# Sheltering 10 billion people in a warming and resource-scarce world: challenges and opportunities

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# Chapter 6: General discussion

Housing is one of the most basic and immediate human needs. The provision of buildings uses large amounts of natural resources and drives many environmental impacts. In a world of a growing population, expanding economy, shrinking natural resources, and warming climate, we must urgently address the major challenges ahead of us to provide safe, low impact housing for all.

This thesis makes several steps in exploring the overarching research question: *What are the main challenges and opportunities in delivering decent shelters for a growing population in a warming and resource-scarce world?* To this end, we outline and address four sub-questions related to three major challenges: resources scarcity (Chapter 2), global warming (Chapters 3 & 4), natural hazards (Chapter 5). Here, we discuss the answers to the specific research questions in Section 6.1 and then return to the overarching main question. We discuss the scientific and policy implications of this thesis in Section 6.2. We finish with a discussion of research limitations and an outlook for further work in Section 6.3.

## 6.1 Answers to the research questions

***SQ1. In the face of an unfolding sand crisis, how might demand for building sand develop in the future and how can we reduce this demand to secure the shelter needed and limit sand-related environmental impacts?***

Globally, building sand demand is likely to increase significantly in the coming decades. In Chapter 2, we find that in a middle-of-the-road social economic scenario (SSP2 consistent, with moderate population and economic growth) building sand demand (including the sand demand to make concrete and glass in 8 types of residential and commercial buildings in 26 world regions) sees a ~45% increase from 2020 to 2060. We will likely need a significant increase in sand supply to meet a growing shelter demand driving further environmental issues.

Regional trends vary markedly, and we find that annual building sand demand may more than triple in the lower-middle-income regions by 2060 due to rapid population growth, economic development, and urbanization. In the coming decades, lower-income regions, mainly in Africa, and Southern and Southeast Asia, may need to dramatically enlarge their sand supply (largely from local mining, but also from overseas). Higher-income regions see a slight decline in both absolute and relative terms in the middle-of-the-road scenario with lower sand pressures.

Globally, half of future sand demand may be reduced if we act rapidly. Chapter 2 finds that cumulative building sand requirements over 2020-2060 can be reduced by between 5 to 23% by adopting six strategies (more intensive use, building lifetime extension, reductions in concrete content by lightweight design, timber framing, component reuse, and natural sand substitution by alternatives). If all interventions are introduced, reductions could be as large as 50%. Priority strategies for reducing this demand should vary from region to region. For example, more intensive use is very important in Europe and the United States but not in lower-income regions across Africa. Building lifetime extension plays an important role in China and Japan where the average service life (some 40 years) is around half that found in European countries. The use of sand alternatives should be dependent on the local resource availability.

***SQ2. How might greenhouse gas emissions related to building materials develop in the future with socioeconomic developments, how can we reduce these emissions by material efficiency strategies, and what does this mean for global climate targets?***

GHG emissions from building material production are likely to see continuous growth to 2060 in the absence of efficiency improvements. Under a SSP2-consistent baseline scenario with moderate population and economic development and in the absence of future climate policies, Chapter 3 finds that GHG emissions from producing several materials (steel, concrete, brick, aluminum, copper, glass, and wood) in residential and commercial buildings increase from 3.5 to 4.6 Gt $CO_2$eq between 2020 - 2060. This increase is mainly driven by the rise of low-and lower-middle-income regions, seeing a rapid annual emission increase from 750 Mt (22% globally) in 2020 to 2.4 Gt (51%) in 2060. In 2060, the top 6 emitters (among 26 world regions) are all in Asia and Africa, led by India and China. Across material types, steel and concrete remain the largest emission sources and represent around two-thirds of the total, followed by brick (18%) and aluminum (8%).

