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

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“Be like a child – clear, loving, spontaneous,

and ready each moment to wonder and accept a miracle.”

- Mother Meera

Table of contents

Chapter 1: General introduction

1.1 Buildings demand worldwide

From more than one million years ago, when there were signs of civilized activities, to the modern age of the 21st century, human beings have developed their own living space from a simple natural cave sheltering from wind, rain, and wild animals to customized artificial buildings, a structure with a roof and walls in a variety of sizes, shapes, and functions. Today, buildings provide basic needs not only for shelter, but also for thermal comfort, communications, the delivery of energy, food, and water, fundamentally determining people's well-being and health[1-4]. The provision for adequate housing (goal 11), and resilient infrastructure (goal 9) for all are considered essential United Nations Sustainable Developments Goals (SDGs)[5].

There are currently 8 billion people on Earth living in building stocks radically out of balance across world regions[6]. Many high-income regions saw large housing stock accumulations over the 20th century[5]. More recently, emerging economies such as China have seen the fastest increase in building stocks in the historic record, boosting economic growth and increases in well-being indicators like the Human Development Index (HDI)[12]. Conversely, low-income countries severely lack housing and infrastructure, especially in some African, Latin American, and Asian regions, and are home to most of the world's over one billion slum dwellers[5,7]. The majority of populations worldwide are projected to get wealthier in real terms and will likely demand larger homes and offices, driving a rapid increase in demand for new buildings, especially in lower-income countries[8].

The global population is projected to grow to nearly 10 billion in the coming decades[9]. These additional one or two billion people, together with the rapid rural-to-urban migration of a similar magnitude, will raise demand for new dwellings even further. Also, note that buildings do not stand forever. At present, a building usually serves decades before being demolished and then replaced by a new building. This building turnover dynamic adds to construction demand on top of the growing needs of building stocks in service and related constructions.

Unchecked construction and maintenance of buildings are extremely resource-and energy-intensive and have substantial impacts on the environment, especially in terms of ecosystem damage and greenhouse gas (GHG) emissions (as detailed in sections 1.2 and 1.3 below). In a resource-scarce and warming world, a sustainable and efficient system transition in shelter supply is urgently needed to limit environmental damage and provide shelter in a dangerous world. Given drastically different current levels and future patterns of development across the world, an integrated regionalized global assessment that maps challenges and opportunities is essential.

1.2 Building materials

Building materials are witnesses to the history of human civilizations. Material choices are driven by not only a need to adapt to nature, but also to human desires for durability, flexibility, comfort, and fashion[10]. These factors may have played varying roles in different periods across different ancient civilizations, which is marked by several general trends.

Among the first example of a human shelter transition was the Stone Age shift over a million years ago from natural shelters like caves to simple artificial shelters made from easily forgeable natural materials such as leaves, branches, and animal hides[11,12]. There was then a rise in more permanent structures made from more durable natural materials like clay, stone, and timber[10]. Then came synthetic materials such as clay bricks, with the first examples dating back to 7000 BCE, making up for the shortage of natural stones in Ancient Mesopotamia, and enabling the construction of large-scale buildings[13]. Soon after, wooden constructions gained momentum with the development of techniques for cutting and shaping woods, with Neolithic longhouses built around 5000 BCE among the first examples[14], and the Chinese Nanchen Temple constructed in 782 AD the oldest surviving wooden building[15]. Given its abundance, wood is still a popular construction material in many parts of the world today mainly in lower-rise homes[16]. Since over 7000 years ago when ancient Egyptians stunningly poured at least one of the pyramids, concrete has played a huge role in shaping the path of human progress to this day[17]. However, the material only became very widely used in building construction since the 19th century with the invention of the modernized Portland cement and the development of the steel-reinforced concrete that improves workability and strength[18,19]. Today, building structures based on steel and concrete play a dominant role across most world regions.

The history of buildings is also a history of the struggle for light through windows[20]. Glass, invented for making vessels and jewelry in 3500 BC, wasn't used to make small window glass panes of uneven thickness until the 1st century in Rome to allow some light pass through but not see through[21]. In the 4th century, stained glass became popular in Europe, creating beautiful biblical images in early churches[22]. It was only until the 20th century that the maturity of the float glass technology promoted manufacturing of large sheets of glass of uniform thickness and perfectly flat surfaces[23]. Modern glass windows of today are clear and fortified, providing customized light, views, and aesthetics, on top of the original insulation function as part of the building enclosure system.

Climatic conditions have always been part of the development of the structural form and material types of buildings, often to resist rain and snow, extreme heat and cold. Vivid examples include how clay bricks were widely used in the ancient Mesopotamian for their resistance to prevalent climatic conditions and insulation from both cold and heat[13] and how traditional Chinese architectures adapted their roofs against extreme snow events[24]. Increasing the durability and thermal performance of buildings needs to consider changing climatic and environmental conditions (e.g. heat, rain, wind, humidity, erosive particles) in the specific locations[25,26].

The building sector today has become one of the major material consumers globally. Every year, the construction of buildings uses nearly half of global concrete, brick, and steel, and a large amount of other metals (such as copper and aluminium) and nonmetallic minerals (such as glass and ceramic tiles), cumulatively reaching gigatones (Gt) each year throughout the 21th century[27,28]. Most non-metallic materials (e.g., concrete, brick, glass) accounting for most building mass, are used only once under current building practices[29]. A huge amount of raw materials are extracted from the earth each year and are not reused or replaced. These extractions, accumulating over decades and centuries have driven a large ecological impact (e.g., ecosystem destruction, erosion, and biodiversity losses) and driven increasing scarcity in resources. For example, recent research efforts have pointed to a severe global crisis with sand - an essential component in concrete and glass - impacting regions as diverse as Cambodia, California, the Middle East and China[30-32]. These impacts may only get worse with continuous increases in demand[33].

1.3 The contribution of buildings to climate change

There are various processes during building construction that may generate GHG emissions that contribute to climate change[34]. These include extracting raw materials (e.g., gravel, sand, metal ores) from the natural environment, transporting raw materials to where they are going to be processed, manufacturing materials for the properties of construction use, which often involves GHG emission-intensive processes requiring high-temperature heat and process-related chemical reactions (e.g., when limestone is heated to form lime during cement production)[35].

In modern society, a building is more than a place to live in. After a building is built, various types of energy such as electricity, heat, natural gas and biofuels are consumed to achieve and maintain multiple building services from heating and cooling to lighting and cooking[36]. Thus, substantial GHG emissions are generated over the lifetime of a building, from the extraction and processing of construction materials (concrete, steel, glass, etc.) to maintaining multiple building services (lighting, heating, cooling, etc.).

At the same time the planet is getting hotter to become less habitable. Estimates show that the global average temperature over 2011 - 2020 was ~1.09 (0.95 - 1.20) °C hotter than it was in the pre-industrial era (1850 - 1900)[37] and the temperature is currently rising by 0.2°C (±0.1°C) per decade[38]. Numerous studies have shown that a warming world is a mounting threat that causes dangerous and widespread disruption to nature and impacts the lives of billions of people[39-41]. Examples of climate impacts include sea-level rise, weather extremes such as increased rainfall intensity and tropical cyclones, heat-related mortality and vector- borne diseases, and direct economic damages[39]. To avoid potentially irreversible climate catastrophe, 195 nations, or the vast majority of global countries, adopted the Paris Agreement in December 2015 to respond to the threat of climate change and aim to hold “the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels"[42]. Considering that temperatures have already increased well over 1 °C, we are left with a very narrow and rapidly shrinking solution space for achieving these ambitious climate goals. Strong actions are urgently needed to mitigate emissions across all sectors and world regions.

At present, the construction and maintenance of global buildings represent nearly 40% (nearly 10% and 30% of emissions, respectively) of total energy-and process-related GHG emissions annually[34]. In particular, the GHG emissions associated with steel and cement production are very hard to decarbonize due to technical challenges. This is because these materials require high-temperature heat (hard to electrify) and process-based carbon dioxide emissions from chemical reactions, respectivly[35]. These emissions are set to increase along with building stock expansions, which in the absence of radical decarbonization actions may put global climate targets in danger[3]. But there is hope. Recent technological developments in the building industry may allow us to use materials and energy more wisely and efficiently through 'material efficiency strategies' such as material recycling, reuse, and substitution[16,43-45]. Understanding the GHG emission reduction potential in these recognized material efficiency strategies is critical to delivering adequate living space and climate targets.

1.4 Impacts from climate change - buildings at risk of natural hazards

Buildings can fail to serve their designed lifetimes for various reasons. A particular problem going forward is the impact of natural hazards on destroying shelters. For example, the 2022 catastrophic flooding of Pakistan destroyed over 1.2 million houses along with thousands of kilometers of road and hundreds of bridges[46]. Not long before, the deadly 2017 Hurricane Maria on Dominica damaged 90% of buildings with 62% 'heavily damaged' and 15% destroyed[47]. Estimates have shown that over half of US building stock is exposed to potentially devastating natural hazards (i.e., earthquakes, floods, hurricanes, tornados, and wildfires) and 1.5 million buildings lie in hotspots for two or more hazards[48]. On a global scale, floods represent the most prevalent and costly natural hazards[49], accounting for nearly half of total disaster events reported over the past two decades[50] and over 70% of modelled hazard-related damages (among earthquakes, cyclones, and floods) to transport infrastructures[51].

To make matters worse, these natural disasters are likely to be exacerbated by changes in climate and land use (e.g., vegetation clearance and subsidence)[52]. Therefore, buildings and materials may be more frequently threatened by worse hazards, leading to an increasing amount of damage and loss. Both building stocks and natural hazards are not evenly distributed on the planet, which complicates adaptation efforts. To form a more concrete knowledge basis, it is essential to understand where and how severe the buildings are to be impacted or damaged across the globe.

1.5 Research questions

This thesis aims to contribute to a better understanding of what the major environmental challenges and opportunities are in delivering the very immediate demand for a decent living space for a growing population. This thesis focuses mainly on the provision of a building space through construction, but also on the general trends of energy use efficiency of building operation because of its key role - along with the material use efficiency - in mitigating building related GHG emissions. We aim to make the first steps in this long-run endeavor to form the knowledge base for housing in an uncertain world.

The main research question posed here is: What are the main challenges and opportunities in delivering decent shelters for nearly 10 billion people in a warming and resource-scarce world? We will start by exploring main challenges in securing the critical material basis of building construction – with one focus on sand, to reducing the impact of shelter provision on the environment – a second focus on increasing global warming, and finally to examining the in-use buildings at risk of devastating natural hazards – with a focus on flooding. Specifically, this endeavor incorporates several sub questions outlined below.

1) 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?

With a sand crisis unfolding across world countries, this question is of increasing significance to the sustainable development of the building stocks. We aim to develop the first global analysis of the development of building related sand use and mitigation potentials from implementing more efficient building practices.

2) 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 the construction of buildings are driven mainly by the production of materials such as steel, concrete, brick. We build a regionalized global analysis of the time-series change of GHG emissions of building material production.

Another major emission source is the energy used for building operations. We explore the developing trends in energy efficiency of building operations in different regions by asking:

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

Finally, this thesis presents the first attempt to understand how building stocks and materials may be at risk of and damaged by flooding hazards under current and future climatic conditions by addressing the following question:

4) 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?

1.6 Guide to this thesis

This thesis consists of 6 chapters as shown in Figure 1.1. The structure of the thesis broadly follows the flow in this first chapter, moving from resource scarcity to global warming to climate-driven natural hazards.

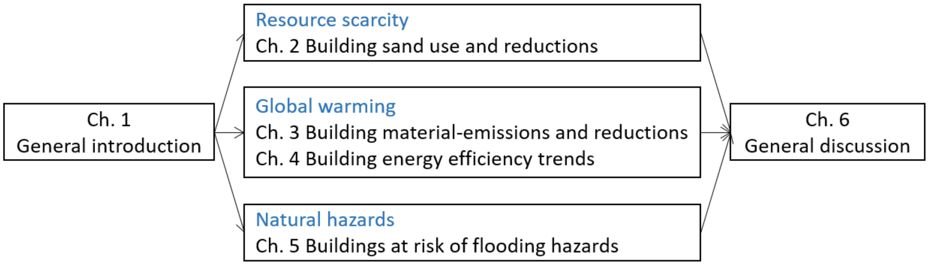

Figure 1.1 Outline of this thesis

This chapter, Chapter 1, discusses a world requiring more buildings to shelter a growing population, having less availability of raw materials, and seeing a warmer climate with more frequent and severe natural hazards. Chapter 2 analyses the development of the sand use to make concrete and glass in buildings construction and how the demand may be reduced by more efficient ways of using buildings and materials. In Chapter 3, we model GHG missions from the production of building materials globally, and how these emissions may be avoided by using buildings and materials more wisely. Chapter 4 discusses how the energy use intensity in buildings may change in the history and how they may develop in the future. In Chapter 5, we map the level of building stocks and materials impacted and damaged by current and future flooding hazards. In Chapter 6, we provide a synthesis of the answers to the research questions, followed by a general discussion about the scientific and policy implications of this thesis. We discuss limitations of the thesis and provide an outlook for future research.

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Chapter 2: Increasing material efficiencies of buildings to address the global sand crisis

This chapter is based on: Zhong, X., Deetman, S., Tukker, A., & Behrens, P. (2022). Increasing material efficiencies of buildings to address the global sand crisis. *Nature Sustainability*, 5(5), 389-392.

Abstract

There is a rapidly unfolding sand supply crisis in meeting growing material needs for infrastructure. We find a ~45% increase in global building sand use from 2020 to 2060 under a middle-of-the-road baseline scenario, with a 300% increase across low-and-lower-middle-income regions and a slight decrease in higher-income regions. Half of this growth may be avoidable using several material efficiency strategies in concert. International cooperation is essential for addressing vulnerabilities and inequalities.

2.1 Introduction

Buildings provide the basic human needs for shelter, social infrastructure and form the foundations of societies. The construction of buildings is also highly material-intensive and consumes a large amount of metallic (e.g., steel and copper) and non-metallic minerals (mainly concrete, brick, and glass)[1]. Previous studies have investigated the environmental impacts of building material production, along with potential mitigation strategies[2-4]. The scarcity of these materials has also seen recent attention[5] and prominent commentaries[6-8] have pointed to a severe global sand crises impacting regions as diverse as Cambodia, California, the Middle East, and China. Sand overexploitation has commonly driven ecosystem destruction/collapse (e.g., shoreline erosion, biodiversity and food loss, disaster resilience degradation) and is set to intensify as building demands increase.

The use of sand and gravel has seen the fastest increase in use across all solid materials used by humans and now represent the largest share of material use (around 68%-85% by mass), surpassing fossil fuels and biomass[9]. Sand is used mostly for making concrete or glass (with concrete comprising 98% of this use in the building sector) and requires chloride-free supplies (to prevent corrosion of other building materials) along with specific physical properties in terms of both size and shape. For example, desert sand is too smooth to be used as a binding agent for concrete and sea sand is too high in chloride levels for most construction purposes[10]. Most construction sand is extracted from rivers, lakes, and shorelines. Sand in these areas has long been a common pool resource, open to everyone largely because monitoring and restricting access to sand is difficult and costly[6]. In a rapidly growing market this has led to overexploitation and degradation. Even when regulated, illegal sand mining and trade has been reported in ~70 countries, often involving highly organized gangs or 'mafias' operating with the complicity of regulators[11]. The livelihoods of an estimated 3 billion people living along rivers are significantly threatened by long-term, unsustainable sand exploitation, along with deep impacts on ecology and land availability[7].

The coming decades are expected to see rapid growth in global building stock driven by population increases, urbanization, and economic development leading to higher living space requirements per inhabitant. However, for the sake of environment conservation, natural sand mining is likely to see increasingly strict regulation or even be banned in many areas[12]. To meet the growing material demand for buildings construction and avoid environmental deterioration due to excessive sand mining, the UN Environment Program has called for action to reduce building sand use through material efficiency strategies[12]. These aim to avoid over-building and over-design (overusing sand-based materials such as concrete), increase recycled materials, and increase the provision of alternative materials to natural sand[12]. However, we have a limited understanding of how sand demand evolves with building stock dynamics across the globe and where the reduction potentials of important material efficiency interventions may lie.

We develop a global dynamic model to investigate the amount of sand used in concrete and glass in residential and commercial buildings (representing nearly half of global concrete-related sand, see Supplementary Information Section 4.1) across 26 world regions by 2060. Sand used in non-building constructions (e.g., roads) and non-concrete/glass materials (e.g., mortar) are not considered. We evaluate this sand demand in a middle-of-the-road scenario that expects moderate population growth, economic and technological development and contains no new policies towards sustainable development[13] (consistent with the second Shared Socio-economic Pathway, or SSP2, see Methods).

2.2 Results

We show that, in this baseline scenario, annual global building sand demand sees a continuous increase from 3.2 Gt/yr in 2020 to 4.5 Gt/yr in 2060, seeing about 45% growth (see Supplementary Information Section 4 for a comparison between overall sand use in this study against the literature). Over half of the cumulative sand demand is seen in upper-middle-income regions, led by the China region, Middle East and Southeastern Asia (Figure 2.1a). However, these upper-middle-income regions see a decline in terms of both absolute and relative sense, from 1.9 Gt/yr (60%) in 2020 to 1.8 Gt/yr (40%) by 2060, mainly due to an overall population decline and stock saturation. High-income regions see similar declines. These trends are set against the rapid growth of the lower-middle-income regions, where annual demand more than triples from 0.7 Gt/yr (22%) to 2.2 Gt/yr (48%). The largest increase is seen in Western and Eastern Africa, where over 500% of current building sand demand is expected by 2060, followed by Rest of Southern Africa (419%), India (294%), and Rest of South Asia (269%) (Figure 2.1b).

