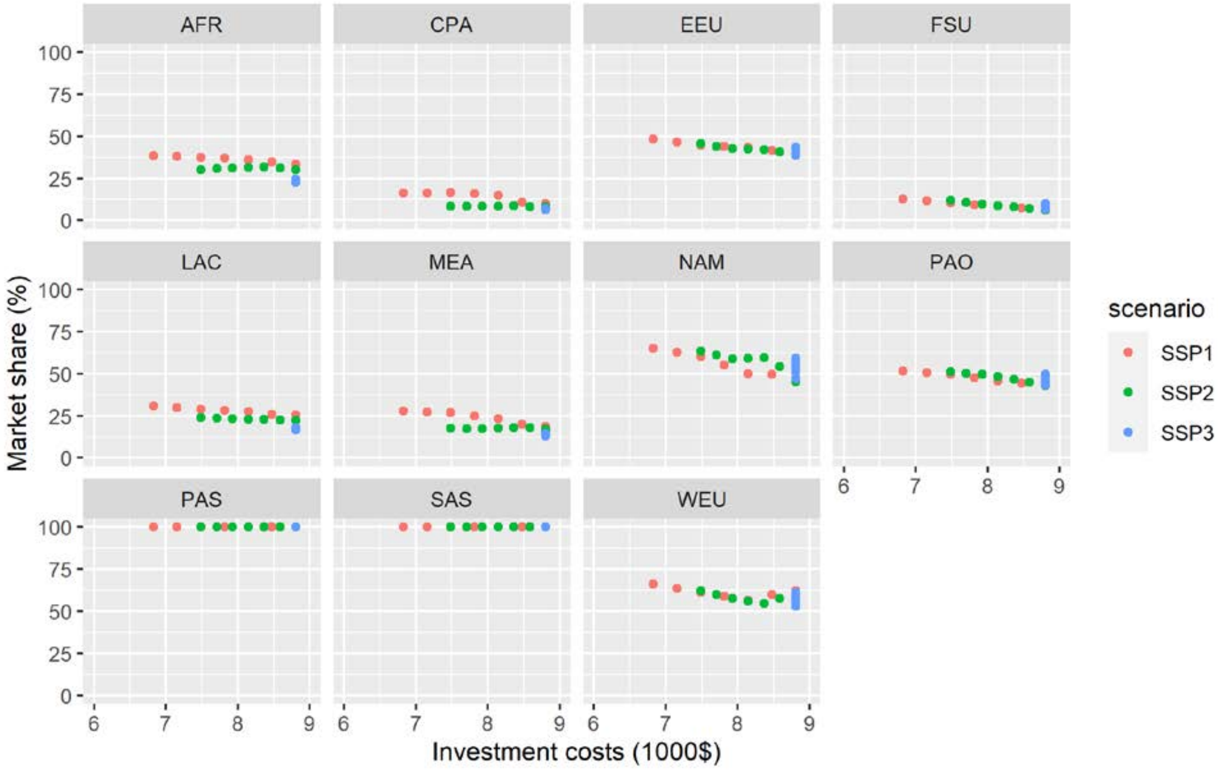


Figure 26 Market share of electricity in new construction versus investment cost of heat-pumps in the period 2020-2050 for SSP1-3.

