PAPER • OPEN ACCESS

Global residential scenarios towards low energy and material demands

To cite this article: A Mastrucci and B van Ruijven 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1196** 012008

Global residential scenarios towards low energy and material demands

A Mastrucci, B van Ruijven

International Institute for Applied Systems Analysis (IIASA), Austria

E-mail: mastrucc@iiasa.ac.at

Abstract. Transition to low energy and material demand (LEMD) for buildings is key to reach climate change mitigation and sustainability targets but will require unprecedent technological and social transformations. Scenarios addressing LEMD transformations for the global building sector are still largely unexplored. In this study, we assess global residential energy and material demands until 2050 for three alternative sustainable development pathways (SDPs): *Economy-driven innovation* (EI), driven by technology and energy efficiency; *Resilient communities* (RC), a post-growth scenario centred around local communities and behavioural change; and *Managing the global commons* (MC), with strong global institutions and high electrification. We use the bottom-up framework MESSAGEix-Buildings, soft-linked to the integrated assessment model MESSAGEix-GLOBIOM, to model the three SDPs for the global residential sector. We show that the RC scenario entails the highest potential towards reducing energy and material demand driven by behavioural change. The EI and MC scenarios are characterized by relatively higher energy and material demand levels and might require additional efforts on the supply-side to reduce total building-related operational and construction greenhouse gases emissions. This study can support decision making on strategies towards sustainability and zero-energy and emission targets in the buildings sector.

1. Introduction

Buildings account for almost 40% of energy and process-related CO_2 emissions [1]. Transition to low energy and material demand (LEMD) in the building sector is key to reach climate change mitigation and sustainability targets but will require unprecedent technological and social transformations. Representing such transformations in building sector modelling requires improved model granularity and heterogeneity, a focus on service provision, and accounting of the interlinkages between the building sector, industry and energy systems.

Integrated Assessment Modelling (IAM) is widely used to explore global mitigation pathways, accounting for future technology mixes and costs of climate change mitigation [2]. In IAM, the demand-side has been commonly represented with less detail than the supply-side [3] limiting the capability to assess strategies for individual the end-use sectors, such as buildings and transportation. In recent efforts [3–5], building sectoral modelling and IAM were combined to develop global climate change mitigation scenarios for the residential and commercial sectors, focusing on operational final energy and CO_2 emission reductions. Other studies [6,7] investigate resource efficiency and energy-material nexus, developing material demand scenarios for buildings. Alternative strategies for climate change mitigation in the built environment under low economic growth conditions have been explored at country level [8]. However, scenarios addressing global transformations for the global building sector under alternative sustainable development pathways (SDPs), including low economic growth and accounting for both energy and material demand, are still largely unexplored.

We investigate LEMD scenarios for the global residential sector based on three alternative SDPs, representing alternative pathways towards sustainability and climate targets. We use the modelling framework MESSAGEix-Buildings soft-linked to an integrated assessment model to project residential energy for space heating and cooling and material demands until 2050 for the three SDPs.

2. Methods

MESSAGEix-Buildings [5] is a bottom-up framework for modelling the global building sector and assessing energy and material demands in future scenarios. MESSAGEix-Buildings combines dedicated modules to assess: energy demands for heating and cooling (CHILLED module); building stock turnover, material demands, and energy efficiency investments of households (STURM module). MESSAGEix-Buildings receives energy price feedback via soft-linkage with MESSAGEix-GLOBIOM [9], an IAM framework for the assessment of energy-environment-economy systems, making it possible to account for supply-side system transformations. The structure of MESSAGEix-Buildings allows for high granularity in representing the residential sector, including housing characteristics (urban/rural location, formal and informal housing, housing type, energy efficiency cohorts, and energy carriers) and household characteristics (income levels, and tenure). The framework is flexible in spatial and temporal coverage and granularity. In this study, we run the model for the residential sector at the global level, considering 60 macro-regions, for the period 2015 to 2050 with 5 years timesteps.