We explore how building sand use might be reduced by implementing six widely suggested strategies, including a relative reduction in floor area by (i) more intensive use and (ii) building lifetime extension, (iii) reductions in concrete content by lightweight design, (iv) timber framing, and (v) component reuse, and (vi) natural sand substitution by alternatives (Supplementary Table S4). We also explore how the adoption of all six strategies simultaneously impact sand use. We assess both partial adoption (50% of total potentials) and complete adoption (100% of total potentials). See Methods and Supplementary Information Section 3 for full details.

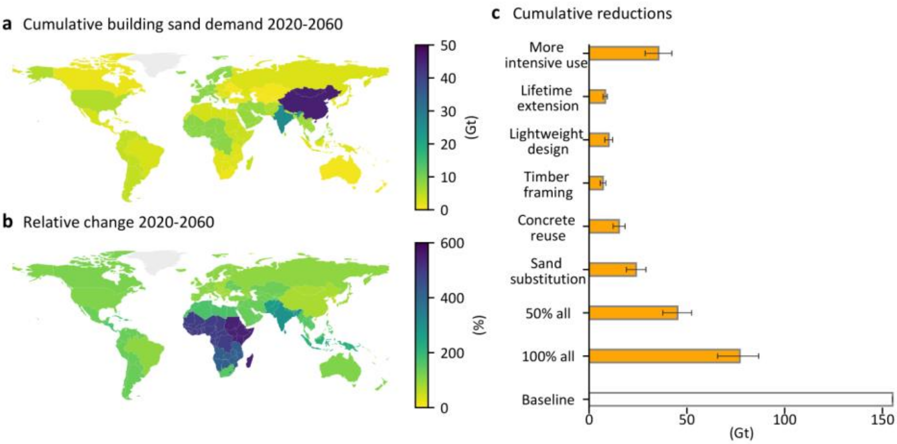

Figure 2.1 Building sand use and reduction scenarios in world regions. a, Cumulative building sand use during 2020–2060 under the baseline scenario. b, Baseline building sand use in 2060 relative to 2020. c, Cumulative sand reductions from material efficiency interventions. The whiskers represent the sensitivity intervals given by 20 percentage point variations for each strategy.

We find that cumulative building sand over 2020-2060 can be reduced by 5 to 23% from adopting each of these strategies individually and by 50% if all strategies are fully implemented simultaneously (Figure 2.1c). Among these strategies, more intensive use represents the largest cumulative sand reduction potential on a global level (~36 Gt) by avoiding surplus construction, growing urban regions in a compact way, reactivating vacant buildings, and more. Through lifetime extension, ~8 Gt natural sand can be avoided due to less frequent demolition and therefore less new construction. For a given building construction demand, a significant amount of sand could be reduced by lightweight design (~10 Gt), timber building substitution (~7 Gt), and concrete reuse (~15 Gt). Replacing natural sand with substitutes for concrete and glass production represents a major reduction potential (~24 Gt).

Priority areas for reducing building sand demand in one region may be less important in another. For example, more intensive use is very important in Europe, the USA, and China due to already spacious buildings (usually more than 40 m^2/cap for housing)[14] and commonly high vacancy rate. However, there is a limited potential for more intensive use in most African countries where people generally have inadequate building access (often below 20 or even 10 m^2/cap for housing)[14]. Policies to improve building longevity are especially important in regions like China and Japan, where the average lifespan is currently below 40 years, around half that found across European countries[14]. Similarly, the selection of alternatives to natural sand should be dependent on the local resource availability. For example, the use of crushed rock may only be a possibility in areas already close to suitable quarries (because of the high cost of transport).

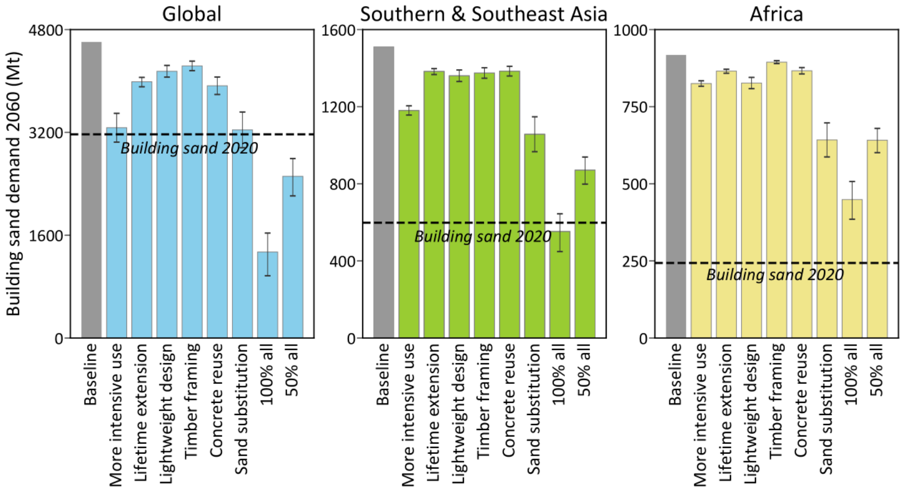

Figure 2.2 Building sand use in 2060 under the baseline and mitigation scenarios. The dashed horizontal lines represent building sand use in 2020. The whiskers represent the sensitivity intervals given by 20 percentage point variations for each strategy.

Since sand is formed by erosive processes over thousands of years, natural sand is currently being extracted at a rate far greater than its renewal[12]. Given the lack of reliable data on sand reserves, it is questionable if the current supply can be maintained or increased in the future, and therefore hard to evaluate if significant increases in sand demand can be met[15] (please see Supplementary Information Section 5 for more details on model limitations). The vulnerability of the building sector to sand supply, if defined as the ratio between future building sand demand and demand in 2020, is extremely unequal across world regions (Figure 2.1b, Figure 2.2). On a global level, either more intensive use or sand substitution could reduce the building sand demand in 2060 to lower than that in 2020. This means maintaining the current sand supply is likely enough for building construction using either of these two strategies. A global implementation of strategies at their 50% potential could reduce 2060 sand demand by 45% (or 71% with 100% implementation), which is approximately 79% of the demand in 2020 (or 42% with 100% implementation). However, if the current supply stays the same none of the six individual strategies alone nor a 50% adoption of all could reduce demand sufficiently by 2060 for some rapidly developing regions, such as Africa and Southern and Southeast Asia. In Africa, a full adoption of all strategies and a nearly-doubled natural sand supply from 2020 levels could be required to meet building construction demand by 2060.

International cooperation is likely essential in addressing the disproportionately distributed vulnerabilities of building sand demand, especially with respect to trade agreements. For example, Singapore has resorted to importing a total of 517 Mt of sand to meet a 20% land area expansion over the last 20 years[12]. However, this has led to soaring prices, environmental harm, and export bans across neighboring countries such as Cambodia and Indonesia[8,12]. Decentralization of exporting regions or even importing from remote regions (e.g., Dubai and Saudi Arabia have previously imported from Australia[12], and Greenland is suggested to be a promising sand exporter[16]) might be a solution to sand scarcity across neighboring countries. However, transport costs could be a challenge for long-distance shipping and the environmental and economic impacts of increased transportation remain highly uncertain. Trade agreements may be necessary in addressing these issues and avoiding or remediating environmental harm. Second, for sand-scarce countries it may be possible to import pre-processed or pre-fabricated building material elements (e.g., windows or pre-fabricated concrete parts) that represent virtual sand (i.e., sand embodied in products[10]), thus relieving pressures on domestic sand resources. Moreover, international cooperation in developing sustainable mining technologies and equipment (e.g., stone crushers) is critical for a sustainable sand industry transition in lower-income countries.

Sand substitutes (manufactured sand, desalted sea-sand and more) could play an increasingly important role, but there are challenges involved in the full life cycle from extraction to utilization. First, it is important to inventory locally available alternative resources and regulate the mining permissions. Quality control is a major task for the processing of manufactured sand and other alternatives for construction use. Standardized methods are needed to both control the fine content and impurities of these alternatives and also the addition of mineral and chemical admixtures to concrete to enhance the mechanical properties[17]. For in-use buildings using alternative sands, targeted quality inspections are needed to ensure no loss of function over time, especially when faced with environmental or climatic changes (e.g., increased subsidence or changes in temperature and humidity). Finally, while lab-scale lifecycle assessments generally show environmental benefits[17] from using sand substitutes in concrete, more research is needed for comprehensively monitoring and quantifying long-term environmental and social impacts of mining activities for sand alternatives (e.g., rock-derived mining and quarrying, and marine sand exploitation) to avoid problem shifting to other materials and negative tradeoffs.

A prominent barrier for a sustainable supply chain transition is the fragmentation of the sand and aggregate industry with 95% of global production represented by small and medium-sized enterprises (SMEs)[8]. The domination of SMEs brings several challenges not only in effective governance and accurate data collection, but for technological and equipment innovation since purchasing advanced fixed processing or manufacturing assets can be costly. Industry cooperatives or consolidation may be advantageous for applying stricter mining permissions and restrictions[8], but such developments come with its own dangers of regulatory capture and political influence[18].

In general, the implementation of material efficiency strategies investigated here would also yield significant greenhouse gas (GHG) emissions reduction[2,4], and therefore are also being driven by climate targets on a global level. Collaborative efforts to conserve sand and mitigate emissions provide large opportunities, from reducing local mining pressures to lowering overall GHG emissions, in a more efficient and sustainable building sector. This analysis develops a picture of global building sand dynamics, highlights major opportunities and challenges of building sand reduction across global regions. We hope this stimulates progress in this crucially important yet underreported area.

2.3 Methods

We developed an integrated global dynamic building-sand model (GloBus) for the assessment of sand use for building material production. We use this to investigate the sand use reduction from different material efficiency interventions (see the model framework in Supplementary Figure 1). We include 4 residential buildings types (detached houses, semi-detached houses, apartments, and high-rise buildings) in urban and rural areas, and 4 non-residential buildings types (offices, retails & warehouses, hotels & restaurants, and other commercial buildings). We evaluate sand used for concrete and glass in buildings by 2060. This period is particularly appropriate as projections suggest it will be within the period of a global population peak and a rise of living standards across lower-income regions which would significantly shape the global building stock profiles (in the absence of extreme climate disruption)[2,4]. A brief description of the model components is given here with full details provided in the Supplementary Information.

Building concrete and glass use

We develop a stock-driven dynamic model to calculate the concrete and glass use for building construction on the basis of refs[4,13,14,19]. Specifically, we first translate the regional socioeconomic trends (i.e., population, GDP, housing space per person, and building type split) into the demand of residential and commercial building stocks on a yearly basis. We then calculate the annual construction (inflow) and demolition (outflow) of building floor space based on documented lifetime distributions. To do this, we first calculate the demolition from the existing building stock using the lifetime model. Then, the construction can be calculated using the basic mass balance (inflow = outflow +stock change). We next estimate the concrete and glass inflows for building construction by combining floor space inflow with the material intensity (in kg/3), which in turn define the demand for sand based as detailed below. For full details please see the Supplementary Information.

Building sand use

Due to a lack of reliable data on sand use, previous estimates are mainly indirect, i.e., based on the sand requirement as a ratio of other material requirements such as cement and bitumen[10,12]. Here we estimate the sand use as a ratio for each metric ton of concrete and glass using weight ratios derived from a number of lifecycle inventory databases and studies (see the Supplementary Information for details).

Scenario development

We first explore a baseline scenario to represent the middle-of-the-road path in that is consistent with the shared socioeconomic pathway SSP2. Data in the baseline scenario are mainly derived from the integrated assessment model IMAGE[13] and complementary studies[14,20]. We then explore eight scenarios whereby the first six give results when the interventions are implemented independently, and the final two when all six strategies are adopted simultaneously at 50% (halfway towards total maximum potential modelled here) and 100% (total maximum potential). Details of all scenarios and interventions are available in Supplementary Information Section 3. Note that this study aims to explore potentials rather than predict the future. Given the data constraints, the model is subject to several limitations as discussed in Supplementary Information Section 5.

2.4 Data availability

This research relies entirely on publicly available data as referenced. We have also deposited them in the Zenodo repository[21] in a form that can be easily used with our model code. Source data are provided with the paper (https://www.nature.com/articles/s41893-022-00857-0#Sec8).

2.5 Code availability

The python code of the building sand model is publicly available from the Zenodo repository[21].

2.6 Supplementary information

See details: https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-022-00857-0/MediaObjects/41893_2022_857_MOESM1_ESM.pdf.

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Chapter 3: Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060

This chapter is based on: 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. *Nature Communications*, 12(1), pp.1-10.

Abstract

Building stock growth around the world drives extensive material consumption and environmental impacts. Future impacts will be dependent on the level and rate of socioeconomic development, along with material use and supply strategies. Here we evaluate material-related greenhouse gas (GHG) emissions for residential and commercial buildings along with their reduction potentials in 26 global regions by 2060. For a middle-of-the-road baseline scenario, building material-related emissions see an increase of 3.5 to 4.6 Gt CO_2eq yr^{-1} between 2020-2060. Low- and lower-middle-income regions see rapid emission increase from 750 Mt (22% globally) in 2020 and 2.4 Gt (51%) in 2060, while higher-income regions shrink in both absolute and relative terms. Implementing several material efficiency strategies together in a High Efficiency (HE) scenario could almost half the baseline emissions. Yet, even in this scenario, the building material sector would require double its current proportional share of emissions to meet a 1.5 °C-compatible target.

3.1 Introduction

Housing is one of the most immediate basic human needs, along with food and clothing[1]. The provision of residential and commercial buildings is responsible for one-third of energy use and energy-related GHG emissions globally[2]. There are two main ways to mitigate building-related emissions: 1) decarbonize/reduce the energy needed for in-use buildings; and, 2) decarbonize/reduce the production of materials and energy in construction. Environmental policies mainly focus on enhancing energy efficiency and renewable energies in the use phase while neglecting material efficiency in construction[3,4]. A policy approach that focuses only on in-use emissions may miss important opportunities in construction[5,6]. Indeed, there may also be important tradeoffs between pre-use and in-use emissions whereby highly energy-efficient buildings may require more materials in construction[7-9]. In 2018, the manufacturing of building materials alone accounted for 11% of global energy-and process-related GHG emissions[2], as a result of consuming over half of global concrete and brick[10], some 40% steel[11], and a large quantity of other metals and nonmetallic minerals[12].

Global trends indicate a rapid increase in demand for new buildings in the coming decades. This is mainly driven by growing populations and increasing wealth around the world (especially in Asian and African regions[13]), but also due to a demand for housing upgrades in highly urbanized areas[14]. As such, large amounts of materials are needed. Building technology has advanced substantially over the past decades. For example, buildings can be built with lower environmental impacts (such as using wood or less metal for the same structural properties[15,16]), designed for a longer lifespan[17], or for a higher post-consumer recycling rate[18]. However, despite these technological advances, less-efficient building practices are still being widely used, especially in regions that will see most of this demand[19,20]. These trends pose a critical challenge in reducing GHG emissions from building materials and meeting global climate targets.

Research on the environmental impacts of building materials and mitigation strategies has gained momentum only in the past decade. Studies have either focused on residential building materials in a single country[17,21-23] or represent a certain material type at one time[24-26]. Further, calculating emissions requires consistent scenarios of both materials demand and process emissions intensities[6], whereas most studies address just one of these aspects[27,28]. A recent study[29] assessed the climate impacts of materials efficiency strategies on residential buildings in 9 large economies. Though valuable, this study omitted most emerging African and Asian regions (which represent much of the increasing housing demand in the future[2,13]) as well as the global non-residential buildings.

Here we develop a global building material emission model that integrates a dynamic material assessment model for estimating future building materials demand, and a prospective life cycle assessment (LCA) model to estimate emissions from materials production. We include 7 materials in 4 residential buildings types and 4 commercial building types across 26 world regions (see Methods). We investigate the development of global GHG emissions of residential and commercial building material production. We investigate the impacts of major material efficiency strategies and the implications of these strategies for meeting climate targets (Methods). We find a continuous increase in building material-related GHG emissions on a global level and dramatically different emission trends across world regions. We observe significant emission reduction and material loop closing potentials in the considered material efficiency strategies. We outline important mitigation opportunities and challenges associated with building materials for achieving global climate targets.

3.2 Results

Scenario narratives

We base our investigation on outputs from IMAGE[30,31], a globally integrated assessment model, and the ecoinvent[32] life cycle inventory database. Different shared socioeconomic pathways (SSPs)[33] are modeled in IMAGE reflecting possible future developments of socioeconomic parameters. We select the "middle-of-the-road" SSP2 pathway[34] which expects a moderate population and GDP growth. We use the socioeconomic[30,31] and energy transition scenarios[35] under IMAGE-SSP2 as inputs for our dynamic building materials model and prospective LCA, respectively. We explore two scenarios for the development of material requirements and emissions to 2060: a Baseline scenario, given by the SSP2-baseline parameters from IMAGE, and a High Efficiency scenario, assuming full implementation of several important materials efficiency strategies drawn from the literature (see Table 3.1). The time period from now to 2060 is characterized by population rise with income converging across economies[30,33], which have dramatic impacts on building construction and material demands. It also gives the industry sufficient time to develop and scale-up technologies for a sustainable transition[36]. The literature supporting the feasibility of these strategies often provides a target by 2050, not 2060. In such cases, we extrapolate these targets to 2060. Please see Methods the Supplementary Information for full details on the model, data, and scenarios.