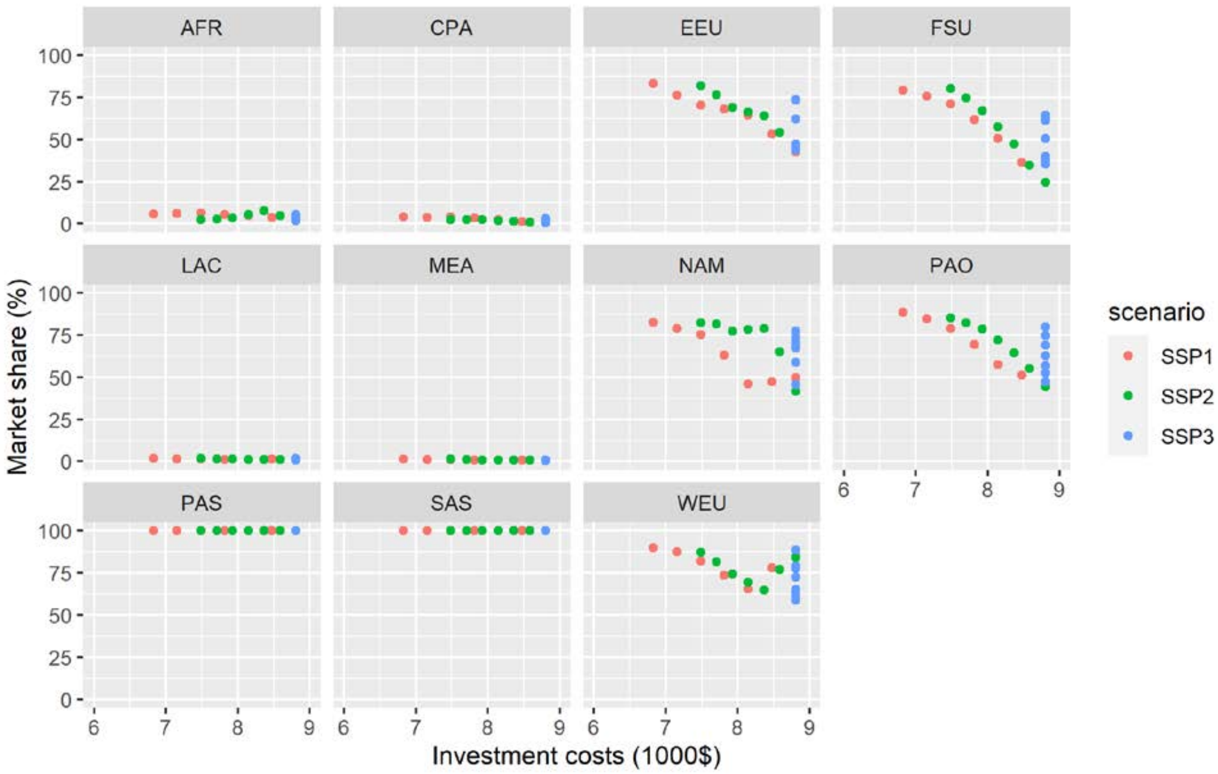


Figure 27 Market share of electricity in renovations versus investment cost of heat-pumps in the period 2020-2050 for SSP1-3.