2.1. Energy demand model

Energy demand for space heating and cooling is calculated in the CHILLED module based on the variable degree days (VDD) method [10]. Similar to the more commonly used standard Degree Days (DD), monthly (m) VDD for heating ($VDD_{h,m}$) and cooling ($VDD_{c,m}$) are calculated as the sum of positive daily differences between the average daily temperature $T_{out,d}$ and a reference monthly balance temperature $T_{bal,m}$ defined as the outdoor temperature at which neither heating, nor cooling is required:

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

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

Differently from standard DD, this method analytically calculates the balance temperature, instead of assuming it as arbitrarily fixed, based on the indoor set-point temperature (T_{sp}), heat flows from solar heat sources ($g_{sol,m}$) and internal heat sources (g_{int}), heat transfer coefficient by transmission (H_{tr}) and by ventilation (H_{ve}):

$$T_{bal,m} = T_{sp} - \frac{g_{sol,m} + g_{int}}{H_{tr} + H_{ve}} \tag{3}$$

The annual final energy for heating (E_h) and cooling (E_c) is then calculated based on the following equations, introducing coefficients for the daily operation time fractions for heating ($f_{op,h}$) and cooling ($f_{op,c}$), share of heated ($f_{fl,h}$) and cooled ($f_{fl,c}$) floorspace, and the efficiency of heating (η_h) and cooling (η_c) systems, and summing results over the twelve months:

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

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

We run the equations at the global level over a spatial grid at 0.5° grid resolution (approximately 50 km at the equator) for a set of archetypes for formal housing (single-family and multi-family housing) and informal (slum) housing and energy efficiency levels, and aggregate the calculated energy demand intensities per unit of floorspace by location (urban and rural), climatic zone, and macro-region, after weighting on population.

2.2. Building stock turnover model and household decision models

We assess the stock turnover, including new constructions, demolitions, and renovations, in the STURM module using Material Flow Analysis (MFA) [11]. The demand for new housing units is driven by population and replacement of demolished buildings, which in turn is calculated based on a set of survival curves and exogenously imposed share of housing types. We use a set of discrete choice models [12], representing the decisions of different households in future years, to estimate the share of newly constructed and renovated housing according to different energy efficiency levels, renovation rates, and switches in heating fuels. We consider two energy efficiency levels for new constructions and renovations: *standard*, corresponding to current practice in different world regions; and *advanced*, corresponding to low-energy design, with passive new constructions and deep renovations in the global North. The model calculates the Life Cycle Costs (LCC) associated with given investment options (j) for new construction ($LCC_{new,j}$) and transition from an initial (i) to a final (f) condition through renovation ($LCC_{ren,i\rightarrow f}$), based on investment costs (C_{inv}), operational costs (C_{op}) and intangible costs (C_{int}), the latter representing barriers towards investment:

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

$$LCC_{ren,i\rightarrow f} = C_{inv,i\rightarrow f} + C_{op,f} + C_{int,i\rightarrow f} \tag{7}$$

The operational costs are calculated based on energy demand for space heating specific to the considered housing type and energy efficiency levels, and energy price for specific energy carriers, obtained for different scenarios via the soft-linkage with MESSAGEix-GLOBIOM. A discount rate specific to different household types is applied to operational costs. The market share (MS) for each option in new construction and renovation is calculated using the following equation comparing the LCC of all possible options (k), and introducing an heterogeneity parameter (ν):

$$MS_{new,j} = \frac{LCC_j^{-\nu}}{\sum_k LCC_k^{-\nu}} \tag{8}$$

$$MS_{ren,i\rightarrow f} = \frac{LCC_{i\rightarrow f}^{-\nu}}{\sum_k LCC_{i\rightarrow k}^{-\nu}} \tag{9}$$

At each timestep the composition of the housing stock (number of housing units by housing type and energy efficiency cohort) is updated, considering demolished, renovated, and newly constructed units. Total floorspace is subsequently calculated by multiplying household size and floorspace per-capita values to the number of units of different housing cohorts. Total energy demand for space heating and cooling is then computed by multiplying the energy intensities, calculated with the CHILLED module, to the floorspace of different housing cohorts. Finally, material demand is calculated by applying material intensity coefficients based on existing literature to the calculated newly constructed floorspace. We include aluminum, cement, concrete, copper, glass, steel, and wood in the material calculations.