Table 3.1. Mitigation strategies for reducing emissions from materials required for buildings construction. Strategies are drawn from the literature as feasible targets (see the second column for specific references). Please see the Supplementary Information for further information.

Strategies	Description
M1-More intensive use	20% lower area per person compared to 2050 baseline[29]
M2-Lifetime extension	Up to 90%lifetime extension (depending on the region and average lifetime) by 2050[29]
M3-Lightweight design	19% reduction in aluminium and steel, 10% in concrete by 2050[6,16,29]
M4-Material substitution	10% more timber buildings by 2050[29,37]
M5-More recovery	Maximum recycling and reuse rates estimated by 2050 (recycling: 90% steel[38], 95% aluminium[26], 93% copper[39]; reuse: 15% steel and concrete[6,29])
M6-Energy transition	An energy transition consistent with the SSP2-RCP2.6[35]
M7-Production efficiency increase	Efficiency increases of material production via manufacturing improvements and process-switching (for example switching from hydrometallurgy to pyrometallurgy processes for copper production)[28,40-42]

Baseline emissions

The Baseline scenario sees a continuous increase in building-material related GHG emissions at a global average of 0.7% yr^{-1} (from 3.5 to 4.6 Gt CO_2eq yr^{-1}) between 2020-2060. This trend varies significantly across income-groups (see Figure 3.1a, 1b). The low-and lower-middle-income group sees the largest increase from 750 Mt (22%) in 2020 to 2.4 Gt (51%) in 2060 (see Figure 3.1b), mainly due to a surge in population and economic development. For example, India, the Rest of South Asia, and Africa (excluding South Africa) will more than double their material related emissions from 2020 to 2060. By comparison, the high-income group sees a slight decline in absolute terms and a sharp fall as a proportion of global emissions, from 595 Mt (17%) in 2020 and 530 Mt (12%) in 2060. A similar trend is seen in the upper-middle-income group (Figure 3.1c). Figure 3.1d shows the regional comparison of cumulative material-related GHG relative to GDP, highlighting contrasting economic challenges for the adoption of mitigation strategies. In general, high-income regions (such as the US, Japan, and Western Europe) will see relatively lower emissions and, therefore, have higher affordability of deep decarbonization.

The China region and India remain the top two emitters for the period 2020-2060, with India becoming the largest emitter by 2053 (Figure 3.1c). The top 6 regional emitters in 2060 will all be in Asia or Africa (Figure 3.1c). Overall, Asian regions see the majority (over 65%) of cumulative building material emissions over 2020-2060, followed by Africa at slightly over 10%. For material types, steel and concrete remain the largest emission sources at around two-thirds of the total, followed by brick (18%) and aluminium (8%) (Figure 3.1a). The share of metal-related emissions see a slight decrease from 43% to 39% over the period 2020-2060 likely due to an increase in secondary metals production.

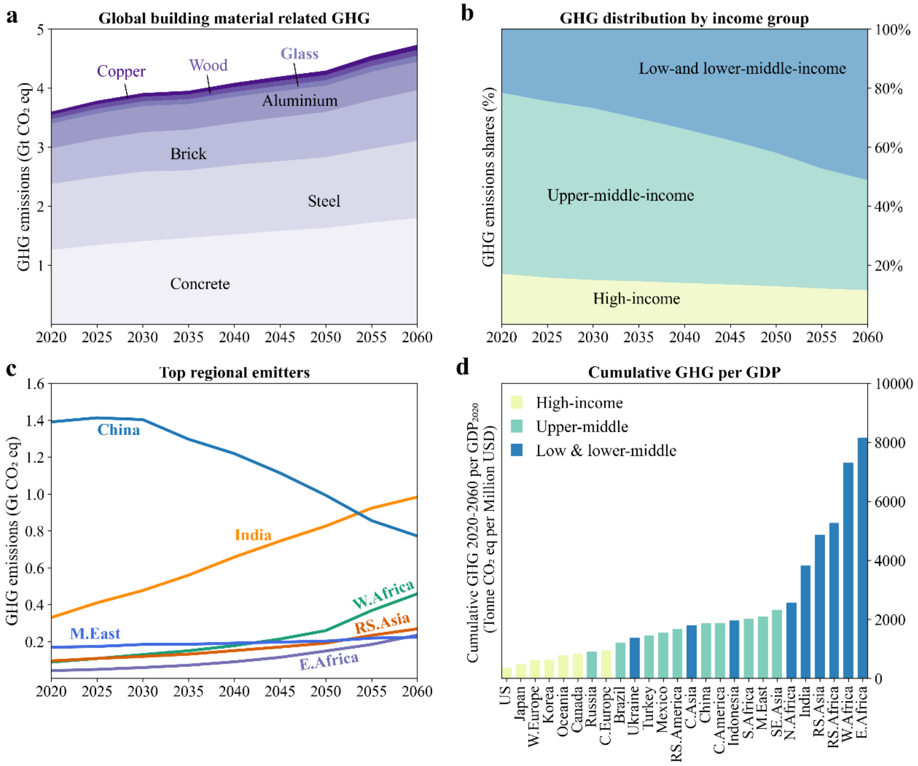

Figure 3.1 Greenhouse gas (GHG) emissions from building materials use for global regions in the baseline scenario. (a) Development of global GHG emissions for 7 materials during 2020-2060. (b) Percentage evolution of GHG emissions for three income groups during 2020-2060. (c) Development of emissions in the top 6 emitting regions (by 2060), occupying over 60% of the total, during 2020-2060. (d) Expected cumulative GHG emissions over 2020-2060 relative to present GDP (2020 value from the IMAGE integrated assessment model, at purchasing power parity) for 26 global regions.

Strategies for emissions mitigation

The mitigation potential of material efficiency strategies depends on the in-use building stock, construction practices, and the future techno socio-economic development in different regions. Figure 3.2 shows the reduction potential for each strategy at their High Efficiency levels during 2020-2060 (in comparison with the Baseline values and when each strategy is adopted independently of each other). In general, the reduction potential decreases from the top layer (building demand) down to the middle layer (material demand) and the bottom layer (material supply). That is, in terms of the feasible interventions drawn from the literature, housing demand reduction has a higher potential for reducing impacts than improving material intensity, which in turn has a higher potential than increasing efficiency in the material supply.

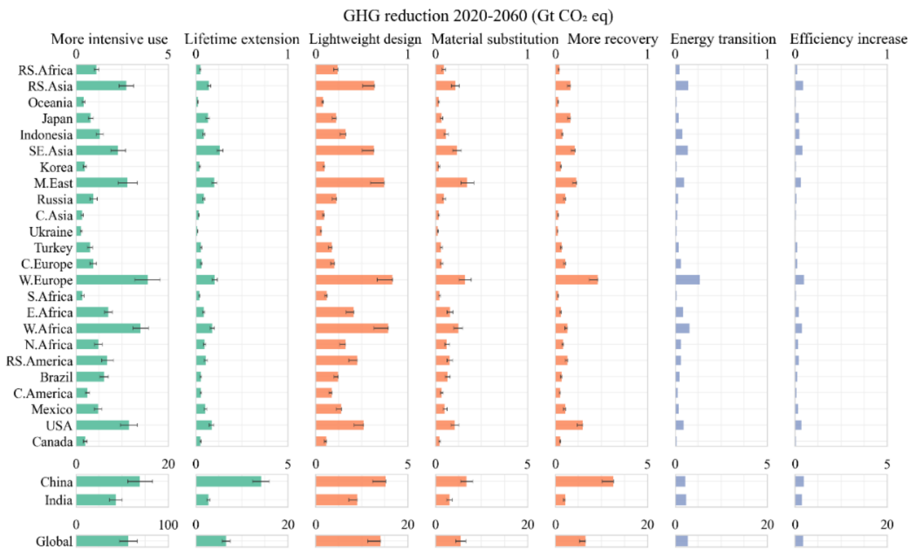

Figure 3.2 Greenhouse gas (GHG) emission mitigation potential during 2020-2060 by different material efficiency strategies. The three colors left to right represent the three layers in the modelling framework: building demand, material demand, and material supply (see Supplementary Figure 1). These three approaches correspond approximately to the general 'avoid–shift–improve' emission mitigation framework[42]. The whiskers represent the sensitivity intervals of GHG in the High Efficiency (HE) scenario (given by 20 percentage point variations for each strategy; see the Supplementary Information for further details). Note that the scales for Global, the China region, and India differ from other regions, and the scale for 'more intensive use' differs from other strategies.

Globally, more intensive use represents the largest emission reduction potential of 56.8 Gt CO_2eq as it simultaneously avoids a percentage of all materials. As a consumption-oriented strategy, more intensive use of the building stock represents the possibility to decouple the growth of buildings demands from economic development[20,44]. It does not necessarily lead to lower wellbeing and can be achieved by e.g., lower vacancy rates[45,46], more shared offices[47], and telecommuting[48]. As such, this strategy is heavily dependent on lifestyle and behavior transitions[20]. This potential is especially large in rapidly urbanizing regions such as China and highly urbanized regions like Western Europe, which will see shrinking populations and an opportunity to increase housing intensity[45,49].

Lifetime extension yields lower demands for new construction and emission reductions of 6.6 Gt globally. The opportunities for lifetime extension vary depending on the region. For example, although some older buildings can have their lifetimes extended in regions where the services life is very short (such as China, Japan, and Southeastern Asia), frequent demolition is often not due to construction quality but because of evolving urban planning and land policies[50-52]. Longer-lived buildings built today will only bring significant environmental returns decades later and only if planners ensure that the urban form is sustainable over the longer-term. Poor urban planning can result in the lock-in of poor, unsustainable urban environments which would require demolition and reorganization in the future.

Light-weighting gives potential cumulative reductions of 14.1 Gt CO_2eq. This may be achieved by large-scale adoption of emerging technologies including novel structural design[53], typology optimization[54], additive construction (such as 3D printing)[55], and the use of high strength steel and aluminium[5]. Some adjustment of building regulations is likely essential for such light-weighting transitions. Depending on the technologies and level of adoption there may be larger opportunities for light-weighting than those adopted in Table 3.1, e.g., 20% or more concrete reduction[29,56]. The current cost barriers to this implementation may reduce over time through deployment-led learning. Increasing the use of timber in buildings would result in GHG emission reduction of 5.5 Gt CO_2eq (due to the lower emission intensity of timber production) and provide long-term carbon storage[37,57]. In a similar manner, secondary production of metals significantly reduces energy use and emissions, avoiding mining and early manufacturing emissions[28]. As post-use scraps become increasingly available, higher-recycling and reuse plays an increasingly important role in mitigation, with a cumulative potential 6.5 Gt GHG over 2020-2060 (Figure 3.2). To approach the maximum recycling potential, rapid up-front industrial investment is needed to develop both new technologies and supporting infrastructure[26,58].

In the material production stage, the energy transition (to decarbonize energy used in the background LCA system) and efficiency improvements (to reduce energy in the foreground LCA system) have the combined potential for reductions of 4.6 Gt CO_2eq by 2060 (Figure 3.2). The environmental impacts of both strategies vary across material types due to differing energy intensities[28]. For example, the emission intensity of aluminium is expected to see significant declines due to the energy transition, whereas the impact on concrete is minor. As such, the effectiveness of the two strategies will reduce in the long term when energy-intensive primary metals are increasingly replaced with low-energy secondary sources[26]. This partly explains the diverging reduction potential across regions. For example, India sees a larger mitigation potential from the energy transition (61 Mt) than the China region (56 Mt) (India sees a smaller reduction when other five strategies implemented individually) because the latter sees a significantly higher share of secondary metals. Another reason contributing to this difference is the larger emission intensity reduction in India's material manufacturing industry from a deeper and faster energy transition.

A high efficiency scenario

The High Efficiency scenario, with all material efficiency strategies (M1-M7) simultaneously applied, sees a 78 Gt CO_2eq reduction (or 49%) in cumulative building-material related GHG emissions during 2020-2060 (Figure 3.3). Note that the total savings from the High Efficiency scenario will not be equivalent to the aggregation of savings from each of the independent strategies because strategies can be mutually exclusive. That is, we apply these strategies (M1-M7) simultaneously and explicitly in the model framework to avoid double counting potential savings. The globally increasing trend in the Baseline scenario is reversed into a continuous decline (at an annual rate of -2.4%) during 2020-2060 (Figure 3.3). Regions seeing the largest mitigation potential between this scenario and the Baseline are: the China region (28%), India (16%), Western Europe (6%), Western Africa (5%), and the Middle East (5%) (in descending proportional order).

Climate targets require deep decarbonization in all sectors[59]. The building materials we consider accounted for ~7.5% of global CO_2 emissions on average between 2015 and 2019. If the building material sector is to keep a share of 7.5% of the carbon budget available in this century, the HE scenario, with cumulative emissions of ~76 Gt CO_2 during 2020-2060 is generally consistent with a 2°C target (with range 81-144Gt at the 33-67th percentile) (see Methods). Reductions in the HE scenario are insufficient for a 1.5°C-compatible pathway, with an emission allowance of 25-57 Gt (33-67th percentile range) during 2020-2060. Figure 3.3a shows the HE scenario and the trajectories stylized for the building materials sector to meet 2°C and a 1.5°C-compatible pathway, assuming an emission allowance of 7.5% of the carbon budget. Figure 3.3b shows that for the HE scenario to be consistent with a 1.5°C-compatible pathway the sector would require a doubling of its emission allowance. We further see that the emission reduction strategies we consider reach a saturation point around 2060 and that further strategies are needed to stay consistent with both the 1.5°C and 2°C pathways. The fact that several building materials are produced by difficult to decarbonize sectors, such as steel and cement production[60], presents a significant challenge.

There are various ways to bridge this emission reduction gap in the 1.5°C-compatible pathway and to address the additional reductions required after 2060. First, we could assume even more ambitious versions of the strategies we investigate. However, it is questionable whether even more intensive use, further lengthening of lifetimes, and further enhancement of recycling or reuse rates are realistic. Second, we could consider other reduction strategies not included here. For example, wood cascading[61] and brick reuse[12] could reduce the use of primary materials, although compared to steel and cement these contributions would likely be small. In the material supply layer, emissions could be reduced in steel and cement production through various carbon capture, utilization, and storage (CCUS) technologies, such as chemical absorption[62], and calcium looping[63], among others. These technologies, and Negative Emission Technologies (NETs) which remove carbon emissions directly from the atmosphere, are still in early development and face with significant technological and socioeconomic barriers[64,65]. Although substantial further developments could take place up to 2060, we consider them as a complement to existing and more predictable technologies (e.g. recycling) and regulatory developments (e.g. building longevity), as broadly highlighted in the literature[4,29]. Finally, we could assume that it is too difficult to rapidly reduce the emissions for building materials in a 1.5°C-compatible pathway with the implication that easier-to-decarbonize sectors should realise a faster and deeper emission reduction.

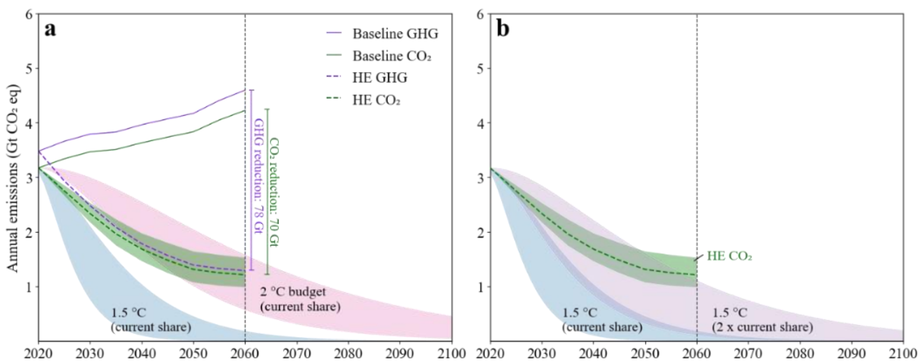

Figure 3.3 Building-material related Greenhouse gas (GHG) emissions by 2060 in the Baseline and High Efficiency (HE) scenarios compared with the 1.5°C/2°C-compatible mitigation pathways where (a) the building material sector shares a proportional carbon budget at 7.5% or (b) sees next to a proportional also a doubling share of the global carbon budget. The shaded bands in green represent the sensitivity intervals of CO_2 emissions in the HE scenario (as defined by 20 percentage point variations for each strategy, for more details see Supplementary Table 13). Other shaded areas represent the assessed range for the GHG emission pathways of the building material sector that are consistent with the 2 °C and 1.5 °C climate targets according to the

IPCC, respectively, for the 33-67th percentile of TCRE (the transient climate response to cumulative carbon emissions (see Methods for details).