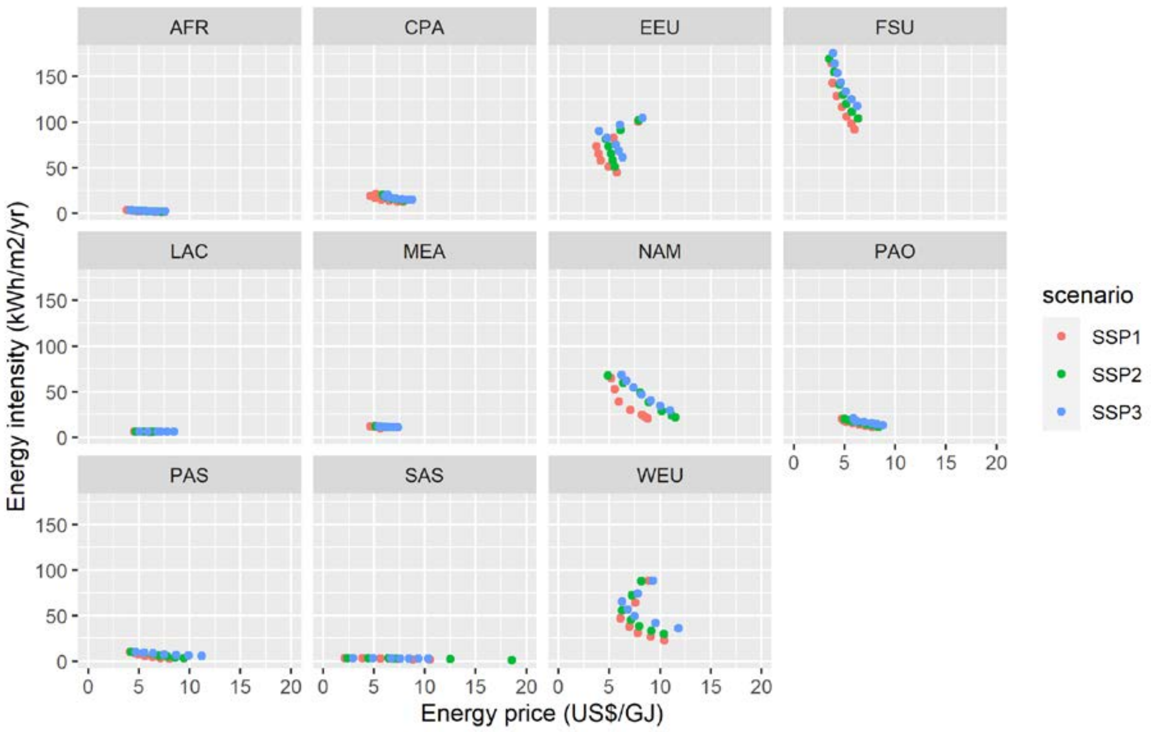


Figure 28 Relation between final energy intensity for space heating and average energy price in the period 2020-2050 for SSP1-3.

SM3.6.2. *Sensitivity to heating and cooling set-point temperatures*

We run sensitivity analysis to investigate the effect of varying the set point temperatures for heating and cooling on energy demand. Starting from the reference values for heating (21°C) and cooling (23°C), we vary set point temperatures by ±1°C, run future scenarios under SSP2 assumptions, and compare regional results against baseline SSP2 in final energy demand terms. For space heating (Figure 29), the highest effect of varying set point temperatures on energy demand for the base year were found for colder Western regions, in particular WEU with ±0.17EJ/yr (±9%), and NAM with ±0.5EJ/yr (±7%). The effects of varying set point temperature reduce as energy demand decreases over time. Absolute variations in heating energy demand are the lowest for cooling-dominated developing regions, noting that they nevertheless experience higher percentage variations, up to around ±25%. For space cooling (Figure 30), we observe the highest absolute variations in energy demand for regions with high AC access and cooling demand, especially NAM, in the range of -0.15 EJ/yr to +0.17 EJ/yr (-22% to +25%), followed by CPA, in the range of -0.08 EJ/yr to +0.09 EJ/yr (-22% to +25%) for the base year. Variations in the base year are lower for other regions in the global South where, despite high cooling needs, access to AC is lower. However, the effect of varying setpoint temperature increases as cooling demand grows driven by increased AC access.