3. Scenarios

We explore scenarios towards LEMD for the residential sector using the three core SDPs developed in the SHAPE project[1]. The *Economy-driven innovation (EI)* scenario is a technology and market driven scenario characterized by high Gross Domestic Product (GDP) growth, high urbanization, predominance of large cities with compact urban form, and high energy-efficient buildings. The *Resilient communities (RC)* scenario is a post-growth scenario centred around human well-being, with small to medium urban settlements built around local communities, passive building design and local construction practices. The *Managing the global commons (MC)* scenario has strong global institutions, driving urban development, high urbanization, high energy efficiency and electrification. Energy and material

[1] Sustainable development pathways achieving Human well-being while safeguarding the climate And Planet Earth (SHAPE). https://shape-project.org/

demands are higher in EI, lower in RC, and medium in MC. Key qualitative assumptions defined in the protocol for modelling the three SDPs are reported in Table 1.

Table 1. Key scenario assumptions in the modelling protocol.

Dimension	Economy-driven innovation	Resilient communities	Managing the global commons
Economic growth	High	Post-growth	Medium
Urbanization	High	Low-Medium	High
Buildings	High rise	Low- to mid-rise	Mix
Housing	Prevalence of Multi-family	Prevalence of Multi-family	Mix of single-family and multi-family
Service demand	High	Low	Medium
Materials	Concrete, glass, steel	Wood and nature-based	Mix

Qualitative assumptions were translated into model parameter inputs, using a variety of data sources, including databases, household survey data, literature, and own projections (Table 2). For some of the parameters, existing projections for the Shared Socioeconomic Pathways (SSP1-3), available from databases or literature [13], were mapped to the three SDPs and used for the scenario runs.

Table 2. Model parameters, scenario settings, and data sources.

Category	Parameter	Scenario settings			Main data sources
		Economy-driven innovation	Resilient communities	Managing the global commons	
Demographics and socio-economics	Population*	SSP1	SSP1	SSP1	Database [13]
	Urbanization*	SSP1	SSP2-3	SSP1	Database [13]
	Household size	Current	Current	Current	Database [14]
	GDP	High	Post-growth	Medium	SHAPE project**
	Inequality	Medium-High	Low	Low-Medium	SHAPE project**
Climate	Temperatures, solar irradiation	Current climate	Current climate	Current climate	Database [15]
Housing characteristics	Formal housing types: share of multi-family in new construction	90% (Urban) 57% (Rural)	90% (Urban) 57% (Rural)	53% (Urban) 4% (Rural)	Survey data [5]
	Informal housing (slum share in urban population)	Driven by GDP	Driven by GDP	Driven by GDP	Database [16]
	Access to air-conditioning	Driven by GDP and climate	Driven by GDP and climate	Driven by GDP and climate	Survey data [5], literature
	Floorspace* (per-cap values)	SSP1 (GN: low, GS: high)	SSP2 (medium)	SSP2 (medium)	Survey data [5], literature [5,17]

	Material intensity coefficients in new construction	Current practice	Switch to wooden construction	Current practice	Literature [18–20]
Techno-economics	Building lifetime				Literature [18]
	U-values*	SSP1	SSP2	SSP1	Literature [3,5]
	Heating and cooling system efficiency*	SSP1	SSP2	SSP1	Literature [5]
	Investment costs*, Intangible costs*, Discount rates*	SSP1	SSP2	SSP1	Literature [5]
	Energy prices*	SSP1	SSP1	SSP1	Output from MESSAGEix-GLOBIOM [21]
Behaviour	Set-point temperature - heating	21°C	20°C	21°C	Survey data [5], Literature [22]
	Set-point temperature - cooling	23°C	24°C	23°C	Survey data [5]

* Parameter settings based on existing Shared Socioeconomic Pathways (SSP) projections available from databases or previous studies, as indicated in the table. GN = global North; GS = global South.
** Projections developed in the framework of the SHAPE project.

4. Results

Residential floorspace projections for the three SDPs are reported in Figures 1-2. At the global level (Figure 1), floorspace keeps on growing in the EI and MC scenarios under increased affluence in the global South, though the pace is lower in EI due to the gradual shift towards compact urban forms. In the RC scenario, floorspace levels are lower due to behavioural change and shifts to smaller homes. Large part of the growth in total floorspace is driven by the global South, while in the global North floorspace stays constant in the MC scenario and slightly decreases in EI and RC scenarios (Figure 2). In per-capita terms, convergence can be observed between floorspace levels in the global South, where living standards increase, and the global North.