Closing material cycles

Past decades have seen an increase in building material outflows from 1.5 Gt in 1980 to 6.5 Gt in 2020, with over 95% comprising of nonmetallic materials (especially concrete and brick) and less than 5% being metals (Supplementary Figure 3). The majority of nonmetallic outflows, except for a small fraction downcycled as base materials, are sent as solid waste to landfills[12]. For metals, despite the already high recycling rate, inflows are much larger than outflows and primary production was still the main input of steel (80%), copper (76%), and aluminum (69%) (over the last decade, Supplementary Figure 3).

In the future, both outflows and inflows will be influenced by housing demand and material use strategies. On a global level, the outflow-to-inflow ratio of building materials will see a continuous increase in both Baseline and High Efficiency scenarios. The High Efficiency scenario would see a significant increase, increasing the material cycle and allowing more secondary production (Figure 3.4a). However, as with other patterns there are significant differences across regions (Figure 3.4b). The potential for closing metal cycles is relatively high in high-and upper-middle-income regions that see a large in-use stock but a shrinking population such as East Asia (i.e., Japan, Korea region, and the China region), Europe, and North America, which see a steady stream of end-of-life outflow and decreasing inflow. These regions have the potential for fully closing the aluminium cycle between 2021-2060 under the High Efficiency scenario (Figure 3.4b). By contrast, low-and lower-middle-income regions, including most African regions, South Asia, and Southeast Asia will be faced with severe scrap shortage for closing the cycles. This is not only due to the rapidly rising inflow driven mainly by population growth but also the reduced outflow from a relatively smaller in-use stock.

Some of the metal shortage in growing regions may be bridged by the surplus in shrinking regions. For example, moving surplus aluminium scrap generated in East Asia to other Asian and African regions could yield a significant reduction in the need for primary aluminium production (around 90 Mt cumulatively between 2041-2060), resulting in a cumulative emission reduction of ~1Gt CO2eq (in the High Efficiency scenario). It is noteworthy that China, the world's largest importer of scrap metals for many years[66], may become a major exporter in the future due to the surging outflow against shrinking inflow In this context, China's policy restrictions on solid waste imports in recent years may be a first sign of this development[67]. Post-consumer scraps of bulk nonmetallic materials are usually processed nearby and mostly consumed by other infrastructural sectors (namely downcycling)[46]. If building demolitions are expected to be very high in certain periods then infrastructure projects should bear this in mind, reducing their requirements for primary materials and using these secondary materials. To ensure material scraps can be collected and turned into valuable resources more generally, it is important to be aware of "where and when which types of material outflows from stocks become available"[12,68,69]. Both interregional and intersectoral cooperation could help in urban mining and future material production capacity planning.

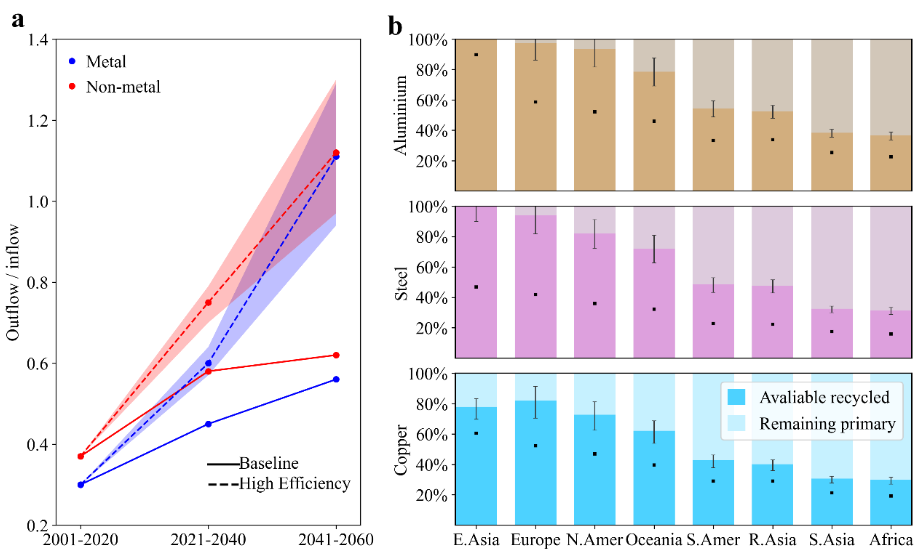

Figure 3.4 The potential for closing building material cycles. (a) Change in outflow-to-inflow ratios over time (in 2001-2020, 2021-2040, and 2041-2060, respectively) under two scenarios. The shaded bands represent the sensitivity intervals of outflow-to-inflow ratios in the High Efficiency (HE) scenario

(given by 20 percentage point variations for each strategy, for more details see Supplementary Table 13). (b) Share of recycled output in total input for aluminium, steel, and copper, respectively, during 2021-2060 in eight global regions (see sub-regions in the Supplementary Table 11). The whiskers represent the sensitivity intervals of the share in the HE scenario. Black dots represent the share in the Baseline scenario.

3.3 Discussion

Building emissions are often complicated by trade-offs along the building lifecycle, especially between the embodied emissions (from building materials production) and operational emissions (from indoor energy use)[9,20]. Among the strategies considered in this study, more intensive use, more recovery, a faster energy transition, and production efficiency improvements are trade-off-free approaches since they don't have negative impacts on energy use during building occupation (more intensive use also reduces the operational energy use[70,71]). For lightweight design, we only consider opportunities for avoiding material overuse through improved design and technological developments, which would not compromise the building's thermal performance, so here indoor energy use will not be affected either. For material substitution by wood, previous research confirms the environmental benefits through case-studies considering both the production-stage savings and potential operation-stage losses[15,72]. In terms of lifetime extension, there are concerns that older buildings tend to have lower-standards so prolonging service life may increase operational energy requirements[73]. Although our analysis does not quantify this trade-off, we should highlight that such an assessment should include a longer research period (far beyond 2060) as many buildings built today will remain in use until the end of the century. On the other hand, today's buildings have generally higher energy performance compared to earlier stocks, with many recent improvements in building codes and standards (73 countries had building codes in 2018)[2,74]. This means the impact of extending the service life on energy use will be declining (even negligible in low-energy buildings). Further, much of the potential improvement in operational energy intensity lies in appliances, lighting, renewable energy, and human behavior that are not necessarily dependent on the main building structure and can be optimized at any time[75,76]. For example, in the Chinese building sector, around half of energy savings by 2050 arise from improvements in lighting, equipment and appliances, fuel switching, and renewable electricity[77]. The other half arise from space conditioning and heating, which requires both newer equipment (such as chillers) and building refurbishments (such as envelope upgrading). The environmental benefits from building refurbishment have been reported in several case studies[21,78]. In general, the deployment of these strategies would not be hindered by trade-offs between pre-use and in-use emissions. This is not only due to the net environmental gains (over the losses) but because of the different characteristics between the embodied and operational emissions, that is, the operational emissions are generally easier to decarbonize and can often be mitigated during a building's service life.

A prominent barrier to the widespread implementation of these strategies is the fragmentation of inter-departmental policy design over time. For example, evolutionary urban planning and land policies – driven by function and/or aesthetic preferences – can force a rearrangement or rezoning of the urban environment, including buildings, streets, or other infrastructure. This would increase the demolition frequency and the risk of shorter building lifetimes (in spite of their good physical condition)[51]. The lack of policy consultation between stakeholders due to political and financial interests can result in uncoordinated land urbanization and social-economic development[49,79]. This can lead to land urbanizing at a faster rate than the population, resulting in 'ghost cities' and a higher vacancy rate, especially in shrinking or population-outflow regions[79,80]. The policy options for dealing with high vacancy rates and underutilized building capacity also rely on cross-sectoral policy packages including upstream land resources management[80] and downstream taxation on vacant and rent dwellings[81]. Another example is the split-incentives faced by tenants and owners in building operation. That is, those shouldering the costs of lower building efficiencies (e.g., tenants pay more for energy costs) are often those not in the position to do anything about them, which could contribute to the construction of low-quality buildings and thus frequent retrofits/demolitions. As such, policy makers are turning more towards multi-criteria decision and stakeholder related analyses[82].

The second barrier facing these strategies is the investment required for infrastructure and technology development[19]. For example, secondary metal production can be economically and technologically challenging for large-scale alloys separation by type[38,83]. This is especially important when we consider that the proportion of emissions from high- and upper-middle income regions may reduce as low- and lower-middle income regions increase. This further increases the global tension between the growth in housing demand and the investment required to mitigate the environmental impacts. As such, these strategies require a coordination across regions on resource extraction, technology and finance.

Notwithstanding these barriers, recent years have seen increasing efforts in promoting material efficiency. In terms of waste management policies, there have been several important developments within circular economy packages, such as the 3R principle (reduce, reuse and recycle) in China[84] and the Circular Economy Action Plan (CEAP) adopted by the European Commission[85]. Strategies like light-weighting require more advanced technologies that are emerging in highly developed regions, highlighting the importance of technology marketization and international collaborations to share best practices. Similarly, higher occupation levels will likely be seen first in highly urbanized regions due to increasing vacancies from shrinking populations. The rise of a sharing economy also creates new opportunities for lower-occupancy. For example, as attempted in French urban renewal projects, parking lots are shared to avoid new infrastructure construction and emissions[2].

Overall, we show that the growing housing demand drives large material-related GHG emissions which are beginning to shift from high-and upper-middle-income to low- and lower-middle-income regions. Nearly half of these emissions can be avoided through scaling up material efficiency strategies on a global level, although efficacy varies significantly with region and strategy. However, with all observed material efficiency strategies simultaneously applied, the expected emissions from building materials are still higher than what would be compatible with the 1.5°C climate target (if the remaining global carbon budget is allocated proportionally across sectors). To meet the 1.5°C target, building materials would require double the current share of their carbon allowance, suggesting the need for faster emission mitigation in easier-to-decarbonize sectors. In the absence of fundamental changes in manufacturing processes, negative emissions technologies seem necessary in the second half of the century to offset process-related emissions that are challenging to avoid. This study may help policymakers to better understand the mitigation opportunities and challenges at regional and global levels and therefore how upfront investment in facilities, guidelines, and collaborations is needed.

3.4 Methods

Overview. We develop an integrated global building-material-emission model that consists of a dynamic building material model and a prospective LCA model. This integrated model allows us to calculate the environmental impacts of materials used to shelter the global population and explore the impact of different material use and supply strategies on emissions. We apply this model to investigate two scenarios determined by seven key strategies in 26 global regions towards 2060 (see Supplementary Figure 1 for a conceptual framework). The time period from now until 2060 is characterized by population rise with income converging across economies[30,33], which have dramatic impacts on building construction and material demands. It also gives the industry sufficient time to develop and scale up technologies for a sustainable transition[36]. The literature supporting the feasibility of these strategies often provides a target by 2050, not 2060. In such cases, we extrapolate these targets to 2060. We include 4 residential building types (detached houses, semi-detached houses, apartments, and high-rise buildings) in urban and rural areas, respectively, and 4 commercial building types (offices, retails & warehouses, hotels & restaurants, and other commercial buildings). We include seven important construction materials: steel, concrete, brick, aluminium, copper, glass, and wood, by extending a comprehensive building material database[27,86]. IMAGE includes 26 regions, which we use as the resolution to illustrate heterogeneity in results across the globe.

Calculation of annual material inflow and outflow. We extend a dynamic building material assessment model (BUMA) to calculate building construction materials on a regional and yearly basis. BUMA is a cohort-based and stock-driven dynamic model, developed by Deetman et al. [27] on the basis of an open dynamic material system of Pauliuk and Heeren[87] and a floorspace model from Daioglou et al[31]. In brief, BUMA allows for the translation from building materials stock, which is determined by socioeconomic parameters and materials use intensity of buildings, to materials inflow and outflow under a certain lifetime distribution. To do this, we derive primary socioeconomic determinants from the IMAGE platform and materials intensity from the literature. The materials intensity across global regions is collected from literature[27,86] and further developed by adding clay brick due to the extensive use of fire clay brick in buildings construction. For building lifespan we apply Weibull distributions with related shape and scale parameters drawn from the literature[27]. Full details are provided in the Supplementary Information.

Calculation of GHG per kg of material production. We use a prospective LCA model to calculate GHG emissions of the production of each material type. Following the LCA procedures standardized by the International Organization for Standardization (ISO)[88], we first select ‘cradle-to-gate’ as the scope of materials production. The ecoinvent 3.6 database[32] is chosen as the lifecycle inventory (LCI) database due to its global coverage and high-resolution product categories. The regional differences in materials production are distinguished where possible. Details are shown in the Supplementary Information. We consider climate change as the key impact category, and Global Warming Potentials (GWPs) (with a 100 year time horizon)[89] are used. Finally, we use the Activity Browser (AB) software to calculate the environmental impacts of the cradle-to-gate production of one kg of materials under different scenarios. AB is an open-source software for advanced LCA calculation, which allows productive scenario-based modeling and intuitive graph exploration[90].

Scenario development. We investigate two scenarios that share the same socioeconomic background including population and GDP development but differ in the material intervention strategies applied. The primary socioeconomic assumptions are based on the Shared Socioeconomic Pathways (SSPs) of IMAGE and for consistency, we select the SSP2 baseline path to represent the “middle-of-the-road” pathway which expects a medium population and GDP growth[34]. In the Baseline scenario, historical trends in the building sectors around the world largely continue. We use this scenario to serve as a baseline for understanding the reduction potentials of any additional strategies. The High Efficiency scenario represents the deep emission mitigation pathway where seven strategies are implemented simultaneously. More details of the assumptions under each scenario and relevant uncertainty analysis can be found in the Supplementary Information.

Estimation of the mitigation rate consistent with the 1.5°C and 2°C budget. To investigate the global importance of the material efficiency interventions on climate targets we also compare the Baseline and HE scenarios with stylized mitigation pathways compatible with 1.5 °C and 2 °C targets. Some sectors, such as electricity, are easier to decarbonize than the building material sector[60]. We therefore assess the efficacy of mitigation scenarios by comparing building material-related emissions against the same proportional share of the global carbon budget as today, and a situation in which the building material share doubles. We follow four steps to generate sectoral mitigation pathways consistent with the 1.5°C and 2°C carbon budgets. First, we derive the global carbon budgets from the IPCC’ 1.5°C special report[59] (see Table 2.2 in the report[59]), which indicates the remaining carbon budgets from 1/1/2018 to the time reaching net-zero carbon (or 2100) to meet the 1.5°C Paris Agreement goal and for the former 2°C Cancun goal. Carbon budgets here are estimated for the 33rd, 50th and, 67th percentile of TCRE (transient climate response to cumulative emissions of carbon)[91]. Second, we subtract the carbon budgets by the CO2 emission in 2018 and 2019[92] to obtain the updated carbon budgets from 2020 onwards. Third, we assume the building material sector is to share the carbon budget by varying proportions. Specifically, we explore two scenarios where the building material sector shares a proportional budget of 7.5% (its average proportion of the total anthropogenic CO_2 emissions during 2015-2019[93]) or is doubled at 15.0%. We have considered CO_2 emission alone (representing ~92% of total GHG emissions in the sector) for this analysis since other GHGs have very different warming dynamics and comprise only a small proportion of total GHG emissions in the building material sector. Note that in practice, multiple factors (e.g., economic costs[8]) may affect sectoral effort-sharing (and therefore carbon budget allocation) in achieving a specific climate target in a period of time. Finally, we calculate mitigation rates under different carbon budgets using the method from the ref.[94] (see equation 4 in ref.[94]).

Limitations and uncertainties

While the construction-material database we use represents the best available on a global level, it could be improved to give higher geographical resolution (e.g., with national-specific and even GIS-based datasets), a higher resolution in building types, and a broader coverage of material types. The materials not considered here (e.g., carpet, paint, and ceramic tiles[95]) represent further emissions on top of those examined here and potentially present different strategies for mitigation. Further, the process-based ecoinvent LCI database may underestimate some emission coefficients via truncation errors (the exclusion of small processes that are hard to quantify or those outside the defined system boundary). The future development of LCI databases for hybrid environmental flow coefficients (integrating bottom-up process data and top-down macroeconomic input-output data) may improve the completeness of assessments[96]. Another improvement of the LCI database could include accounting for the carbon sequestration effect of wood-based products using dynamic sub-models to capture the temporal effect of a slow, gradual uptake of carbon in forests, along with other important factors such as the origin and rotation periods of harvesting[97]. A similar improvement could also include a dynamic sub-model to incorporate CO_2 reabsorption for concrete once construction is complete[25]. Finally, it is worth noting that our results are not predictions of the future but represent scenarios or pathways by which efficiency strategies can be implemented to mitigate building-material related emissions. A sensitivity analysis (see Figure 3.2-3.4 and the Supplementary Information for more details) is performed for understanding key interventions in the High Efficiency scenario, which further confirms both significant mitigation potentials and challenges for achieving ambitious climate goals.

3.5 Data availability

The data that support the dynamic material and emission modelling are available from the corresponding literature references and the Supplementary Information. We have also deposited them in the Zenodo repository[98] in a form that can be easily used with our model code: https://doi.org/10.5281/zenodo.5171943. The energy system transition scenarios are not publicly available as part of the data is under license, but are available from the corresponding author upon reasonable request. Source data are provided with this paper.

3.6 Code availability

The python code used to generate the results on material inflow, material outflow, and greenhouse gas emissions is available on Zenodo[98]: https://doi.org/10.5281/zenodo.5171943.

3.7 Supplementary information

See details: https://static-content.springer.com/esm/art%3A10.1038%2Fs41467-021-26212-z/MediaObjects/41467_2021_26212_MOESM1_ESM.pdf.