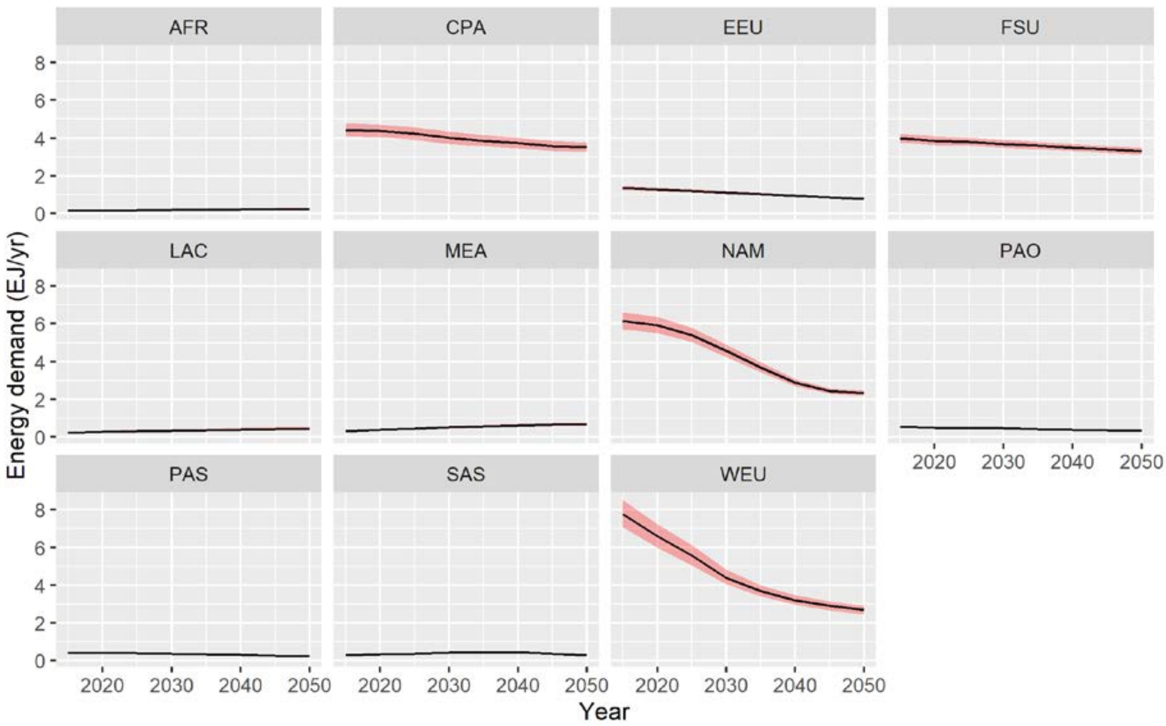


Figure 29 Sensitivity analysis results for space heating: effect of varying set point temperature by ±1°C on total final energy demand by region. Reference set point for heating: 21°C.

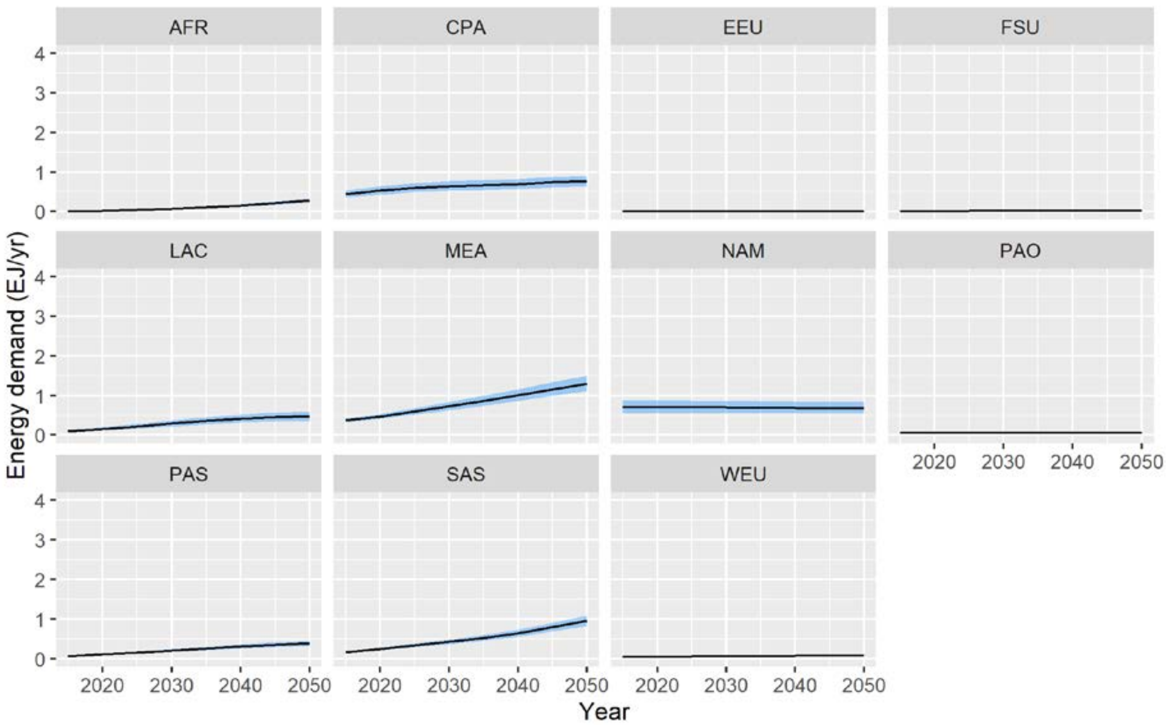


Figure 30 Sensitivity analysis results for space cooling: effect of varying set point temperature by ±1°C on total final energy demand by region. Reference set point for cooling: 23°C.