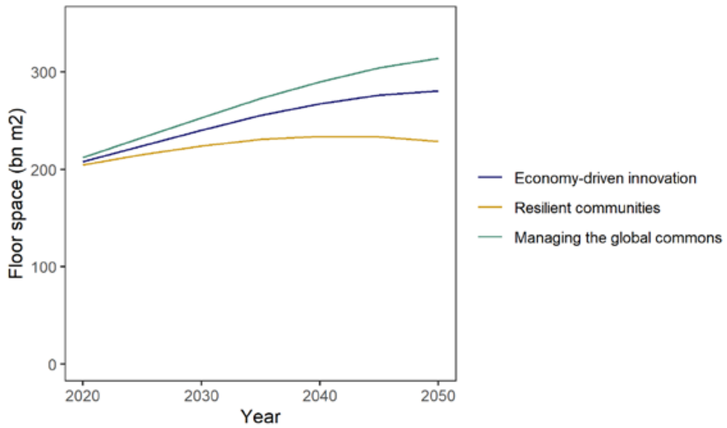

Figure 1. Projections of global residential floorspace for the three SDPs.

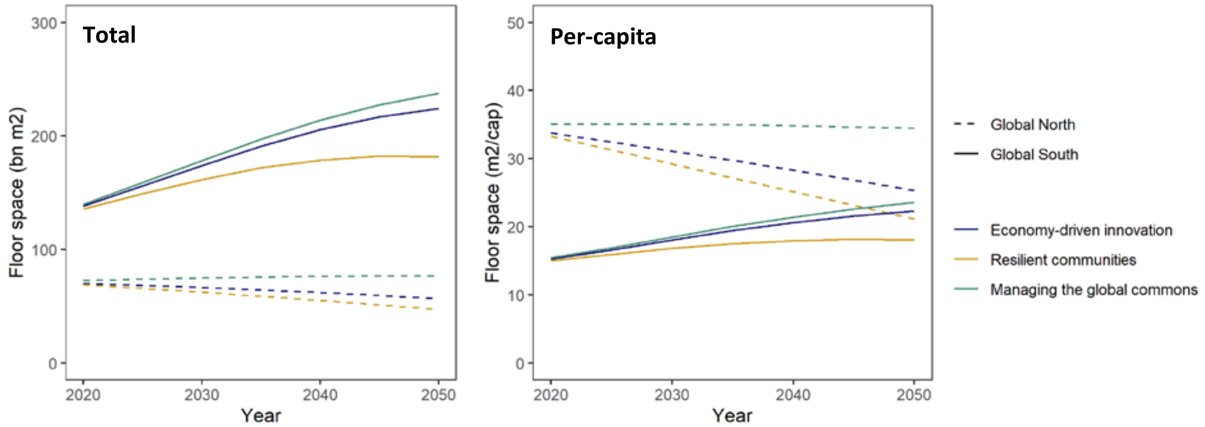

Figure 2. Projections of residential floorspace for the three SDPs in the global North and global South: total (left panel) and per-capita (right panel) projections.

The residential stock composition (Figure 3) also differs across scenarios, with the EI scenario having larger share of new buildings by 2050, due to changes in urban form requiring new construction, more renovated buildings and efficient new construction in MC under tighter building codes, and the RC scenario in between the previous two.

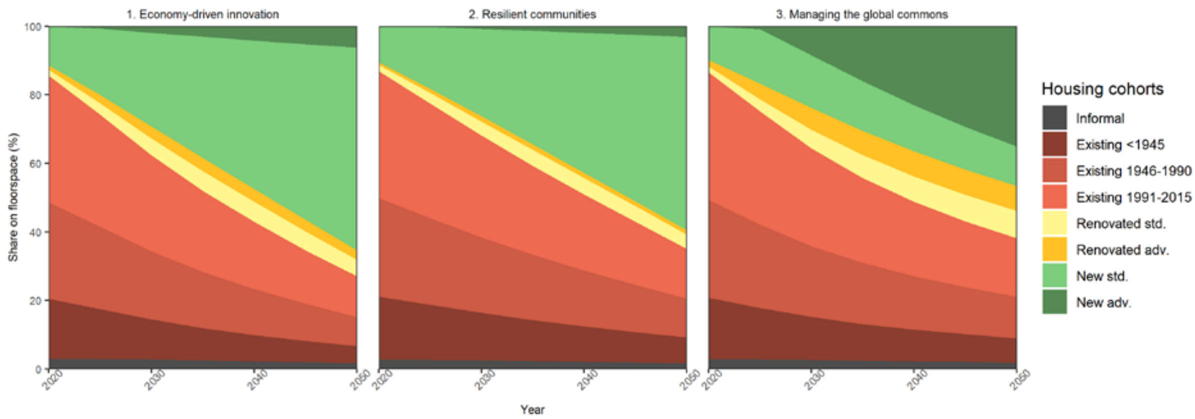

Figure 3. Projections of global housing stock composition for the three SDPs, based on different energy efficiency cohorts for informal, existing (built before 1945, between 1946-1990, and between 1991-2015), renovated (standard or advanced) and new (standard or advanced) housing.

