# Supplementary material

## Global scenarios of residential heating and cooling energy demand and CO₂ emissions

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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| GN: medium | GN: medium |
|                                | GS: high| GS: 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| 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).

| 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 Estatística               | https://andine.ine.gov.ao/nada4/index.php/catalog/11                      |
|        | 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           |                                                                            |
|        |              |              |                                                                 |          |                                                                        |                                                                            |
| EEU    | Poland       | POL          | Eurostat, EU Statistics on Income and Living Conditions (EU-SILC) | 2015     | Eurostat                                                               | https://ec.europa.eu/eurostat/web/microdata/europe-an-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/rllms/downloads                                      |
| Belarus | BLR          |              | Multiple Indicator Cluster Surveys (MICS)                      | 2012     | Unicef                                                                 |                                                                            |
| LAC    | Brazil       | BRA          | Pesquisa de Orçamentos Familiares (POF)                        | 2008-09  | Instituto Brasileiro de Geografia e Estatística                      | https://www.ibge.gov.br/estatisticas/multidominio/ciencia-tecnologiae-inovacao/9056-pesquisa-de-orcamentos-familiares.html?&t=micodados |
|        | 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/estadisticas/index.php/usuario/encovi              |
| Country | Code | Description                                                                 | Year | Source                                                                 | Website                                                                 |
|---------|------|------------------------------------------------------------------------------|------|------------------------------------------------------------------------|-------------------------------------------------------------------------|
| 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 | Iraq Household Socio-Economic Survey (IHSES)                                 | 2012 | Economic Research Forum                                               | http://www.erfdataportal.com/index.php/catalog/108                     |
| Morocco | MARR | Morocco Household and Youth Survey (MHYS)                                    | 2009 | World Bank                                                            | https://microdata.worldbank.org/index.php/catalog/150015               |
| NAM     | USA  | Residential Energy Consumption Survey (RECS)                                 | 2015 | U.S. Energy Information Administration                                | https://www.eia.gov/consumption/residential/data/2015/                 |
| PAO     | JPN  | Housing and Land Survey*                                                     | 2018 | Statistics Bureau of Japan                                            | https://www.stat.go.jp/english/data/jyutaku/index.html                |
| PAS     | IDN  | Indonesia Family Life Survey                                                 | 2014 | RAND Corporation                                                       | https://www.rand.org/well-being/social-and-behavioral-policy/data/FLS/|
|         |      | Home Energy Standing Survey (HESS)                                          | 2017 | Korea Energy Statistical Information System                           | https://www.stat.go.jp/english/data/jyutaku/index.html                |
| SAS     | IND  | National Sample Survey (NSS) - Household Consumer Expenditure               | 2000-01 | National Sample Survey Office - M/o Statistics and Programme          | https://microdata.gov.in/nada43/index.php/catalog/91                   |
|         |      | Enquête Budget de famille                                                   | 2010-11 | Institut national de la statistique et des études économiques         | https://www.insee.fr/fr/metadonnees/source/serie/s1194                |
|         |      | Household Budget Survey                                                     | 2013 | Istituto Nazionale di Statistica                                      | https://www.istat.it/en/archivio/193939                               |

Note: *Statistical tables used instead of microdata.
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.
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 |
|--------|----------|---------------|---------------|--------------|
| 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
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.](image)

**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 (urb). 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 (urb). 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 (urb). 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:

$$AC_{MaxSat} = 1 - 0.949e^{-0.00187 \times CDD}$$

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

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

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 (m²/ m²) | Roof area (m²/ m²) | Windows area (m²/ m²) | Envelope area (m²/ m²) |
|-------------------------------|---------------------|--------------------|-----------------------|------------------------|
| 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 | Existing before 1945 | Existing before 1945 | New standard | New advanced |
|--------|----------------------|----------------------|--------------|--------------|
| AFR    | 3.48                 | 3.26                 | 3.03         | 0.59         |
| CPA    | 3.15                 | 1.65                 | 1.53         | 0.59         |
| EEU    | 1.63                 | 0.96                 | 0.71         | 0.30         |
| FSU    | 1.63                 | 0.96                 | 0.71         | 0.30         |
| LAC    | 3.15                 | 2.68                 | 2.65         | 0.59         |
| MEA    | 3.53                 | 2.64                 | 2.50         | 0.59         |
| NAM    | 2.45                 | 1.48                 | 2.50         | 0.30         |
| PAO    | 2.42                 | 1.04                 | 0.94         | 0.30         |
| PAS    | 3.48                 | 3.26                 | 3.03         | 0.59         |
| SAS    | 3.48                 | 3.26                 | 3.03         | 0.59         |
| WEU    | 2.35                 | 0.81                 | 0.59         | 0.30         |
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, 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 (tCO₂/TJ) |
|---------|---------------------------|
| Coal    | 94.6                      |
| Gas     | 56.1                      |
| Oil     | 73.3                      |
| Biomass | -                         |

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.
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.*

| 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).