SM4. Literature review summary

We report in Table 30 a summary of the findings of the literature review on the features of bottom-up global residential sector energy models. We focus on three main model features: granularity, represented dynamics and output variables.

Table 30 Literature review summary: bottom-up global residential sector energy models.

Model name	**Reference**	**Granularity**							**Dynamics**					**Output**		
		Regions	Location	Household types	Housing types	Vintage / Energy efficiency	End-uses	Access	Stock turnover	Floorspace	Energy demand	New construction	Renovation	Floor-space	Energy demand	CO_2 Emiss.
MESSAGEix-Buildings	This study	C (174), R (11), CZ	U/R	IC, TN	SFH, MFH, INF	BC (7)	H,C	HS, AC	STM	END/EXG	VDD	END	END	✓	✓	✓
3CSEP HEB	(GEA 2012; Ürge-Vorsatz et al. 2012; Güneralp et al. 2017)	R (11), CZ	U/R	-	SFH, MFH, INF	BC (5)	H,C,O	HS	EXG	EXG	EXG	EXG	EXG	✓	✓	✓
EDGE buildings 3.0	(Edelenbosch et al. 2021)	R (41)	-	IC	-	BC	H,C	HS	STM	END	EXG	END	END	✓	✓	
EDGE	(Levesque et al. 2018, 2019)	R (11)	-	IC	-	-	H,C,O	-	-	END	DD	-	-	✓	✓	
FTT:Heat	(Knobloch et al. 2019)	R (59)	-	-	-	-	H	-	-	END	DD	-	-	✓	✓	✓
REMG	(van Ruijven et al. 2011; Daioglou et al. 2012)	R (26)	U/R	IC	-	-	H,C,O	EL, AC	-	END	DD	-	-	✓	✓	✓
-	(Isaac and van Vuuren 2009)	R (11)	-	-	-	-	H,C,O	AC	-	EXG	DD	-	-	✓	✓	✓
-	(Harvey 2014)	R (10)	-	-	-	-	H,C,O	-	STM	END	EXG	EXG	EXG	✓	✓	

Abbreviations:
Regions: C = countries, R = regions, CZ = climatic zones
Location: U/R = Urban/Rural
Housing types: MFH = Multi-family house, SFH = Single-family house, INF = informal
Household types: IC = income classes; TN = tenure
Vintage/Energy efficiency: BC = building cohorts
End-uses: H = heating, C = cooling, O = others
Access: HS = housing; AC = air-conditioning; EL = electricity
Model dynamics: END = endogenous; EXG = exogenous; DD = degree days; VDD = variable degree days; STM = stock turnover model

Bibliography

Agency IE (2019) IEA Energy efficiency indicators database (2019 edition) – short version

Bolt J, Inklaar R, de Jong H, Zanden JL van (2018) Maddison Project Database, version 2018

Connolly D, Lund H, Mathiesen B V., et al (2014) Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 65:475–489. https://doi.org/10.1016/j.enpol.2013.10.035

Daioglou V, van Ruijven BJ, van Vuuren DP (2012) Model projections for household energy use in developing countries. Energy 37:601–615. https://doi.org/10.1016/j.energy.2011.10.044

Deetman S, Marinova S, van der Voet E, et al (2020) Modelling global material stocks and flows for residential and service sector buildings towards 2050. J Clean Prod 245:. https://doi.org/10.1016/j.jclepro.2019.118658