Final energy for space heating (Figure 4) decreases in all scenarios as a result of fast energy efficiency improvements in EI and MC, driven by renovations and switch to heat pumps, and reduction in activity levels in RC. Projections of energy demand for space heating are similar in the EI and MC scenarios, while being lower in the RC scenario due to lifestyle and behavioural changes. Space cooling increases under improved access to air-conditioning in the global South, and doubles by 2050 in the EI and MC scenarios. Cooling demand remains significantly lower in the RC scenario due to floorspace reductions and more frugal use of cooling.

IOP Conf. Series: Earth and Environmental Science 1196 (2023) 012008 doi:10.1088/1755-1315/1196/1/012008

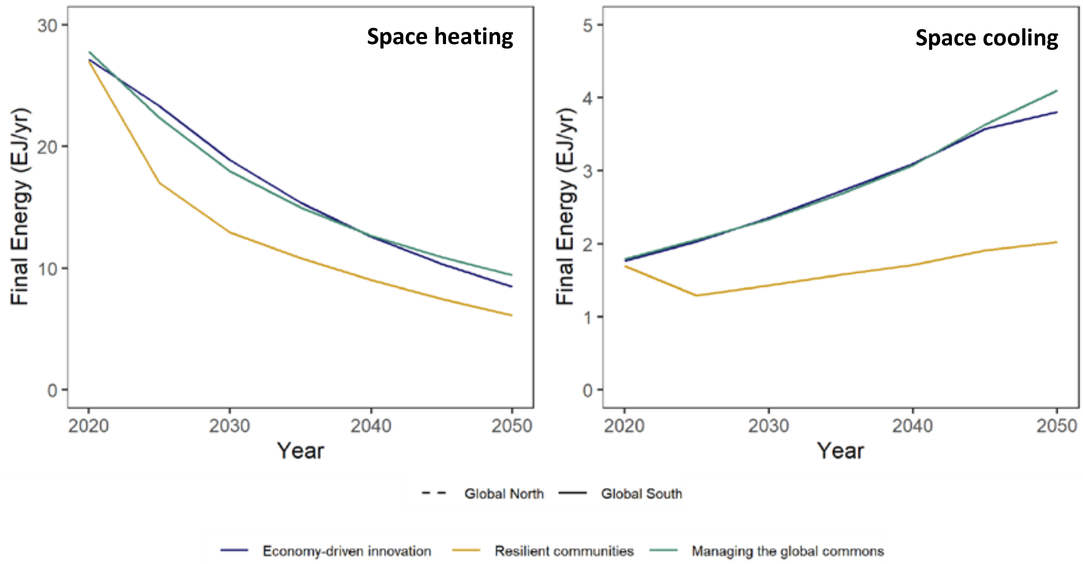

Figure 4. Global projections of residential energy demand for space heating (left panel) and cooling (right panel) for the three SDPs.

Material demand projections (Figure 5) significantly differ across scenarios as a result of combined residential activity levels and building design. In the EI scenario, material demand increases due to growing floorspace and continuous use of concrete and steel as construction materials. In the RC scenario, the material demand is the lowest because of smaller housing size and progressive substitution of current construction materials with wood and nature-based materials. The MC scenario is in between the previous two due to the growing floorspace compensated by lower material intensity of new buildings.