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Chapter 4: The evolution and future perspectives of energy intensity in the global building sector 1971–2060

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Abstract

Energy efficiency plays an essential role in energy conservation and emissions mitigation efforts in the building sector. This is especially important considering that the global building stock is expected to rapidly expand in the years to come. In this study, a global-scale modelling framework is developed to analyze the evolution of building energy intensity per floor area during 1971-2014, its relationship with economic development, and its future role in energy savings across 21 world regions by 2060. Results show that, for residential buildings, while most high-income and upper-middle-income regions see decreasing energy intensities and strong decoupling from economic development, the potential for further efficiency improvement is limited in the absence of significant socioeconomic and technological shifts. Lower-middle-income regions, often overlooked in analyses, will see large potential future residential energy savings from energy intensity reductions. Harnessing this potential will include, among other policies, stricter building efficiency standards in new construction. For the commercial sector, during 1971-2014, the energy intensity was reduced by 50% in high-income regions but increased by 193% and 44% in upper-middle and lower-middle-income regions, respectively. Given the large energy intensity reduction potential and rapid floor area growth, commercial buildings are increasingly important for energy saving in the future.

4.1 Introduction

Global development has long been associated with increasing resource and energy consumption [1]. Socioeconomic development raises living standards and has directly contributed to the increase in building energy consumption. In addition, the majority of people today spend almost 90% of their time indoors[2]. These factors combine to make the building sector one of the largest energy consumers in the world[2] and comprise one-third of energy-related greenhouse gas emissions[3]. Recent research noted that the expected emissions from existing and proposed infrastructures are probably inconsistent with the goal to keep global warming this century below 2°C above pre-industrial levels, let alone the more ambitious 1.5 °C limit[4]. As such, a rapid and deep transition towards efficient and sustainable building stocks plays a key role in attaining the 2050 climate targets[5].

An important variable in this dynamic is the global building floor area which continues to increase at an annual average rate of around 2.3%, driven by a growing population and increasing floor area per person[6]. The fastest growth will be seen in lower-middle-income regions (especially in Asia and Africa) which are not yet fully covered by compulsory energy codes[7]. As a result, significant growth can be expected in building energy consumption, especially in rapidly developing regions such as India[8] and China[9]. Research using different methodologies and scenarios expect global building energy consumption to increase by 31%-95% between 2005 and 2050[10]. Therefore, against the growing stock demand, energy efficiency improvement plays an increasingly important role in energy saving and emissions mitigation in the long run[11].

Energy efficiency can be defined from either macroeconomic or physical perspectives[12]. Energy-to-GDP is easy to compute but does not offer a good sectoral resolution. Energy consumption per unit of floor area is preferable since it is more relevant for understanding the driving forces of energy requirements in the building sector[13]. As such, much of the literature uses energy consumption per unit of floor area as the proxy of building energy efficiency on the macro level[14]. For example, Sandberg et al.[15] investigated historical trends and driving factors of energy intensity per square meter in Norway's residential stocks since 1960, confirming the effect of large-scale efficiency improvement on energy savings. To understand how efficiency shapes building energy use, Huo et al.[16] estimated China's building floor area and analyzed the evolution of residential energy intensity per square meter in urban China, which was observed to be much lower than in some high-income nations. However, due to different conceptual frameworks, these nation-specific studies are difficult to compare, and more importantly, such research mainly focuses on regions in China or Europe, leaving most lower-middle-income but rapidly growing regions unanalyzed. Moreover, energy intensity in non-residential buildings is rarely discussed on a regional or global level due to data limitations[17]. This has limited the understanding of how building energy intensity evolves with the economic development across regions and energy saving potentials may lie.

To address these research gaps, this study presents a novel integration of IEA's building energy databases (see Methods) with data from an integrated assessment model (IAM). Specifically, the IMAGE model[18], one of the most widely used IAMs, is selected for its global coverage, regional resolution, and broad time range. Under a series of scenarios, IMAGE provides consistent datasets required for multiregional building stock modeling such as the long-term socioeconomic parameters, urbanization rate, floor area per capita for 26 global regions[18]. These data are combined to build a global-scale building energy intensity modelling framework that enables analyses of time series evolution, decoupling status, and decomposition under different scenarios. Note that, in this study, energy intensity is given by the regional average building energy consumption per square meter (see methods for detailed building types and energy end-users). This study brings in a historical perspective of energy intensity transformation, investigate whether building energy intensity has decoupled from economic development across different regions, and how large potential efficiency-driven energy savings may be to 2060.

Details of the modeling approach and data sources are described in the methods section. The results section first reports the energy intensity per floor area of residential and commercial sectors for 21 global regions during 1971-2014. Then the Tapio decoupling index is employed to identify the long-run decoupling between energy intensity and economic development. The Logarithmic Mean Divisia Index (LMDI) is then used to assess the potential energy savings attributed to energy intensity reduction by 2060 under the middle-of-the-road Shared Socioeconomic Pathway (SSP2) scenario. Policy implications specific to region groups are discussed in a subsequent section. Conclusions and future research prospects are also proposed.

4.2 Methods

4. 2.1 Energy intensity in the residential and commercial building sectors

The residential energy intensity (per floor area) is defined as:

$$EI_R = \frac{E_R}{F_R} \qquad (1)$$

where EI_R represents the residential energy intensity (MJ/m^2), E_R is the energy consumption in the residential sector (MJ), F_R is the floor area of residential buildings (m^2) as calculated by equation (2).

$$F_R = \sum_m \left(\sum_n \left(Pop_{m,n} * Fcap_{m,n} \right) \right) \qquad (2)$$

where m and n denote the building type and area type, $Pop_{m,n}$ and $Fcap_{m,n}$ represent the population and floor area per capita in each type of residential building and area, respectively. The residential building types considered represent detached houses, semi-detached houses, apartments, and high-rise buildings. Area types are urban and rural. The hierarchy of residential building and area types is illustrated in Figure S1. The commercial energy intensity is defined as:

$$EI_C = \frac{E_C}{F_C} \qquad (3)$$

where EI_C represents the commercial energy intensity (MJ/m^2), E_C and F_C are the energy consumption (MJ) and floor area (m^2) in the commercial sector, respectively.

$$F_C = \sum_k \left(Pop_k * Fcap_k \right) \qquad (4)$$

where k denote the commercial building type, Pop_k and $Fcap_k$ represent the population and floor area per capita in each type of commercial building. The hierarchy of commercial building types is illustrated in Figure S1.

4.2.2 Decoupling analysis of energy intensity and economic growth

Decoupling of energy use from a growing economy is necessary if economic development is to continue while meeting sustainability goals across many rapidly-growing regions[19]. Decoupling is often characterized by relative or absolute decoupling[20]. Relative decoupling means that growth in an environmental indicator is lower than the economic indicator, while absolute decoupling indicates that the environmental indicator shows negative growth, i.e.

reduces, regardless of the trend in economic growth. This decoupling framework is straightforward to calculate but fails to capture more diverse decoupling states[21]. Tapio[22] further refined the decoupling framework by distinguishing eight intermediate decoupling states, among which strong decoupling equates to absolute decoupling (see details in Figure S4). The Tapio decoupling index is widely used in industrial sectors to depict decoupling trends between an environmental variable A and an economic variable B[23]. The index is defined as the percentage change of A divided by the percentage change of B over a specific period. Here GDP per capita is used as the economic indicator that influences energy use in residential buildings. According to previous studies[24], the economic output of the service industry mainly originates in commercial buildings. As such, the economic development of the commercial sector is represented by the economic output of the service sector, termed as Service Value Added (SVA).

The Decoupling Index (DI) of A from B during $[t_1, t_2]$ can be calculated as follows:

$$DI_{A,B} = \frac{(A_{t_2} - A_{t1})/A_{t_1}}{(B_{t_2} - B_{t_1})/B_{t_1}} = \frac{\%\Delta \mathrm{A}}{\%\Delta \mathrm{B}} \quad (5)$$

Therefore the DI of residential energy intensity (EI_R) from GDP per capita (GDP_{cap}), denoted by DI_R , can be calculated as:

$$DI_R = \frac{(EI_R^{t_2} - EI_R^{t_1})/EI_R^{t_1}}{(GDP_{cap}^{t_2} - GDP_{cap}^{t_1})/GDP_{cap}^{t_1}} = \frac{\%\Delta EI_R}{\%\Delta GDP_{cap}} \quad (6)$$

The DI of commercial energy intensity (EI_c) from SVA per capita (SVA_{cap}), denoted by DI_C, can be calculated as:

$$DI_C = \frac{(EI_C^{t_2} - EI_C^{t_1})/EI_C^{t_1}}{(SVA_{cap}^{t_2} - SVA_{cap}^{t_1})/SVA_{cap}^{t_1}} = \frac{\%\Delta EI_C}{\%\Delta SVA_{cap}} \quad (7)$$

The decoupling status can be characterized in eight ways according to the triplet of values of ΔA, ΔB, and DI [22], as shown in Figure S4. Among these, strong decoupling (where $\Delta A<0$, $\Delta B>0$) followed by weak decoupling (where $\Delta A>0$, $\Delta B>0$，$0<\Delta A/\Delta B<0.8$) are most desirable from an environmental perspective. The former indicates a decrease in energy intensity with economy rising while the latter indicates that improvements in energy intensity go faster than growth in GDP.

4.2.3 Energy saving potential from energy efficiency improvement

The Logarithmic Mean Divisia Index (LMDI) is an index decomposition analysis (IDA) often used to assess the contribution of energy intensity to energy consumption in buildings[25]. Following the existing literature, the trend in energy use in the building stock can be decomposed into three drivers: energy intensity, floor space use intensity, and activity, i.e., population (for residential energy) or SVA (for commercial energy)[17]. The residential energy consumption can be decomposed as follows.

$$E_R = \frac{E_R}{F_R} * \frac{F_R}{P} * P = \mathrm{EI_R} * \mathrm{EF_R} * \mathrm{EP_R} \quad (8)$$

where, $\mathrm{EI_R} = \frac{E_R}{F_R}$ is the energy intensity driver, $\mathrm{EF_R} = \frac{F_R}{P}$ represents building floor area per person (floor space use intensity driver), $\mathrm{EP_R} = P$ denotes population (activity driver).

The change in E_R (ΔE_R) between two given years t_2 and t_1 is decomposed by using LMDI method as follows.

$$\Delta E_R = \Delta \mathrm{EI_R} + \Delta \mathrm{EF_R} + \Delta \mathrm{EP_R} \quad (9)$$

where, $\Delta \mathrm{EI_R}$ shows the contribution of energy intensity to energy consumption in residential buildings, and $\Delta \mathrm{EX_R}$ (X=I, F, P) is calculated as follows.

$$\Delta \mathrm{EX_R} = \frac{E_R^{t_2} - E_R^{t_1}}{lnE_R^{t_2} - lnE_R^{t_1}} \ln\left(\frac{EX_R^{t_2}}{EX_R^{t_1}}\right) \quad (10)$$

The decomposition of energy consumption in the commercial sector is similarly:

$$E_C = \frac{E_C}{F_C} * \frac{F_C}{SVA} * SVA = \mathrm{EI_C} * \mathrm{EF}_C * \mathrm{ES_C} \quad (11)$$

where, $\mathrm{EI_C} = \frac{E_C}{F_C}$ is the energy intensity driver, $\mathrm{EF}_C = \frac{F_C}{SVA}$ represents building floor area per SVA (floor space use intensity driver), $\mathrm{ES_C} = SVA$ denotes the activity driver.

This transformed equation (9) into:

$$\Delta E_C = \Delta \mathrm{EI_C} + \Delta \mathrm{EF}_C + \Delta \mathrm{ES_C} \quad (12)$$

where, $\Delta \mathrm{EI_C}$ shows the contribution of energy intensity to energy consumption in commercial buildings, and $\Delta \mathrm{EX_C}$ (X=I, F, S) is calculated as follows.

$$\Delta \mathrm{EX_C} = \frac{E_C^{t_2} - E_C^{t_1}}{lnE_C^{t_2} - lnE_C^{t_1}} \ln\left(\frac{EX_C^{t_2}}{EX_C^{t_1}}\right) \quad (13)$$

This is used to quantify building energy savings from energy intensity change between 1971-2014, and 2014-2060, respectively (Section 4.1).

4.2.4 Data sources

For variables during 1971-2014, GDP (in 2010 constant US dollars), SVA (Service Value Added, in 2010 constant US dollars), and population are derived from The National Accounts Section of the United Nations[26]. Energy consumption data for residential and commercial sectors during 1971-2014 are obtained from the IEA energy balances[27].

For consistency among future variables, the population growth, economic development, and residential energy consumption by 2060 are all based on the IMAGE model [18], under the Shared Socioeconomic Pathways (SSP). Specifically, the SSP2 is used to represent the middle-of-the-road scenario in which "social, economic, and technological trends do not shift markedly from historical patterns"[28]. For energy consumption in commercial buildings, this study uses data from the IEA's Reference Technology Scenario (RTS) [3] that reflects the world's current ambitions with existing energy related commitments by countries. The energy consumption data here mainly refers to the energy used by space heating, water heating, space cooling, lighting, appliances, and cooking.

The residential floor area per person during 1971-2060 is derived from IMAGE (under SSP2)[29]. Commercial floor area per person during 1971-2050 is derived from Deetman et al[30] and then extended to 2060 using the regression approach developed in the same study. Deetman et al[30] assumed a time-independent Gompertz-type relationship between the per capita Service Value Added and per capita commercial floor area. Such Gompertz curves are widely used for housing floor space estimates[29]. The calculation of residential and commercial building floor area is based on the python codes developed by Deetman et al[30]. See detailed floor area data in the Supplementary data.

The number of building energy efficiency policies in different groups is estimated based on IEA's Energy Efficiency Policies and Measures Database[31]. As listed in Table 4.1, the 21 global regions include 7 high-income regions, 8 upper-middle-income regions, and 6 lower-middle-income regions according to the World Bank Atlas classification[32].

Table 4.1. Region classification and regional abbreviations

Income group	**Regions**
High-income (HI)	Canada, United States, Western Europe, Central Europe, Korea region, Japan, Oceania (CA, US, WE, CE, KR, JP, OC)
Upper-middle-income (UMI)	Mexico, Brazil, Other America, South Africa, Turkey, Middle East, China region, Southeast Asia (MEX, BR, OA, SA, TU, ME, CN, SA)
Lower-middle-income (LMI)	Northern Africa, Rest of Southern Africa, Western & Eastern Africa, India, Rest of South Asia, Indonesia region (NA, RSA, WEA, IN, RSAS, ID)

4.3 Results

4.3.1 The evolution of energy intensity in global building sectors during 1971-2014

On the global level, residential energy intensity exhibited a clear downward trend from 897 to 476 MJ/m^2 between 1971 and 2014 (with some small fluctuations). However, diverging trends were observed across regions and income groups, with most high-income regions continuously decreasing their energy intensity (see solid lines in Figure 4.1), most lower-and upper-middle-income regions experienced an increase during the beginning decades (dashed lines) or even the whole study period (dotted lines). In the high-income group, Canada (CA), the United States (US), Oceania (OC), and Western Europe (WE) reduced their residential energy intensity by 60%, 53%, 39%, and 29%, respectively over the period. One exception is Japan (JP), where residential energy intensity increased during 1971-2005 and decreased slightly after. This can be partially explained by the already low energy intensity compared to other high-income regions. Similar patterns of first increasing then decreasing intensities were observed in most lower- and upper-middle-income regions including Mexico (MEX), Other America (OA), Western & Eastern Africa (WEA), Middle East (ME), Southeast Asia (SAS), Indonesia region (ID). It is noteworthy that the China region (CN), India (IN), and Brazil (BR), as three of the largest emerging economies, also continuously decreased their residential energy intensity, showing the positive impact of their energy efficiency policies. In comparison, in poorer regions such as Western & Eastern Africa (WEA) and Rest of Southern Africa (RSA), the per floor area residential energy intensity was very high, which was likely due to insufficient energy efficiency policies [31]. Similarly, Northern Africa (NA) and Rest of South Asia (RSAS), the other two lower-middle-income regions, saw no peak by the end of the period.

Commercial building energy intensity, while significantly higher than the residential sector, also demonstrated dramatic declines globally (in spite of a slight initial increase). The differences among regions and income groups were more significant than those in the residential sector. On average, the high-income group reduced energy intensities by 50%, while upper-middle and lower-middle groups increased intensities by 193% and 44%, respectively. Most high-income regions saw continuously decreasing commercial energy intensities from 1971 to 2014, with Canada, the United States, Western Europe, and Oceania having more than halved their intensity values. On the contrary, the increasing trend continued in many lower-and upper-middle-income regions, led mainly by Asian regions such as the Indonesia region, Turkey, Southeast Asia, and China region, where commercial energy intensities more than tripled over the period 1971- 2014.