Dellink R, Chateau J, Lanzi E, Magne B (2017) Long-term economic growth projections in the Shared Socioeconomic Pathways §. Glob Environ Chang 42:200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004

Edelenbosch O, Rovellia D, Levesque A, et al (2021) Long term, cross-country effects of buildings insulation policies. Technol Forecast Soc Change

Esser A, Dunne A, Meeusen T, et al (2019) Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU Final report. 87

EU Building Stock Observatory (2020) EU Buildings Database

Eurostat (2020) Energy consumption in households

Fabrizio E, Monetti V (2015) Methodologies and advancements in the calibration of building energy models. Energies 8:2548–2574. https://doi.org/10.3390/en8042548

Feist W, Pfluger R, Kaufmann B, et al (2007) Passive House Planning Package 2007. 1:7

Fink-Jensen J (2015) World Countries Urbanization ratio, 1500-2000.

Fishman T, Heeren N, Pauliuk S, et al A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modelling. J Ind Ecol. https://doi.org/10.31235/osf.io/tqsc3

Fleiter T, Steinbach J, Ragwitz M (2016) Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables) - Work package 2: Assessment of the technologies for the year 2012

GEA (2012) Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria

Giraudet LG, Guivarch C, Quirion P (2012) Exploring the potential for energy conservation in French households through hybrid modeling. Energy Econ 34:426–445. https://doi.org/10.1016/j.eneco.2011.07.010

Güneralp B, Zhou Y, Ürge-Vorsatz D, et al (2017) Global scenarios of urban density and its impacts on building energy use through 2050. Proc Natl Acad Sci U S A 114:8945–8950. https://doi.org/10.1073/pnas.1606035114

Harvey LDD (2014) Global climate-oriented building energy use scenarios. Energy Policy 67:473–487. https://doi.org/10.1016/j.enpol.2013.12.026

Harvey LDD, Korytarova K, Lucon O, Roshchanka V (2014) Construction of a global disaggregated dataset of building energy use and floor area in 2010. Energy Build 76:488–496. https://doi.org/10.1016/j.enbuild.2014.03.011

Hoyer S, Hamman JJ (2017) xarray: N-D labeled Arrays and Datasets in Python. J Open Res Softw 5:1–6. https://doi.org/10.5334/jors.148

IEA (2018) The Future of Cooling

International Energy Agency (2019) IEA Energy efficiency indicators database (2019 edition) – extended version

International Energy Agency (IEA) (2016) Energy Technology Perspectives 2016 - Annex E: Buildings sector model

IPCC (1996) Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: The

Workbook (Volume 2)

Isaac M, van Vuuren DP (2009) Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37:507–521. https://doi.org/10.1016/j.enpol.2008.09.051

Jiang L, O’Neill BC (2017) Global urbanization projections for the Shared Socioeconomic Pathways. Glob Environ Chang 42:193–199. https://doi.org/10.1016/j.gloenvcha.2015.03.008

Jiang Y, Yan D, Siyue G, et al (2017) China Building Energy Use 2017

Jones R V., Fuertes A, Boomsma C, Pahl S (2015) Space heating preferences in UK social housing: A socio-technical household survey combined with building audits. Energy Build 127:382–398. https://doi.org/10.1016/j.enbuild.2016.06.006

KC S, Lutz W (2017) The human core of the shared socioeconomic pathways : Population scenarios by age , sex and level of education for all countries to 2100. Glob Environ Chang 42:181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004

Knobloch F, Pollitt H, Chewpreecha U, Mercure J-F (2019) Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5°C. Energy Effic 12:521–550

Lange S (2016) EartH2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP (EWEMBI)

Lange S (2019) EartH2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP (EWEMBI). V. 1.1.