Efficient building construction and material supply/use strategies may help avoid around half of total emissions**.** The seven solutions considered represent efficiency improvements across three layers: building demand (more intensive use), material demand (lightweight design, material substitution, and more recovery), and material supply (energy transition, and production efficiency increase). In general, the reduction potential decreases from the top layer (building demand) down to the middle layer (material demand) and then the bottom layer (material supply), highlighting the particular importance of material-related emission mitigation from the demand side. More specifically, more intensive use of buildings, i.e., limiting the size of big homes (or using a less spacious living space) especially in higher-income countries makes the largest difference.

Emission mitigation of building materials remains a big challenge even with all material efficiency strategies implemented. Maintaining today's share of global total GHG emissions, the building material sector is likely to exceed the remaining emission allowance to achieve the 2 and 1.5 °C climate targets in the absence of material efficiency strategies. With all the considered strategies fully implemented in a high-efficiency (HE) scenario, building material related emissions are generally consistent with a 2 °C target. Yet, even in this HE scenario, this sector would require double its current proportional share of emissions to meet a 1.5 °C-compatible climate target. This means we urgently need to act to improve the efficiency of how we use buildings and materials while still upscaling other technologies such as negative emission technologies (NETs) that will likely be needed to bridge emission reduction gaps.

Material efficiency strategies could help close building material cycles in some regions with declining populations. In the absence of material efficiency strategies, even with the continuous increase in outflow-to-inflow ratio of building materials, all regions are likely to need primary materials to fulfill their building material demand during 2041-2060 from a cumulative perspective. In the HE scenario, regions that are expected to shrink in population (such as Japan, Korea, and China) may see a closed material cycle (especially for metals such as aluminium and steel) and therefore a potential to bridge the material cycle gaps in growing regions around the midcentury. This will require international collaboration in resource recycling and building practices.

***SQ3. What are the trends in energy intensity of residential and commercial buildings, their relationship with economic development, and their future role in energy savings around the world?***

Residential energy intensity has significantly reduced on a global level (from 897 to 476 $MJ/m^2$ between 1971 and 2014) with clear difference across regions and income groups. Most high-income regions and emerging regions (e.g., China, Brazil, and India) saw a continuous decrease in their residential energy intensity while lower income regions generally saw little or no reduction. Behind this were a much higher number of building energy efficiency policies in higher-income regions, indicating a significant payoff. Commercial building energy intensity, while much higher than residential buildings, also demonstrated dramatic declines globally, with larger differences observed across regions with different income levels than those in the residential sector.

The decoupling between the energy intensity and the economic growth in residential and commercial buildings across various regions show specific trends. In general, decoupling has deepened for most regions, largely transitioning from weak or no decoupling to strong decoupling between 1971 and 2014. Second, building energy intensities decoupled earlier and more strongly from economic development in higher-income regions. Third, the decoupling status in residential buildings is generally deeper than that in commercial buildings, which might be due to industrial development patterns, i.e., some countries transition to service industries only after the economy has passed through an industrializing process.

Future energy savings from energy intensity reductions are likely to be much higher in lower-income regions, due mainly to the large room for energy efficiency improvements and fast-expanding residential stocks to shelter a rising and increasingly rich population. Harnessing this potential may include, among other policies, stricter energy efficiency standards and advanced construction technologies in new buildings to avoid a lock-in (i.e., accumulating large amounts of low efficiency stocks that may hinder a rapid decarbonisation of the building energy system). Similarly, given the large energy intensity reduction potential and rapid floor area growth, commercial buildings may have a larger energy saving potential from efficiency improvements than residential buildings.

***SQ4. Under current and future climatic conditions, what are the building stocks and materials at risk of riverine and coastal flooding hazards and embodied emissions of material losses?***

We explore how several main materials (concrete, steel, copper, aluminium, wood, and glass) of residential and non-residential buildings maybe at risk of riverine and coastal flooding hazards in 49 European countries / regions. We show that currently a total of 11.7 Gt building materials are at risk from a 1-in-100-year riverine or coastal flooding events, representing ~11.6% of total building material stock (109 Gt) in these regions. Leading nations are Italy, France, and the Netherlands, followed by Germany and Spain. These countries generally have large building stocks accumulated along long coastal lines and river banks or in low-lying areas.