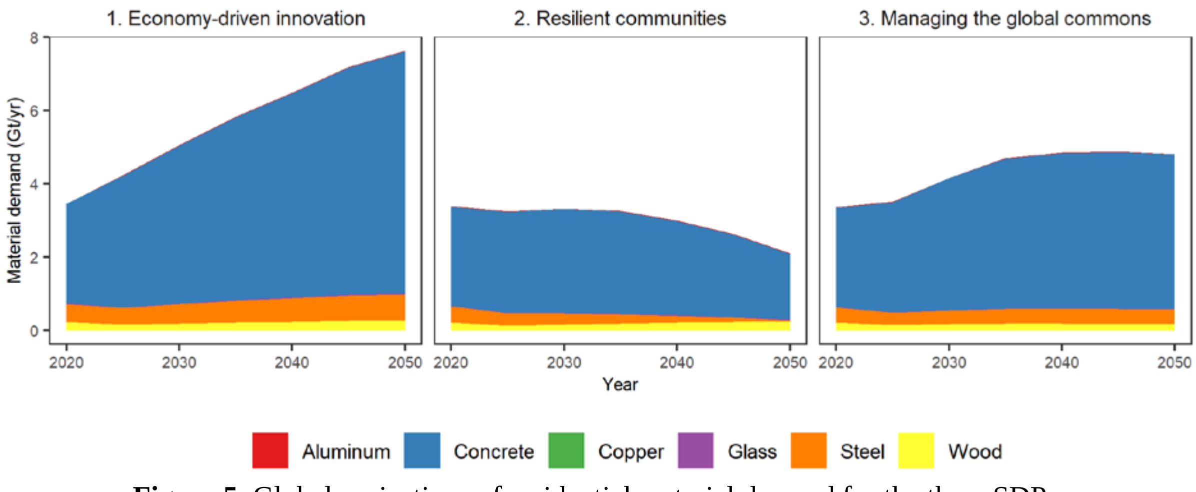

Figure 5. Global projections of residential material demand for the three SDPs.

Figure 6 shows the per-capita material demand projections for three key materials (cement, steel and wood) in the global North and global South. Material demands increase for all materials in the global South in the EI and MC scenarios, while they stay constant or decrease in the global North. Material substitution and switch to wooden construction in the RC scenario drives a decrease in cement and steel demands, and increase in wood demand. Overall, per-capita material demand levels are lower in RC due to floorspace reductions and switch to lighter constructions.

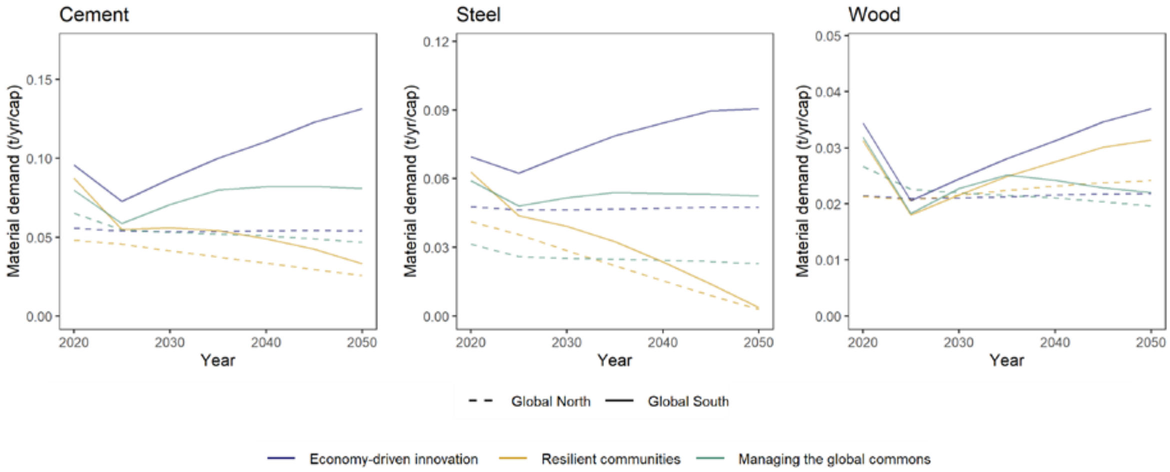

Figure 6. Per-capita projections of residential demand for three key materials (cement, steel, and wood) in the global North and global South for the three SDPs.

5. Conclusions

We investigated LEMD scenarios for the residential sector under alternative SDPs. The results of this study show that the RC scenario entails the highest potential towards reducing energy and material demand driven by floorspace reductions and behavioural change. The EI and MC scenarios are characterized by relatively higher energy and material demand levels and might require additional efforts on the supply-side to reduce total building-related operational and construction energy and greenhouse gases emissions. Future developments include extension of the analysis to the commercial sector and further linkages with IAM and industrial sectoral models for improved representation of supply-side aspects and comprehensive accounting of greenhouse gases emissions. This study can support decision making on strategies for reaching climate change mitigation and sustainability targets in the building sector.