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

![Diagram showing the workflow of the STURM model]

*Figure 15 Scenario runs workflow. Iteration at timestep t.*
\[ S_t = \frac{P_t}{H_t} \quad (1) \]

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 (MSj) for option j is then calculated by comparing the LCC of all possible options (k) using the following equation:

\[ MS_{new,j} = \frac{LCC_j^T}{\sum_k LCC_k^T} \nu \quad (5) \]

Where \( \nu \) 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\textsubscript{ren,i→f}) and the market share (MS\textsubscript{ren,i→f}) on all possible final solutions (k) are similar to the case of new construction:

\[ LCC_{ren,i→f} = C_{inv,i→f} + C_{op,f} + C_{int,i→f} \quad (6) \]
\[
MS_{\text{ren},i\rightarrow f} = \frac{LCC_{i\rightarrow f}}{\sum_{k} LCC_{i\rightarrow k}}
\]  \hspace{1cm} (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 \((j)\):

\[
S_{h,j,t} = S_{h,j,t-1} \cdot \left(1 - \sum_{k \neq j} MS_{\text{ren},h,j\rightarrow k,t} \right) - D_{h,j,t} + N_{h,t} \cdot MS_{\text{new},h,j,t} + \sum_{k \neq j} (S_{h,k,t-1} \cdot MS_{\text{ren},h,k\rightarrow j,t})
\]  \hspace{1cm} (8)

where \(MS_{\text{ren},h,j\rightarrow k,t}\) represents the total market share for renovations from \(j\) to a different cohort \(k\) (units exiting building cohort \(j\)), \(MS_{\text{ren},h,k\rightarrow j,t}\) the total market share for renovations to \(j\) from a different category \(k\) (units entering building cohort \(j\)), and \(MS_{\text{new},h,j,t}\) 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 \((F_{\text{cap},h,t})\) are used to calculate the total floorspace by building cohort \((F_{h,j,t})\):

\[
F_{h,j,t} = S_{h,j,t} \cdot H_{h,t} \cdot F_{\text{cap},h,t}
\]  \hspace{1cm} (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 CO2 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 CO2 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.](image)

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.

| Model name             | Reference | Granularity | Dynamics | Output |
|------------------------|-----------|-------------|----------|--------|
| MESSAGEix-Buildings    | This study | Regions: C (174), R (11), CZ  Location: U/R  Household types: IC, TN  Housing types: SFH, MFH, INF  Vintage / Energy efficiency: BC (7)  End-uses: H, C  Access: HS, AC  Stock turnover: STM  End/EXG  Floorspace: END  Energy demand: EXG  CO2 Emiss. |
| 3CSEP HEB              | (GEA 2012; Ürge-Vorsatz et al. 2012; Güneralp et al. 2017)  Regions: R (11), CZU/R  Location: -  Household types: SFH, MFH, INF  Vintage / Energy efficiency: BC (5)  End-uses: H, C, O  Access: HS  Stock turnover: STM  End/EXG  Floorspace: END  Energy demand: EXG  CO2 Emiss. |
| EDGE buildings 3.0     | (Edelenbosch et al. 2021)  Regions: R (41)  Location: IC  Household types: SFH, MFH, INF  Vintage / Energy efficiency: BC  End-uses: H, C  Access: HS  Stock turnover: STM  End/EXG  Floorspace: END  Energy demand: EXG  CO2 Emiss. |
| EDGE                  | (Levesque et al. 2018, 2019)  Regions: R (11)  Location: IC  Household types: SFH, MFH, INF  Vintage / Energy efficiency: BC  End-uses: H, C, O  Access: HS  Stock turnover: STM  End/EXG  Floorspace: END  Energy demand: EXG  CO2 Emiss. |
| FTT:Heat              | (Knobloch et al. 2019)  Regions: R (59)  Location: -  Household types: SFH, MFH, INF  Vintage / Energy efficiency: BC  End-uses: H, C, O  Access: HS  Stock turnover: STM  End/EXG  Floorspace: END  Energy demand: EXG  CO2 Emiss. |
| REMG                  | (van Ruijven et al. 2011; Daioglou et al. 2012)  Regions: U/R  Location: IC  Household types: SFH, MFH, INF  Vintage / Energy efficiency: BC  End-uses: H, C, O  Access: HS  Stock turnover: STM  End/EXG  Floorspace: END  Energy demand: EXG  CO2 Emiss. |
| -                     | (Isaac and van Vuuren 2009)  Regions: R (11)  Location: -  Household types: SFH, MFH, INF  Vintage / Energy efficiency: BC  End-uses: H, C, O  Access: HS  Stock turnover: STM  End/EXG  Floorspace: END  Energy demand: EXG  CO2 Emiss. |
| -                     | (Harvey 2014)  Regions: R (10)  Location: -  Household types: SFH, MFH, INF  Vintage / Energy efficiency: BC  End-uses: H, C, O  Access: HS  Stock turnover: STM  End/EXG  Floorspace: END  Energy demand: EXG  CO2 Emiss. |

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
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