Expected annual damage (EAD) equal 329 Mt in the absence of any flood protection. The replacement of these materials would be equivalent to ~106 Mt $CO_2$eq of GHG emissions. After introducing potential flood protection standards, these embodied emissions could be reduced by ~92% or ~100 Mt$CO_2$eq, roughly 20% of the current annual building-material-related emissions in Europe.

Climate and land-use changes may have significant impacts on the flooding risks. The EAD-related embodied emissions, not considering any flood protection, see an increase of 71% to 180 Mt $CO_2$eq per year in 2080 under a high-emission climate scenario (RCP 8.5, including land subsidence). Climate mitigation from RCP 8.5 to RCP 4.5 reduces these embodied emissions by 25 Mt $CO_2$eq (14%) to 147 Mt$CO_2$eq per year. Overall, we find that climate mitigation and flood protection are critical to reducing building material losses and embodied emissions.

***Main research question. What are the main challenges and opportunities in delivering decent shelters for nearly 10 billion people in a warming and resource-scarce world?***

We can now reflect on the overall research question of this thesis based on the exploration of the sub-questions. Continuing population and wealth growth indicate that we will need more homes and offices. Overexploitation of natural resources, shrinking emission allowances, and worsening natural hazards, among others, may increasingly reduce our operating space to provide and maintain buildings. We need to produce materials and construct and maintain buildings more wisely and efficiently. We need to do this urgently. To this end, we first need to map the key challenges that may impact our future shelter security on global and regional scales. We should then explore the available and emerging solutions to each of these challenges, the cost and barriers of implementing these solutions, the trade-offs across solutions, as well as the priority areas needing urgent investment.

This thesis makes a step in understanding a few key global challenges and promising solutions. In general, global housing presents a significant challenge. Lower-income regions are faced with larger problems, from housing shortages today to increasing pressures from an expansion driven by rapid economic and population growth including resource and investment problems combined with increasing climate damages. Higher-income countries will experience some of these pressures but probably to a lesser extent. Improving the efficiencies of material supply and use in building construction and operation has a substantial potential in both resource conservation and emission mitigation around the world. Negative emission technologies (NETs) are likely necessary in the longer term to achieve a net-emission building construction industry globally. Buildings should be designed and constructed in a more resilient way for longer longevity against the extreme weather and natural hazards that increase with climate change. Flood protection standards are vital in terms of ensuring the safety of buildings against flooding events and need to be broadly strengthened. A multifaceted global strategy that integrates environmental, economic and social dimensions is required to ensure sustainable and equitable shelter security around the world.

### *6.2 Scientific and policy implications*

#### *6.2.1 Scientific implications*

This thesis makes several scientific contributions. First, we showcase an integrated framework to systematically model global shelter security and connect it to environmental challenges. We make a first step and explore key intersecting challenges i.e., resources scarcity, climate change, and natural hazards (further steps are discussed in section 6.3.3 below). We propose that the sustainable development of the global shelter system need to be picked up as an integrated multidimensional area with higher priority in both scientific and policy dialogues (nationally and internationally). Second, we make multiple modelling advances. The models we present can be easily applied for a broad range of research purposes. For example, the dynamic building sand model (Chapter 2), as the first of its kind, can be used to understand the development of sand crisis and other resource scarcity issues across different global regions and sectors. The stock driven material emission model (Chapter 3) can be applied to modelling other environmental impacts such as air pollution, human toxicity, and biodiversity loss. In developing this model, we reach a high level of consistency across sub-models by basing the main input data for both dynamic MFA (e.g., population and economic scenarios) and prospective LCA (e.g., the electricity system transitions) from the same IAM framework. This approach may be used to endogenize material sectors (e.g., buildings and infrastructure) and associated emissions in other IAMs using industrial ecology tools (i.e., dynamic MFA and prospective LCA)[1]. Further, we develop the approach to assessing material losses from flooding hazards under climatic scenarios. We model the adaptation of climate change (i.e., developing flood protection infrastructure) with the mitigation of climate change (i.e., reducing embodied emissions from material replacement). This approach can be applied to other stock types and hazard types to model the benefits of climate mitigation (represented by climate change scenarios such as RCPs) and adaptation (such as flood protection measures) on global and local infrastructure development.