Acknowledgments

This work received funding from the SHAPE project, which is part of AXIS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (SE), FFG/BMBWF (AT), DLR/BMBF (DE, Grant No. 01LS1907A-B-C), NWO (NL) and RCN (NO) with co-funding by the European Union (Grant No. 776608) and from the Energy Demand changes Induced by Technological and Social innovations (EDITS) project, which is an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA), and funded by Ministry of Economy, Trade, and Industry (METI), Japan.

References

[1] IEA 2019 2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector
[2] Pauliuk S, Arvesen A, Stadler K and Hertwich E G 2017 Industrial ecology in integrated assessment models *Nat. Clim. Change* **7** 13–20
[3] Edelenbosch O, Rovelli D, Levesque A, Marangoni G and Tavoni M 2021 Long term, cross-country effects of buildings insulation policies *Technol. Forecasting Social Change* **170** 120887
[4] Daioglou V, Mikropoulos E, Gernaat D and van Vuuren D P 2022 Efficiency improvement and technology choice for energy and emission reductions of the residential sector *Energy* **243** 122994
[5] Mastrucci A, van Ruijven B, Byers E, Poblete-Cazenave M and Pachauri S 2021 Global scenarios of residential heating and cooling energy demand and CO2 emissions *Clim. Change* **168** 14

[6] Pauliuk S, Heeren N, Berrill P, Fishman T, Nistad A, Tu Q, Wolfram P and Hertwich E G 2021 Global scenarios of resource and emission savings from material efficiency in residential buildings and cars *Nat. Commun.* **12** 5097
[7] Zhong X, Hu M, Deetman S, Steubing B, Lin H X, Hernandez G A, Harpprecht C, Zhang C, Tukker A and Behrens P 2021 Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060 *Nat. Commun.* **12** 6126
[8] Francart N, Malmqvist T and Hagbert P 2018 Climate target fulfilment in scenarios for a sustainable Swedish built environment beyond growth *Futures* **98** 1–18
[9] Huppmann D, *et al*. 2019 The MESSAGE Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development *Environ. Modell. Software* **112** 143–56
[10] Al-Homoud M S 2001 Computer-aided building energy analysis techniques *Build. Environ.* **36** 421–33
[11] Sandberg N H, Sartori I, Heidrich O, Dawson R, Dascalaki E, Dimitriou S, Vimm-r T, Filippidou F, Stegnar G, Šijanec Zavrl M and Brattebø H 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
[12] Giraudet L-G, Guivarch C and Quirion P 2012 Exploring the potential for energy conservation in French households through hybrid modeling *Energy Econ.* **34** 426–45
[13] Riahi K, *et al*. 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Global Environ. Change* **42** 153–68
[14] UN 2019 Household Size and Composition
[15] Lange S 2019 EartH2Observe, WFDEI and ERA-Interim data merged and bias-corrected for ISIMIP (EWEMBI) 1 Files
[16] World Bank 2020 World Bank Open Data
[17] Fishman T, Heeren N, Pauliuk S, Berrill P, Tu Q, Wolfram P and Hertwich E G 2021 A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modeling *J. Ind. Ecol.* **25** 305–20
[18] Deetman S, Marinova S, van der Voet E, van Vuuren D P, Edelenbosch O and Heijungs R 2020 Modelling global material stocks and flows for residential and service sector buildings towards 2050 *J. Cleaner Prod.* **245** 118658
[19] Marinova S, Deetman S, van der Voet E and Daioglou V 2020 Global construction materials database and stock analysis of residential buildings between 1970-2050 *J. Cleaner Prod.* **247** 119146
[20] Berrill P and Hertwich E G 2021 Material flows and GHG emissions from housing stock evolution in US counties, 2020–60 *Buildings and Cities* **2** 599–617
[21] McCollum D L, *et al*. 2018 Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals *Nat. Energy* **3** 589–99
[22] Jones R V, Fuertes A, Boomsma C and Pahl S 2016 Space heating preferences in UK social housing: A socio-technical household survey combined with building audits *Energy Build.* **127** 382–98