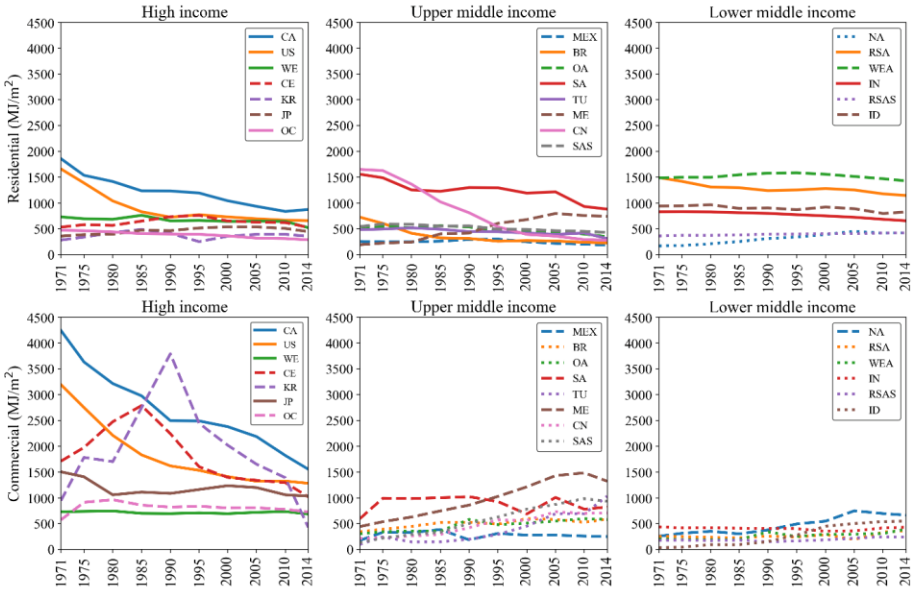

Figure 4.1 The evolution of regional building energy intensity per floor area during 1971-2014. The solid lines represent regions where energy intensities continuously decreased during the study period. The dashed lines represent regions where energy intensity peaked after a long increase. Finally, the dotted lines represent regions whose energy intensity did not peak by the end of the period. Full region names and countries in each region are listed in Table 4.1 and Table S1 in the Supplementary Information.

Further analysis here examines the intensity change by fuel types (Figure 4.2), which is generally characterized by an increase in electricity and a decrease in coal, oil, and biofuel products. The decline of residential energy intensity was mainly driven by fossil fuels (especially oil and coal products) in high-income regions and biofuels in lower-and upper-middle-income regions. This is likely due to the switch from oil and coal to renewables in high-income regions[33] and rapid urbanization in lower-and upper-middle-income regions, with biomass being the principal fuel form for developing rural communities[34].

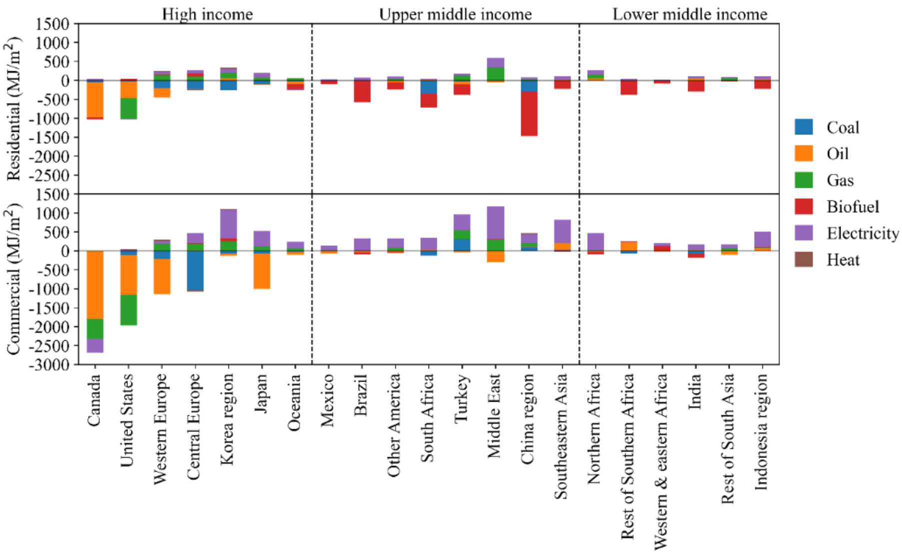

Figure 4.2 Change in energy intensity per floor area by different energy resources in residential and commercial sectors during 1971-2014

As for the commercial sector, electricity intensity increased for all regions excluding Canada, which already had the highest intensity at the start of the period. However, in high-income regions, the intensity increase of electricity was compensated by the intensity decrease in fossil fuels. The Korea region saw the only exception, with a marked increase in the intensity of electricity, gas, and biofuels. This increase was mainly seen during the first half of the study period, which then shifted into a long decrease (Figure 4.1). In the lower-and upper-middle-income regions, increases in electricity intensity were not offset by decrease in other fuels. Instead, increases in gas and oil intensity were also commons. Overall, the largest increase in commercial energy intensities was seen in upper-middle-income regions, mostly in Asian regions such as the Middle East, Turkey, and Southeast Asia.

Note that electricity, as a form of secondary energy, is generated from primary energy. Despite regional divergence, over 60% of global electricity was produced by fossil fuels, of which coal's share was roughly constant between 1974-2014, oil decreased and natural gas increased (Figure S2). The change in electricity use intensity is further translated into the change in coal, oil, gas, and biofuels (Figure S3). The patterns examined in the residential sector remain largely unchanged because the electricity intensity changes in residential buildings were insignificant. However, the increase in electricity intensity in commercial buildings can indirectly increase fossil fuel intensities (depending on the generation mix), which could offset reductions in the direct use of fossil fuels on-site. For example, the direct decrease in coal intensity across commercial buildings in Korea, Japan, South Africa, and India was converted into a net increase after accounting for electrification and associated upstream/indirect fossil fuel use. Along with increasing efficiencies and further electrification, a transition towards greener electricity is also critical to primary energy savings.

4.3.2 Energy intensity and economic growth decoupling

Regional decoupling indexes for energy intensity are presented in Figure 4.3 (full details are available in Table S2). For ease of inspection, three decoupling categories, i.e., strong decoupling, weak decoupling, and other decoupling states (see full states in Figure S4), are illustrated. Here three main findings are highlighted.

Firstly, decoupling status has improved over the period for most regions. In the first period (1971-1981), strong decoupling was observed in only a few regions, mainly in the high-income group (especially in commercial sectors). Several regions saw weak decoupling, mainly due to rapidly growing economies with energy intensity increasing more slowly. Regions fitting this characteristic include Other America, Central Europe, Southeast Asia, and Japan. In the final period (2004-2014), most regions strongly decoupled their energy intensity in both residential and commercial sectors. This is likely due to the gradual effects of increasingly deploying energy efficiency strategies.

Second, the decoupling status in residential buildings is generally deeper than that in commercial buildings. During the final years of the investigation (2004-2014), residential energy intensity in 20 out of 21 regions had strongly decoupled from economic growth, the remaining region from the lower-middle-income group also weakly decoupled. By contrast, only 13 regions achieved strong decoupling in their commercial sectors and 2 regions failed to weakly decouple. This might be due to industrial development patterns, i.e., some countries transition to service industries much later and only after the economy has passed through an industrializing process. This development pattern is especially applicable to China, India, and Brazil, the largest emerging economies in the world.

Third, building energy intensities of high-income regions decoupled earlier and more strongly from economic development. Some of the highest-income regions, i.e., the United States and Canada, succeeded in achieving strong decoupling after 1971. Strong decoupling was also observed, but only later in Western Europe, Oceania, and Japan. Many lower-and upper-middle-income regions achieved strong decoupling only recently and several saw no strong decoupling over the period. This could be due to two reasons: firstly, high-income economies invested more to improve the energy use performance of buildings via technological improvements and house renovation, while lower-and upper-middle-income regions were still building a large amount of less efficient buildings; and, secondly, many lower-and upper-middle-income regions were still increasing energy use in pursuit of higher indoor living quality, which was probably accomplished in advanced countries previously.

Strong decoupling | Weak decoupling | Other states

Region	Period	Residential $DI_R = \Delta EI_R\% / \Delta GDP_{cap}\%$				Commercial $DIc = \Delta EIc\% / \Delta SVA_{cap}\%$			
		1971-1981	1982-1992	1993-2003	2004-2014	1971-1981	1982-1992	1993-2003	2004-2014
HI	Canada	-1.38	-0.86	-0.82	-0.79	-0.92	-1.67	-0.32	-2.06
	United States	-2.34	-1.16	-0.48	-0.88	-1.36	-1.22	-0.49	-0.64
	Western Europe	-0.36	0.18	-0.17	-4.23	-0.61	-0.63	-0.41	-1.18
	Central Europe	0.19	-3.32	-0.52	-0.48	1.08	-21.98	-0.71	-0.80
	Korea region	0.75	-0.28	0.94	-0.16	6.34	0.57	-0.79	-0.94
	Japan	0.31	0.25	0.47	-2.98	-0.47	-0.15	0.57	-2.86
	Oceania	-0.49	-0.22	-0.61	-1.10	2.69	-0.23	-0.04	-0.85
UMI	Mexico	-0.10	-4.89	-1.72	-3.28	1.75	45.49	-0.68	-1.14
	Brazil	-0.69	-4.39	-1.08	-0.63	0.51	1.09	0.40	0.01
	Other America	0.20	-38.57	-0.59	-1.00	0.88	24.23	2.37	-0.02
	South Africa	-7.79	-1.52	-0.79	-1.58	5.00	2.21	-0.35	-0.60
	Turkey	0.10	-0.47	-0.87	-0.41	1.96	2.25	11.80	1.39
	Middle East	5.12	-5.58	3.83	-0.04	0.73	-2.28	1.88	-0.06
	China region	-0.49	-0.40	-0.36	-0.17	0.20	0.51	0.06	-0.02
LMI	Southeastern Asia	0.17	-0.18	-0.23	-0.21	2.18	2.26	1.13	0.17
	Northern Africa	0.88	8.41	0.92	-0.09	0.66	0.71	1.07	-0.17
	Rest of Southern Africa	0.70	1.37	0.05	-0.21	0.52	-17.53	-0.78	1.30
	Western & eastern Africa	0.74	-0.55	-0.21	-0.17	-0.30	-7.66	1.14	0.62
	India	-0.05	-0.11	-0.15	-0.16	0.05	0.01	-0.08	0.25
	Rest of South Asia	0.28	0.22	0.17	0.06	-0.17	-0.28	0.88	0.44
	Indonesia region	0.00	-0.06	0.15	-0.17	1.85	1.88	6.32	0.14

Figure 4.3 Decoupling indexes (DI) of energy intensity and economic growth in the residential and commercial sectors

Turning to energy types, significant differences are observed between electricity and non-electricity resources (as shown in Figure 4.4 and Figure S5). Electricity use intensity was tightly coupled with economic growth in most regions before 2000, for both residential and commercial buildings. By the final period 2000-2014, only high-income regions saw strong decoupling. Most lower- and middle-income regions saw consistent rising electricity intensity in building sectors, with rapidly developing Asian regions seeing the largest increases. For example, the Indonesia region experienced a more than twenty-fold increase in electricity consumption per floor area, with a roughly ten-fold growth of economic output. This might be attributed to the increase in household appliances (especially air-conditioning) demand, as well as increasing electrification[35]. By comparison, almost all regions strongly decoupled their non-electricity energy intensity from their economic development during the whole study period. The only exception is the commercial energy intensity in the upper-middle-income regions, presently experiencing weakly decoupling in a trend that became stronger over the period. The continuous reduction of non-electricity energy intensity is broadly due to the decreasing consumption of traditional fuels for heating and cooking purposes[36], which is also an achievement of the expansion in electrification[37].

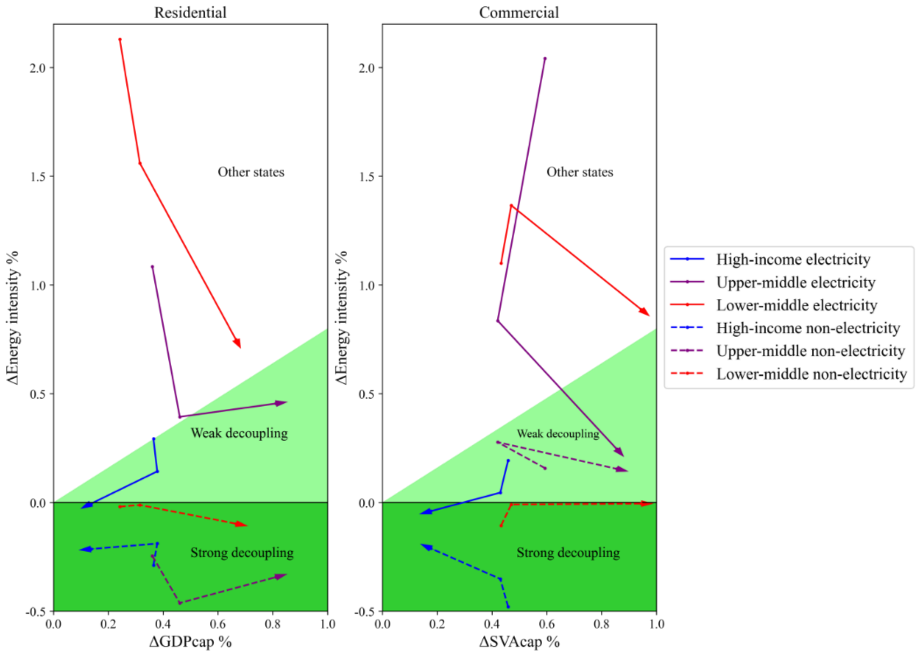

Figure 4.4 The state map of decoupling between energy intensity and economic development. Left: the change of the decoupling index (DI) of residential energy intensity (ΔEr/Fr) from GDP growth (ΔGDP_{cap}); Right: the change of DI between commercial energy intensity (ΔEc/Fc) and Service Value Added growth (ΔSVA_{cap}). Each line shows three data points representing the time periods of 1971-1985, 1985-2000, 2000-2014, respectively. The changing directions in all groups (blue for high-income, purple for upper-middle-income, red for lower-middle-income) are shown by the arrows. The solid lines represent the electricity intensity and the dashed lines represent the non-electricity energy.

In sum, most regions managed to decouple their building energy intensity by varying degrees. However, electricity and non-electricity energy resources show very different decoupling trends. This can be explained by two reasons. From the consumption side, there was an increase in cooling and digital needs, mainly satisfied by electricity, and a decrease in heating demand related to other fuels. From the supply side, decarbonization efforts and phasing out of traditional biofuels drove electrification and energy efficiency improvements.

4.4 Discussion

4.4.1 The potential contribution of energy intensity changes to energy savings by 2060

Globally, around 28 exajoule (EJ; 1 EJ = 10^{18} J) of residential energy (equal to 30% of the total in 2014) can be saved during 2014-2060 as a result of efficiency improvements, which is slightly smaller than during 1971-2014 (32 EJ), as shown in Figure 4.5. The role of energy intensity in residential energy savings varies significantly across regions and income-groups (Figure 4.6, and Figure S6-S9 in the Supplementary Information). The high-income group has limited energy saving potential during 2014-2060, perhaps due to limited options for further efficiency improvement in the SSP2 scenario with no marked shift expected in socioeconomic and technological systems. Most of the efficiency-driven energy savings are to be gained in the lower-middle-income regions, especially in the rapidly growing African and Asia regions, with Western & Eastern Africa and India being the top two hotspots. This is mainly due to the large room for energy efficiency improvements in the fast-expanding residential stocks to shelter a rising population and bigger houses. Unlike other emerging middle-income regions (which expect a decline in energy intensity), China is likely to witness a significant increase in the residential energy intensity during 2014-2060 (from 278 to 370 MJ/m^2). This is likely due to the fact that the energy intensity in the China region is very low at present, so it could still climb (driven by the desire for increased indoor living quality) faster than any technological improvements. Therefore, more investment and strict policies are needed to improve energy-saving performance, especially in the efficiency of cooling systems[38] and digital appliances[9] in residential buildings.

By comparison, potential energy savings from efficiency improvements in commercial buildings (28.9 EJ) overtakes those in residential buildings between 2014 and 2060 (Figure 4.5). This is mainly because commercial energy intensity could significantly decrease by 467 MJ/m^2 (from 911 to 444 MJ/m^2), while the residential energy intensity may only slightly decrease from 498 to 383 MJ/m^2. Also note that the commercial building sector may triple the floor area from 33970 to 114834 km^2 during 2014-2060, which makes commercial energy savings increasingly important.