### *6.2.2 Policy implications*

This thesis provides important policy messages from regional and global perspectives. Starting with regional policy, policy makers need to incorporate sustainability holistically into the overall process of building stock development.

• First, investment decisions in urban development should be coordinated with socioeconomic development (e.g., regional population trends) and consider future disaster risks under climate change. This is mainly to reduce future vacancy rates and buildings with a short life (e.g., due to increasing natural disasters and changing urban planning), reducing the unnecessary construction of new buildings in the long-term. Another implication for efficient future urban design is to reduce the number of big homes, especially in aging and shrinking communities. Also note that this is not only about future development. This also requires making the most of existing homes and offices, reducing vacancy rates and increasing use intensity. For example, to use properties more efficiently and reduce building emissions, the European Commission plans to empty half of its office buildings by 2030 and allows more flexible ways of working[2].

• Second, adopt circularity and sustainability principles in the design phase to make new buildings more eco-friendly, circular, and climate resilient. Crucial examples include: 1) adopting passive design principles (to maximize the use of 'natural' sources of heating, cooling and ventilation) and high-efficiency insulation and heating/cooling systems can significantly reduce energy use in homes[3]; 2) circular building design makes components easy to dismantle, replace and reuse at the end of their life; 3) structures designed to allow water go through and constructed with water-resistant materials are helpful for buildings to survive water risks in flood-prone areas. These are mostly 'no-regret' options that will not be superseded by newer technology and will see benefits in their own right, such as lower heating costs from heating system improvements. Combining multiple strategies such as high-efficiency insulation and circular component design can result in greater environmental benefits. However, for buildings with special requirements such as flood-resistant structures, further research is needed to determine how to simultaneously achieve building resilience and building energy savings and emission reductions.

• Third, maintenance and renovation are crucial for building energy performance improvement and service life extension of buildings and components. For existing buildings in areas of current or potential future natural hazard risk, hazard protection infrastructure such as dykes plays a key role in limiting damages.

• Forth, end-of-life of buildings and components should be properly managed to reduce adverse environmental effects and make sure that valuable resources are to be recycled or reused. Deploying the required technologies and infrastructure is important for efficient recovery and reuse of materials.

From a global perspective, we first show that deploying negative emission technologies are likely needed to compensate emission reductions in the hard-to-decarbonize material sector to achieve the 1.5 °C-compatible climate target. Second, we show the need for a rise in international cooperation in technology, investment, and resources. In general, lower income regions have a rapidly growing population and poorly developed infrastructure with less access to new technologies. International cooperation in financial investment, sustainable construction practices, and material supply is essential in addressing the inequalities, where trade agreements may play an important role in lowering barriers and increasing efficiency.

### *6.3 Limitations and future research*

#### *6.3.1 Reflections on scenario development*

Scenarios are not future projections, but are based on potential futures based on different sets of assumptions. For example, results on the future material flows in several chapters are driven by SSP2-consistent population and economic trends that represent a 'middle-of-the-road' path. However, socioeconomic trends can vary significantly across different SSPs and population projections can be updated both globally and across different regions (e.g., global population peak ranges from some 9 to 11 billion)[4-6]. We can say that regional estimates probably see larger uncertainties than global averages under different socioeconomic scenarios. Similarly, choosing different climate scenarios may have a significant impact on future flooding hazards and building materials at risk. One way of evaluating a broader spectrum of potential futures is to develop further scenarios that incorporate, for instance, more ambitious socioeconomic and technological transitions, along with more rapid sea level rise or climatic impacts.