Levesque A, Pietzcker RC, Baumstark L, et al (2018) How much energy will buildings consume in 2100? A global perspective within a scenario framework. Energy 148:514–527. https://doi.org/10.1016/j.energy.2018.01.139

Levesque A, Pietzcker RC, Luderer G (2019) Halving energy demand from buildings: The impact of low consumption practices. Technol Forecast Soc Change 146:253–266. https://doi.org/10.1016/j.techfore.2019.04.025

Mastrucci A, Byers E, Pachauri S, Rao ND (2019a) Improving the SDG energy poverty targets:

Residential cooling needs in the Global South. Energy Build 186:. https://doi.org/10.1016/j.enbuild.2019.01.015

Mastrucci A, Byers E, Pachauri S, Rao NDND (2019b) Improving the SDG energy poverty targets : Residential cooling needs in the Global South. Energy Build 186:405–415. https://doi.org/10.1016/j.enbuild.2019.01.015

Mastrucci A, Pérez-López P, Benetto E, et al (2017) Global sensitivity analysis as a support for the generation of simplified building stock energy models. Energy Build 149:368–383. https://doi.org/10.1016/j.enbuild.2017.05.022

Mastrucci A, Rao ND (2017) Decent housing in the developing world: Reducing life-cycle energy requirements. Energy Build 152:629–642. https://doi.org/10.1016/j.enbuild.2017.07.072

Mastrucci A, Rao ND (2019) Bridging India's housing gap: lowering costs and CO2 emissions. Build Res Inf 47:8–23. https://doi.org/10.1080/09613218.2018.1483634

McCollum DL, Zhou W, Bertram C, et al (2018) Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nat Energy 1. https://doi.org/10.1038/s41560-018-0179-z

Mcneil MA, Letschert VE (2010) Modeling diffusion of electrical appliances in the residential sector. https://doi.org/10.1016/j.enbuild.2009.11.015

O'Neill BC, Kriegler E, Ebi KL, et al (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob Environ Chang 42:169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Perpiñán O (2012) solaR : Solar radiation and photovoltaic systems with R. J Stat Softw 50:1–32. https://doi.org/10.18637/jss.v050.i09

Poblete-Cazenave M, Pachauri S, Byers E, et al Global scenarios of household access to modern energy services. Nat Energy

Riahi K, Vuuren DP Van, Kriegler E, et al (2017) The Shared Socioeconomic Pathways and their energy , land use , and greenhouse gas emissions implications : An overview. 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rocklin M (2015) Dask : Parallel Computation with Blocked algorithms and Task Scheduling. Proc 14th Python Sci Conf 130–136

Romanov D, Pelda J, Holler S (2020) Technical, economic and ecological effects of lowering temperatures in the Moscow district heating system. Energy 211:118680. https://doi.org/10.1016/j.energy.2020.118680

Roy D, Lees MH, Palavalli B, et al (2014) The emergence of slums: A contemporary view on simulation models. Environ Model Softw 59:76–90. https://doi.org/10.1016/j.envsoft.2014.05.004

Sandberg NH, Sartori I, Heidrich O, et al (2016) Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. Energy Build 132:26–38. https://doi.org/10.1016/j.enbuild.2016.05.100

UN-HABITAT (1970) Compendium of Human Settlements Statistics

UN (2019) Household Size & Composition

Ürge-Vorsatz D, Petrichenko K, Antal M, et al (2012) Best Practice Policies for Low Energy and Carbon Buildings: A Scenario Analysis

van Ruijven BJ, van Vuuren DP, de Vries BJM, et al (2011) Model projections for household energy use in India. Energy Policy 39:7747–7761. https://doi.org/10.1016/j.enpol.2011.09.021

Walsh A, Cóstola D, Labaki LC (2017) Comparison of three climatic zoning methodologies for building energy efficiency applications. Energy Build 146:111–121. https://doi.org/10.1016/j.enbuild.2017.04.044

World Bank (2020) World Bank Open Data

World Health Organization (2007) Housing, Energy and Thermal Comfort: A review of 10 countries within the WHO European Region 5072464. World Heal Organ 1–27

Yu B, Wei YM, Kei G, Matsuoka Y (2018) Future scenarios for energy consumption and carbon emissions due to demographic transitions in Chinese households. Nat Energy 3:109–118. https://doi.org/10.1038/s41560-017-0053-4