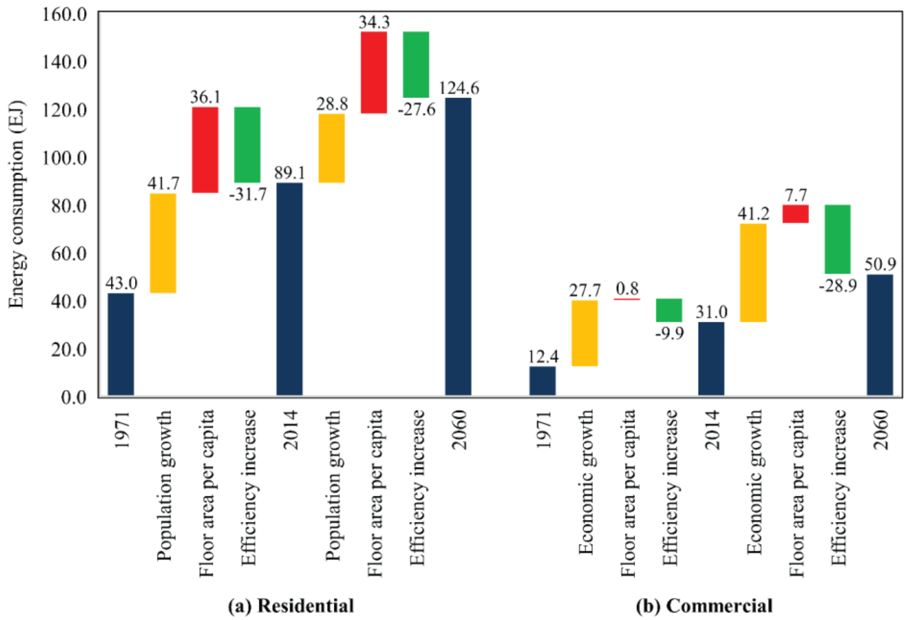

Figure 4.5 Decomposition of change in residential (a) and commercial (b) energy consumption

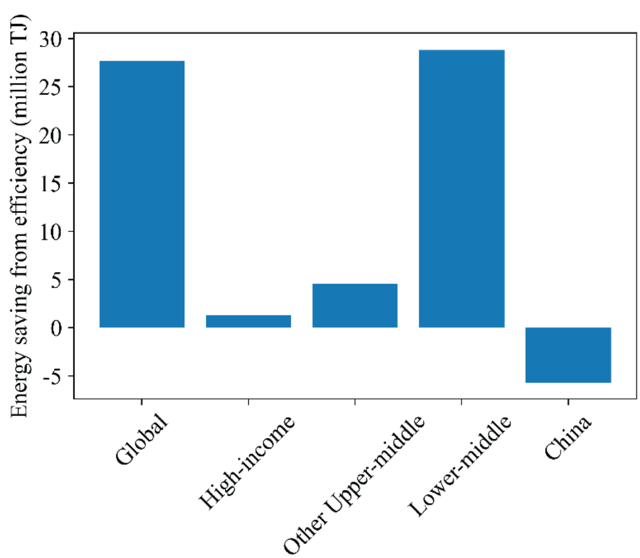

Figure 4.6 Energy savings via improved energy efficiency for residential buildings between2014 and 2060. Regions included in each group are shown in Table 4.1.

4.4.2 Policy implications

This study analyses historical trend, decoupling status, and the future potential of energy intensity per floor area for 21 global regions categorized into 3 income groups. In the residential sector, most regions already saw a peak in energy intensity and decoupling between energy intensity and economic growth before 2014, indicating the decreasing trends were likely to continue. However, results also show that there is limited room for energy efficiency improvement in residential buildings under the SSP2 scenario without dramatic social, economic, and technological shifts. Most of the future potential for efficiency-driven residential energy saving lies in lower-middle-income regions, especially in rapidly urbanizing African and Asian regions. One often-overlooked reason is that the current residential energy consumption per floor area in the lower-middle-income regions is as high as that in the high-income regions, probably due to the wide usage of low-efficiency appliances and buildings, and therefore has larger reduction potentials (Figure 4.1 and Figure 4.6). In terms of the commercial sector, energy intensity across many regions did not exhibit a peak and achieved only weaker decoupling. As expected, potential efficiency-driven energy savings in the commercial sector are slightly higher than in residential due to the larger reduction potential of energy intensity and a sharp increase in the floor area.

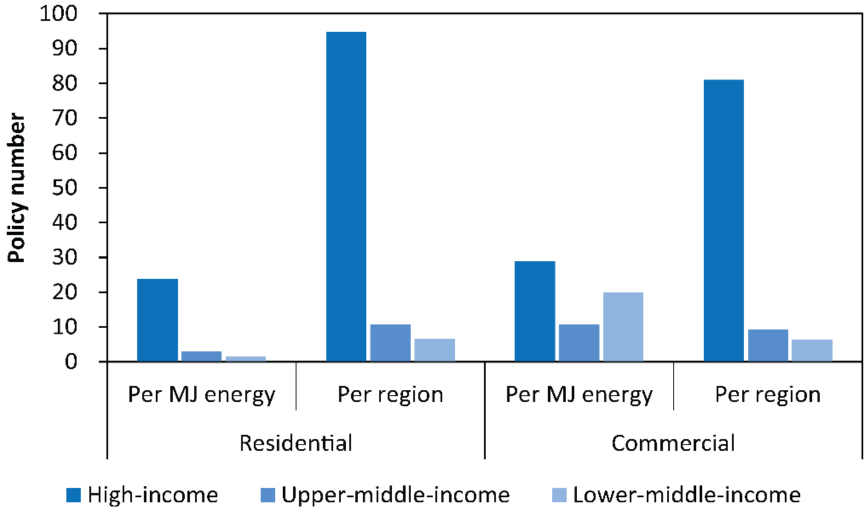

Figure 4.7 The average number of building energy efficiency policies per MJ energy and per region in each income group. Source: Own estimation from IEA's Energy efficiency Policies and Measures Database[31]. For policy number counting, only in-force policies are considered. The building energy efficiency policies and those multi-sectoral energy efficiency policies related to the buildings are all included. Regions included in each group are shown in Table 4.1.

Figure 4.7 illustrates a wide variation in the number of policies concerning building energy efficiency in different income groups. There seems to be a direct correlation between energy intensity change and the number of building energy efficiency policies, indicating the significant payoff of the in-force efforts. To curb energy demand growth in the building sector, locally customized policies are required according to the region and type of development.

In general, for high-income regions, energy efficiency policies have effectively reduced the energy intensity in the past decades, but their further potentials seem to be limited under the current strength. More ambitious energy reduction goals require stronger actions to achieve a drastic shift in socio-economic and technological systems. Further efficiency gains could be obtained by greener lifestyles[39] and ongoing zero-energy initiatives[40]. At the same time, deep renovations of existing buildings are especially important in highly urbanized regions where most buildings that will be still standing in 2060 have already been built.

In middle-income regions, current policy efforts to improve building energy efficiency are not sufficient to offset the demand growth. As such, there are large potentials in energy savings through policy enhancement. In particular, in most emerging African and Asian regions, where building infrastructure is predicted to increase rapidly, strict building efficiency standards for new buildings should be implemented as soon as possible, to avoid costly retrofits (and lock-in). By adopting modern construction technologies and principles, emerging regions have the opportunity to avoid accumulating a stock of inefficient buildings[41]. Concerning the high level of coupling between electricity use and economic growth in lower-middle-income regions, special attention should be paid to more efficient air-conditioners and other electricity-use appliances which may see high demand in the coming decades[9].

4.5 Conclusions and prospects

This study provides a comprehensive investigation of the historical trends in building energy intensity, its relationship with economic development, and the future role of energy intensity improvements regionally. Energy efficiency has been significantly improved over the past decades in both residential and commercial buildings and has generally decoupled from economic growth. However, the study shows that future gains in efficiency will require more aggressive policies. In the context of addressing climate change, an ambitious improvement of the energy intensity of buildings is required in parallel with an energy transition towards emission-free electrification.

Further extensions to this work could integrate the influence of urbanization trends on energy use per unit of floor area. In some rapidly developing regions, the energy use of some appliances (e.g., lighting and electronic equipment) has not increased as fast as the expanding floor area per household. In other words, larger homes with the same appliances. This leads to a 'dilution effect', i.e., a decline in energy use per floor area even in the absence of technological improvements in energy-saving[14]. This dilution effect should be quantified so that energy use per square meter can be more reliable as an efficiency measurement.

Another area for future investigations is the impact of climate change on energy use per unit of floor area. Global warming generally increases cooling and decreases heating demand in buildings. While the increment of cooling may overtake the decrease in heating in most regions, there are exceptions in heating-dominated regions like Canada and Russia[42]. That is, even with no energy efficiency change in buildings, the energy intensity changes over time in different directions and by varying extents.

A final suggestion for future work is the investigation of potential trade-offs between operational and embodied energy intensity. Previous studies have explored the trade-off between the embodied and operational emissions in specific buildings regarding different material choices and construction methods. This could be expanded more broadly to larger-scale analyses.

4.6 Supplementary data

See details online:
https://www.sciencedirect.com/science/article/pii/S0959652621013172#appsec1

4.7 References

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Chapter 5: Embodied emissions from building materials at risk of climate-driven flooding hazards in Europe

This chapter is based on the manuscript Embodied emissions from building materials at risk of climate-driven flooding hazards (Zhong, X., Fishman, T., Behrens, P.). In preparation for submission to Nature Climate Change.

Abstract

Climate and land-use changes have driven an increasing risk of extreme flooding events to life and infrastructure. These events may drive large material losses and associated embodied emissions. Here we map building materials at risk of flooding hazards and material-related greenhouse gas (GHG) emissions across 49 European countries under current and future climate-change and land-subsidence. We show that currently 11.7 Gt of building materials, or 11.6% of those in-use, are at risk of a 1-in-100-year flooding event. Expected annual damage (EAD) to building materials, in the absence of flood protections, reaches 329 Mt per year, equivalent to ~109 MtCO_2eq per year of embodied GHG emissions. With assumed current flood protection standards fully in place, the current emissions from EAD are reduced by nearly 92% (~100 MtCO_2eq, nearly 20% of the current annual building material related emissions in Europe). Emissions see an increase of 71% to 180 MtCO_2eq per year in 2080 under a high-emission climate scenario (RCP 8.5). Climate mitigation from RCP 8.5 to RCP 4.5 reduces these embodied emissions by 25 MtCO_2eq (14%) to 147 MtCO_2eq per year. Overall, we show that climate mitigation and flood protection are crucial in reducing material losses and embodied emissions.

5.1 Introduction

Buildings provide basic needs for shelter, survival, and well-being[1-3]. Adequate housing for all is an essential Sustainable Development Goal (Goal 11) of the United Nations[4]. The development of new buildings uses about half of the world's mineral materials (nearly 20 Gt)[5-7] and sees investment of 6 trillion USD (7% of GDP)[8,9] annually. Material extractions and financial investments are expected to only increase in meeting the demands of growing consumption and populations[7,10,11]. However, material extraction and production at such scales have contributed to major climate and ecological impacts and present a significant challenge to multiple national and international targets[12-18].

Natural hazards present major risks to numerous established buildings and proposed new infrastructure globally. For instance, the 2022 deadly flooding in Pakistan destroyed more than 1.2 million houses and thousands of kilometers of road and hundreds of bridges[19]. The devastating 2021 European floods damaged tens of thousands of homes across Germany, Belgium, and the Netherlands. Over half of US building stock is estimated to be at risk of potentially catastrophic natural disasters (i.e., earthquakes, floods, hurricanes, tornados, and wildfires) and 1.5 million buildings are located in hotspots of two or more disasters[20].

Floods represent the most prevalent and costly natural hazards globally[21], accounting for nearly half of total disaster events reported over the past two decades[22] and over 70% of modelled hazard-related damages to transport infrastructures (among earthquakes, cyclones, and floods)[23]. Global flooding is expected to intensify with climatic changes and land-use change (e.g., vegetation clearing and subsidence)[24-26], posing an increasing threat to buildings. Flood impacts on buildings and materials are also especially severe in lower-income regions where buildings are less developed, have lower protection[27,28], and which face disproportionate increases in flooding risk[24,29].

These combined trends may cause substantial material losses to floods, a need for repairing and rebuilding, and additional material-related environmental impacts such as GHG emissions, further threatening local and global climate targets. Previous studies have explored flood risks on population[21,25-29] and the economy[25,29-35]. However, none have evaluated flooding impacts on actual materials and embodied emissions due to a lack of high-resolution geospatial information on how in-use building stocks and major types of materials consisting them are distributed on large scales from continental to global[36,37]. Recent advances in computational, digital and earth observation technologies (e.g., satellite-derived night-time lights) have given rise to new possibilities for such assessments[38,39].

Here we make the first step by estimating the European building materials at risk of flooding hazards and GHG emissions related to this loss under climate, land-use and flood protection scenarios. We use two types of high-resolution maps: 1) night-time lights-based building material stocks (including 6 material types for residential and non-residential buildings)[38] and 2) inundation maps of riverine and coastal floods across different return periods for the baseline (reference year 2010) and future climatic and land-use conditions - under moderate (RCP 4.5) and high (RCP 8.5) emission scenarios by 2080. We analyse the exposure of building materials to riverine and coastal flooding events, i.e., materials located in areas where inundation depth is over 0. We then estimate the expected annual damage (EAD) of building materials by further considering the full range of 9 return periods (1-in-2, -5, -10, -25, -50, -100, -250, and -1000 years) and damage probabilities given by a depth–damage function. We calculate the embodied GHG emissions of building materials for repairing and rebuilding using a life cycle assessment (LCA) approach.

A known limitation of flood risk analysis is limited information on flood protection measures especially on large scales. Existing research either do not consider any protection[27,40] or consider only roughly estimated protection standards based on proxies such as income levels[23,41]. In this study, we calculate current EAD and embodied emissions in two scenarios: in the absence of flood protection and the implementation of estimated subnational flood protection standards[41]. This allows for an estimate of the benefits of envisaged protection measures or, in other words, the cost of protection failures (please see Methods for further details on methods and data).

5.2 Results

We find that currently ~11.7 Gt of building materials (11.6% of the total building material stock) may be exposed to 1-in-100-year riverine (11.4 Gt) or coastal (1.2 Gt) flooding events in 45 out of 49 investigated European regions (the remaining are small regions not on major rivers such as the Faroe Islands, Gibraltar, Monaco, and Vatican City) (Figure 5.1). Italy, France, and the Netherlands see significant exposure (each representing over 10% of the European total), followed by Germany, Spain, and the UK. These nations have accumulated a large quantity of building stocks in coastal, large river basins or lowland areas. By mass, the main material type exposed to 1-in-100-year floods is concrete, accounting for ~80% of the total, followed by wood and steel, each responsible for nearly 8%.

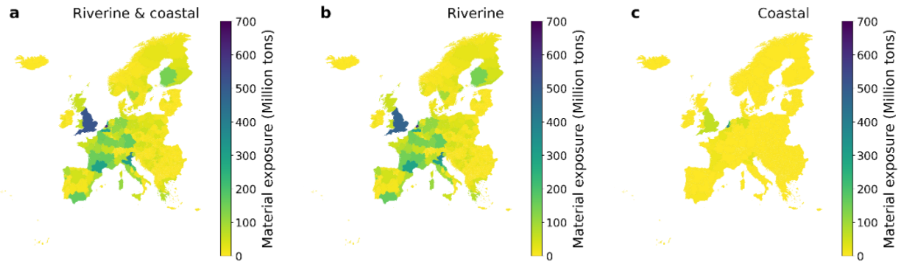

Figure 5.1 Building materials at risk of 1-in-100-year riverine and coastal flooding events under the baseline climatic conditions (reference year 2010).

In the absence of flood protection, the current EAD to building materials from riverine and coastal floods is ~329 Mt, very unevenly distributed among 41 out of 49 countries (again, regions having material exposure and no EAD are small states including Aland, Andorra, Malta, and San Marino). The highest EAD is seen in the Netherlands (185 Mt), where land is generally lower and flood depth can be much higher than other nations seeing similarly high material exposure values. This is why the Netherlands is developing some of the best flood protection systems in the world that have largely reduced the risks[42]. Germany (23 Mt), France (20), Italy (18), and Spain (17) all have EADs of over 10 Mt.

Climatic and land use changes (such as subsidence) are likely to significantly impact the EAD of materials in coming decades. Not considering flood protections, the overall EAD is likely to increase by 46% under moderate emissions (RCP 4.5, including land subsidence), reaching 482 Mt of material in 2080 (material stocks modelled at the current level, see Methods) (Figure 5. 2). High emissions (RCP 8.5) will further increase the EAD to 557 Mt in 2080. Regional EAD trends vary widely, with 22 regions increasing (in absolute terms led by the Netherlands, Italy, and Germany) and 19 regions decreasing (in absolute terms led by Spain, Greece, and the Czechia) under RCP 4.5. Particularly pronounced increases are seen in Jersey, Cyprus, Belgium, Ireland, Denmark, and Lithuania, which may more than double their EADs.

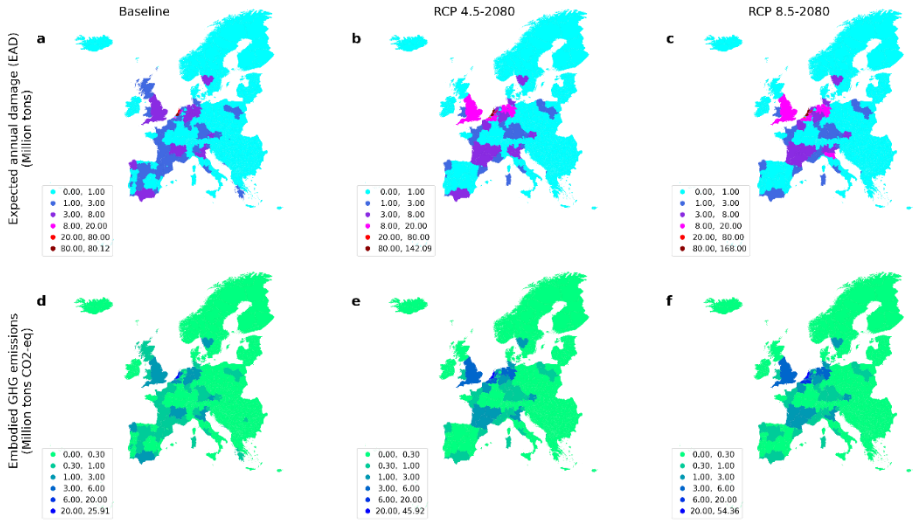

Figure 5.2 Expected annual damage (EAD) of building materials from riverine and coastal flooding hazards in the absence of flood protection (in Mt) and embodied greenhouse gas (GHG) emissions (in Mt CO_2eq). **a-c**, EAD under the baseline (reference year 2010) and future climatic and land use conditions. **d-f,** GHG emissions from the production of materials equivalent to the EAD across scenarios.