However, regardless of scenario choice, we believe that the main trends are robust to many different futures. For example, 1) there is likely to be a remarkable rise of building material use and emissions in the coming decades in lower-income regions regardless of the overall peak in population and wealth development, 2) implementing material efficiency strategies could nearly halve future building materials and related emissions globally but these strategies alone may not be enough to achieve the material emission reductions compatible with the ambitious

1.5 °C climate target, 3) climate changes are likely to put more buildings and materials at risk of flooding hazards and require enhanced protection to limit negative impacts.

### *6.3.2 Reflections on material intensity and composition*

Researchers are increasingly estimating building-material requirement using a service-oriented approach and relate the demand for materials to the demand for shelter[7,8]. However, there are many challenges in data availability, especially related to material intensity and composition. For example, material use per floor area can vary significantly by building type (in terms of both function of use and the framing type), region, and even the time of construction. Capturing these differences can be very difficult, especially for multiregional, large-scale and time-series studies. This has impacts on the accuracy of the estimates for building sand use (Chapter 2) and building materials related emissions (Chapter 3) in this study. One avenue for improvement is to review a larger number of studies and datapoints to cover more regions and building types[9-11]. Another is to adopt region-specific (instead of globally uniform) building type divisions. This is especially crucial for low-income countries where informal homes such as slums represent an important percentage of shelters and are rarely represented in global studies[12,13]. Yet, we believe that this remains an inherent limitation of employing this kind of bottom-up approach and needs to be considered when interpreting results and comparing across studies (e.g., across studies with a more top-down approach or more production-based perspective). Similarly, for better estimates of sand used in construction materials such as concrete and glass, data uncertainties, while likely impossible to eliminate, could be eased by collecting more data points representing a more diverse range of regions, manufacturing technologies, and environmental conditions. Data remain scarce on some building types (e.g., industrial and agricultural buildings) and material types (e.g., paint, mortar, and ceramic tiles), which may represent a notable contribution yet are not included in this thesis. More research is needed to address these data gaps.

### *6.3.3 Reflections on research scope and future directions*

There is a lot of work to be done in understanding the impacts of natural hazards on building stocks and materials. In this thesis, we make the first step in exploring the building materials at risk of riverine and coastal floods in Europe. Future work is needed to extend this into a global analysis. In addition to flooding events, other natural disasters such as earthquakes, tsunamis, tornadoes, hurricanes and wildfires may also put a large number of homes at risk[14]. The quantification and management of these risks are not well understood across world regions.

Another area for future research is to integrate renovation into dynamic building models. Renovation plays an increasingly important role in improving energy efficiency of buildings in the urbanized world[15,16]. For example, the European Commission published the Renovation Wave initiative to boost renovation and decarbonisation of buildings[17]. A deeper understanding is needed on the feasibility of building renovations and the impacts on building materials, energy and related emissions at local and global scales.

Future extensions of this research could integrate more resources and challenges. To sustainably shelter all, we need four main types of resource: land, material, energy, and labor. Our future demand for these resources across the globe may be significantly shaped by several socioeconomic and climatic developments. To begin with, socio-economic developments (i.e., changes in population, GDP, urbanization, and lifestyles) drive an overall growing demand for these resources and increase resource scarcity. Then climate change complicates this picture in three main ways related to emission mitigation, natural disasters, and the climate migration. First, emission mitigation requires constructing and maintaining shelters using these four resources in a different form, e.g., energy that is greener and renewable, low-carbon materials and new labor skills. Second, a changing climate is driving more intense and frequent natural hazards, and puts a large number of existing houses and offices at risks. For example, the 2022 flooding of Pakistan destroyed over 1.2 million houses in a short period of time[18]. These lead to a need for repairs and rebuilds associated with further resource use and impacts. Third, climate change among other factors is expected to cause numerous people to flee their homes[19]. New homes and thus further resources are required to relocate the migrants. It is important for future research to systematically quantify global and local requirement of the main resources under these socioeconomic and climate related developments.

The building system is a part of the global social economy and is closely interacted with other human (such as power supply) and earth (such as temperature and extreme weather events) systems. Future work could integrate the building system into global integrated assessment models (IAMs) to improve modelling coherence and scalability, and make it easy to simulate the impact of any policy intervention in the overall system on buildings. In the long run, this may benefit the global shelter system in terms of both scientific research and real-world practices.

## 6.4 References


1 Pauliuk, S., Arvesen, A., Stadler, K. & Hertwich, E. G. Industrial ecology in integrated assessment models. *Nature Climate Change* **7**, 13-20 (2017).

2 European Commission. *European Commission to close half of its buildings as telework is 'new norm'*, <https://www.politico.eu/article/european-commission-to-close-half-of-its-buildings-as-teleworking-becomes-the-new-norm/> (2021).

3 Harkouss, F., Fardoun, F. & Biwole, P. H. Passive design optimization of low energy buildings in different climates. *Energy* **165**, 591-613 (2018).

4 Kc, S. & Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change* **42**, 181-192, doi:https://doi.org/10.1016/j.gloenvcha.2014.06.004 (2017).

5 United Nations. World population prospects 2019: Volume II: Demographic Profiles (2019).

6 Vollset, S. E. *et al.* Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. *The Lancet* (2020).

7 Deetman, S. P. *Stock-driven scenarios on global material demand: the story of a lifetime*, Leiden University, (2021).

8 Hertwich, E. G. *et al.* Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. *Environmental Research Letters* **14**, 043004, doi:10.1088/1748-9326/ab0fe3 (2019).

9 Heeren, N. & Fishman, T. A database seed for a community-driven material intensity research platform. *Scientific data* **6**, 1-10 (2019).

10 Sprecher, B. *et al.* Material intensity database for the Dutch building stock: Towards Big Data in material stock analysis. *Journal of Industrial Ecology* **n/a**, doi:https://doi.org/10.1111/jiec.13143.

11 Marinova, S., Deetman, S., van der Voet, E. & Daioglou, V. Global construction materials database and stock analysis of residential buildings between 1970-2050. *Journal of Cleaner Production*, 119146, doi:https://doi.org/10.1016/j.jclepro.2019.119146 (2019).

12 Deetman, S. *et al.* Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production* **245**, 118658, doi:https://doi.org/10.1016/j.jclepro.2019.118658 (2020).

13 IRP. Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N. A report of the International Resource Panel. *United Nations International Resource Panel (IRP): Nairobi, Kenya* (2020).

14 Iglesias, V. *et al.* Risky Development: Increasing Exposure to Natural Hazards in the United States. *Earth's Future* **9**, e2020EF001795, doi:https://doi.org/10.1029/2020EF001795 (2021).

15 Liu, G., Li, X., Tan, Y. & Zhang, G. Building green retrofit in China: Policies, barriers and recommendations. *Energy Policy* **139**, 111356 (2020).

16 Jensen, P. A., Thuvander, L., Femenias, P. & Visscher, H. Sustainable building renovation–strategies and processes. **40**, 157-160 (2022).

17 European Commission. A Renovation Wave for Europe—Greening Our Buildings, Creating Jobs, Improving Lives. (2020).

18 Mallapaty, S. Why are Pakistan’s floods so extreme this year? *Nature*, doi:https://doi.org/10.1038/d41586-022-02813-6 (2022).

19 Pörtner, H.-O. *et al.* Climate change 2022: Impacts, adaptation and vulnerability. *IPCC Sixth Assessment Report* (2022).