The current EAD of building materials without considering flood protection, if remanufactured in the same quantity and type to repair and reconstruct, is associated with ~106 Mt CO_2eq of GHG emissions (Figure 5.2d), with steel (58%), concrete (33%), and wood (6%) being the main emitters. These emissions see an increase by 47% and 71% to 156 and 180 Mt CO_2eq, respectively, under moderate (RCP 4.5) and high (RCP 8.5) emission scenarios by 2080. This demonstrates the scale of embodied GHG emissions that can be avoided through ultimate protections.

In general, there is a lack of accurate fine-scale datasets of flood protection measures due to limited information on existing protection and the fact that flood protection implementation is by nature a highly dynamic process. However there is an evolving global database[41] available with sub-national protection standard estimates (based on literature or income levels). Assuming these potential flood protection standards across Europe, results in embodied GHG emissions are almost 92% lower when compared to no flood protection (Figure 5.3). The reduced emissions, ~100 Mt CO_2eq per year, are almost 20% of the building material related emissions in Europe in 2020 (assuming that building materials were responsible for 11% - the share of global building materials in global total GHG emissions[11] - of total GHG emissions in Europe). This highlights the vital role of flood protection measures in mitigating material losses and regional emission pressures in addition to the widely recognised / verified benefits of livelihood and economic savings[29,35,43].

Regional reductions vary significantly. With estimated flood protection standards implemented, we find > 95% EAD reductions in the Netherlands, Denmark, Iceland, Belgium, and the UK, whereas over half of the EAD remains in 14 regions such as Bosnia and Herzegovina, Albania, Bulgaria, Montenegro. In general, lower-income regions have significantly less developed flood protection systems[27,41] as designing and maintaining long-term adaptation strategies can be complex and costly[44,45].

International cooperation in technology and investment are thus important to address flooding risks in lower-income regions. An example of such development is the “loss and damage” funding developed at the 27th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27), which may help address flooding risks and losses in lower-income nations suffering severe climate impacts. In addition, local geographic and socio-economic conditions need to be considered to select resource-and cost-effective flood protection measures[44]. Overall, against future climate and land use changes, flood protection standards need to be upgraded in many regions especially in those having low-level protections (mainly in poorer regions) and those that may have higher protection standards but see intensified flooding hazards (such as the Netherlands)[46].

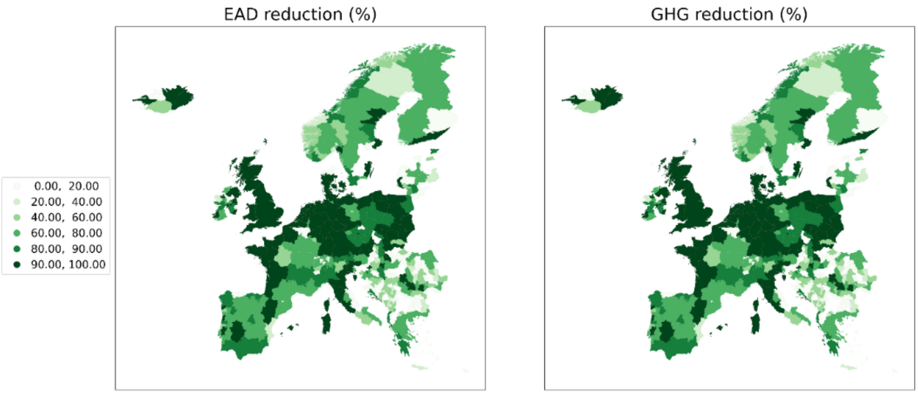

Figure 5.3 Percentage reduction in current expected annual damage (EAD) of building materials and embodied greenhouse gas (GHG) emissions for simulations run with assumed current flood protection standards compared to no flood protection.

In addition to strengthening flood protection measures, increasing flood hazards call for a systematic transformation in the built environment. First, future urban planning and real estate investment decisions should consider hazard hotspots and climate outcomes, avoiding urban planning failures such as accumulating cities and homes in flood-prone areas as seen around the world in the past decades[20,21,47,48]. Further, the next generation of engineers will need to build resilience into buildings during construction[49]. For example, structures designed to allow water entry and exit[50], foundations with higher depth and corrosion resistance[51], waterproof materials[52] may significantly help buildings survive flooding. Finally, flood-prone regions should develop waste management protocols to properly and efficiently inventory and dispose of construction materials post-disaster[53,54]. Dedicated efforts are needed to reduce harm and pollution, accelerate reconstruction and rehabilitation, and make sure the right type of impacted materials can be sorted and recovered[54,55].

Overall, the framework presented in this work may be used to map flooding impacts on building material stocks and embodied emissions on multiple scales. Our ongoing efforts are dedicated to conduct a high-resolution global analysis. A future improvement is to consider the trend of building material stocks over time, driven by socioeconomic changes, which is especially important for rapidly developing countries where the majority of homes in 2080 are to be built. Another improvement is to estimate the net emission savings from flood protection measures. To this end, embodied emissions of flooding protection infrastructure such as dikes are to be assessed. Finally, we propose that future cost-benefit analysis of flood protections need to also incorporate avoided GHG emissions given a rapidly shrinking emission budget.

5.3 Method

Flood under scenarios

We used global riverine and coastal flood maps from the Aqueduct Floods Hazard dataset (updated October 20, 2020)[56,57]. The dataset provides information on the extent and depth of riverine and coastal floods, gridded to 30 arc seconds (roughly 1 km at the equator). It provides simulated flood events for current (2010) and future projected climate conditions in 2030, 2050, and 2080 at several return periods (2, 5, 10, 25, 50, 100, 250, and 1000 years). Future climate conditions are projected based on RCP 4.5 and RCP 8.5. Future riverine flood hazards are distinguished by five global climate models (GCM): HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1-M. Future coastal flood hazards are distinguished by whether future land subsidence is considered. The dataset represents the best open-source information of the impact of future climate changes on riverine and coastal flood hazards on a global level[35,58].

Building material stocks

Material stocks of buildings used in this study are derived from ref[38]. The material dataset provides the volume of six types of building materials (concrete, steel, aluminium, copper, glass, wood; distinguished by residential and non-residential uses) located in each Nighttime Light Cell (NLC) across Europe. NLCs are distinctly shaped cells of variable sizes with the smallest composed of a single pixel of 0.1 km (i.e., isolated patches of light, surrounded by areas with no nighttime lights).

Calculation of material exposure

Materials exposure in this study define the volume of materials impacted by floods, that is materials located in a flooding area where inundation depth value exceeds 0 m. It is computed by intersecting the gridded inundated areas with building material stocks. For pixels where riverine and coastal floods overlap, we retain the higher inundation depth values of the two datasets, following the approach used elsewhere in the literature[27].

Calculation of maximum potential material damages

A fraction of materials exposed to flood hazards may be damaged. Maximum potential material damages in floods can be evaluated by combining impacted material volumes and inundation depth values that are further translated into a damage percentage via the flood depth-damage functions. The flood depth-damage functions in this analysis are derived from ref[59], a globally consistent database depicting fractional damage function of water depth across continents and building classes (residential, commercial, and industrial buildings). A further disaggregation between the material stock data (residential and non-residential) and the depth-damage function classes (residential, commercial, and industrial) is necessary. Following the literature[56], we assume that non-residential building material stocks consist of 60% commercial, and 40% industrial building materials.

Calculation of expected annual material damages

Different return periods (2, 5, 10, 25, 50, 100, 250, and 1000 years) of flood hazards represent different annual average exceedance probabilities (i.e., 1/return periods). Each impact indicator (e.g., material exposure, maximum potential material damage) is calculated per return period (probability). By considering the material damage of flooding over the full range of probabilities, flood risk can be further measured as the expected average annual damage (EAD) of building materials from flood hazards[60]. EAD is calculated using the damage-probability curve, where the flood probabilities (i.e., 1/return periods) are plotted on the x-axis and the maximum material damages on the y-axis. The area or the integral under the curve is the EAD (before incorporating flood protections; see the following paragraph). Future EADs are calculated for each of the five GCMs and the reported values in this study are the average.

Material damage from flood hazards can be reduced with infrastructure such as dikes. We account for flood protection standards by adding a vertical flood protection line[56] to the damage-probability curve, which truncates the overall area under the curve into two areas showing the protected/avoided (i.e., the area to the left of the flood protection line) and the unprotected/expected (i.e., the area to the right of the flood protection line) damages. That is, the represented damage to the right of the flood protection line is assumed as avoided (and set to zero). Current flood protection standards are derived from the FLOPROS[41], a database providing state-level flood protection estimates across the globe.

Calculation of material-related emissions

Material-related GHG emissions are equal to material production volumes required to reconstruct or repair buildings multiplied by the GHG emission factors (i.e., emissions per kg of materials production). To estimate material volumes, we assume a one-to-one replacement ratio between the new materials needed and the old materials damaged. That is, the same magnitudes and categories of building materials will be reproduced after the flood hazards to revive the impacted building stocks. The GHG emission factor for each type of materials are derived from the Ecoinvent 3.6 database[61], employing the global warming potential (with a 100-year time horizon) approach, and the 'cradle-to-gate' material production system boundary (referring to only the production of materials, from raw material extraction to the manufacturing of finished products).

5.4 Data availability

This research relies entirely on publicly available data as referenced.

5.5 Code availability

Python and R code used for the modelling is available from the authors upon request.

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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_2eq 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_2eq of GHG emissions. After introducing potential flood protection standards, these embodied emissions could be reduced by ~92% or ~100 MtCO_2eq, 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_2eq 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_2eq (14%) to 147 MtCO_2eq 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.

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Summary

Sheltering is an immediate human need and determines well-being and health. However, we face many challenges in providing homes and offices for all on this rapidly changing planet. In the 21st century, climate change, resource crises, and population expansion will combine to exacerbate existing challenges. We need to better understand and tackle these issues. Therefore, the overarching research question of this thesis is:

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

To this end, this thesis makes the first steps in exploring several key intersecting challenges related to resources scarcity, global warming, and natural hazards. Specifically, four sub-questions are investigated in Chapter 2 to 5, respectively.

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?

Chapter 2 explores future trends of building sand use in the face of the unfolding global sand crisis. A dynamic building sand model is developed and a set of different scenarios are discussed. Results show that under a middle-of-the-road baseline scenario, global building sand use (for making concrete and glass) sees a 45% increase from 2020 to 2060. Regional trends vary significantly with a nearly 300% increase in low-and-lower-middle-income regions and a slight decrease across higher-income regions. Increasing efficiencies of building and material use could nearly halve the cumulative building sand requirements globally. However, even under high efficiencies, the lowest-income African regions will still need to double their demand for building sand in 2060 compared to 2020. International cooperation on investment, technology, and resources are of great importance to address vulnerabilities and inequalities.

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?

Chapter 3 investigates the hard-to-decarbonize emissions from building material production. It assesses the changes in greenhouse gas (GHG) emissions from the production of several building materials (steel, concrete, brick, aluminum, copper, glass, and wood) in residential and commercial buildings in 26 global regions. Results shows a continuous emission increase from 3.5 to 4.6 Gt CO_2eq yr^{-1} between 2020–2060 under a baseline scenario, with a shift from high-and upper-middle-income to low- and lower-middle-income regions driven by economic, population, and urbanization trends. Nearly half these emissions may be avoided through scaling up material efficiency strategies on a global level in a high efficiency scenario. However, even under this scenario, the expected emissions from building materials are still higher than what would be compatible with the 1.5 °C climate target (if the remaining global carbon budget is allocated proportionally across sectors). In the absence of fundamental changes in manufacturing processes, negative emissions technologies are likely necessary in the second half of the century to offset process-related emissions that are challenging to avoid.

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

Chapter 4 examines the trends of energy intensity (energy use per floor area) in global building stocks. Results show that 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. While most high-income and upper-middle-income regions see decreasing energy intensities and strong decoupling from economic development, the potential for further efficiency improvement is limited in the absence of significant socioeconomic and technological shifts. Lower-middle-income regions, often overlooked in analyses, will see large potential future residential energy savings from energy intensity reductions. 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. Given the large energy intensity reduction potential and rapid floor area growth, commercial buildings are increasingly important for energy saving in the future.

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?

Chapter 5 maps how several types of building materials (concrete, steel, copper, aluminium, wood, and glass) are at risk of riverine and coastal flooding hazards in 49 European countries / regions. Results show that currently nearly 11.7 Gt building materials (~11.6% of total building material stocks) are at risk from a 1-in-100-year riverine or coastal flooding events. Countries facing the highest risk are Italy, France, and the Netherlands, generally having accumulated large building stocks along long coastal lines and river banks or in low-lying areas. Climate and land-use changes may have significant impacts on the flooding risks. Expected annual damage (EAD) is ~329 Mt in the absence of flood protection. The replacement of these materials would be ~106 Mt CO_2eq of GHG emissions. Introducing potential flood protection standards could reduce these embodied emissions by ~92% or ~100 MtCO_2eq, nearly 20% of the current annual building-material-related emissions in Europe. The EAD-related embodied emissions, not considering any flood protection, see an increase of 71% to 180 Mt CO_2eq 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 CO2eq (14%) to 147 MtCO_2eq per year. Overall, climate mitigation and flood protection are critical to reducing building material losses and embodied emissions.

We can now reflect on the above overall research question on the basis of the exploration of the sub-questions. Continued growth in population and wealth means we will need more homes and offices. The overexploitation of natural resources, reduction of emission allowance and exacerbation of natural disasters, among others, may increasingly reduce the operating space in which we provide and maintain buildings. We need to produce materials, build and maintain buildings more efficiently and wisely. 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 in a warming and resource-scarce world. Lower-income regions face larger problems, from today's housing shortages to mounting pressures from a stock expansion driven by economic and population growth including resource and investment issues 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 across the globe. Negative emission technologies (NETs) may be necessary in the longer term to achieve a global net-emission building construction industry. Buildings should be designed and constructed in a more resilient manner for longer longevity against the extreme weather and natural disasters that increase with climate change. Flood protection standards are critical to ensuring the safety of buildings against flooding events and need to be broadly strengthened. A multifaceted global strategy integrating environmental, economic and social dimensions is needed to ensure sustainable and equitable shelter security around the world.

This thesis provides several scientific and policy implications. Scientifically, we first showcase an integrated framework to systematically model global shelter security and connect it to environmental challenges. Second, we make multiple modelling advances. The models we present can be easily applied for a broad range of research purposes. As an 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. This thesis also 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, from investment decisions in urban development to building design and construction, from maintenance and renovation to end-of-life management of buildings and components. 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. We then show the need for a rise in international cooperation in technology, investment, and resources. in addressing regional inequalities, where trade agreements may play an important role in lowering barriers and increasing efficiency.

Extensions of this research could integrate more resources (such as land use and labor forces) and challenges (such as climate migrations and biodiversity issues). Other improvements may be related to modelling and data. For example, future models could integrate renovation into dynamic building models against the renovation wave of existing buildings that can be expected in the next decades and include a larger number of scenarios to explore a broader spectrum of potential futures. Dedicated efforts are needed to improve data availability and robustness for global and regional analysis.

Samenvatting

Onderdak is een essentiële menselijke behoefte en is bepalend voor het welzijn en de gezondheid. We staan echter voor veel uitdagingen bij het bieden van woningen en kantoren voor iedereen op deze snel veranderende planeet. In de 21e eeuw zullen klimaatverandering, grondstoffencrises en bevolkingsuitbreiding samenkomen om de bestaande uitdagingen te verergeren. We moeten deze problemen beter begrijpen en aanpakken. De overkoepelende onderzoeksvraag van dit proefschrift luidt dan ook:

Wat zijn de belangrijkste uitdagingen en kansen bij het bieden van fatsoenlijke onderdak voor bijna 10 miljard mensen in een opwarmende en grondstoffen-schaarse wereld?

Daartoe zet dit proefschrift de eerste stappen in het verkennen van verschillende belangrijke elkaar versterkende uitdagingen met betrekking tot grondstoffenschaarste, opwarming van de aarde en natuurlijke gevaren. Concreet worden in hoofdstuk 2 tot en met 5 respectievelijk vier deelvragen (DV) onderzocht.

DV1. Hoe zou de vraag naar bouwzand zich in de toekomst kunnen ontwikkelen in het licht van een zich ontvouwende zandcrisis en hoe kunnen we deze vraag verminderen, de milieueffecten gerelateerd aan zandwinning beperken en toch de behoefte aan woonruimte realiseren ?

Hoofdstuk 2 verkent toekomstige trends van het gebruik van bouwzand in het licht van de zich ontvouwende wereldwijde zandcrisis. Er wordt een dynamisch bouwzandmodel ontwikkeld en verschillende scenario's worden besproken. De resultaten tonen aan dat onder een gemiddeld basisscenario het wereldwijde gebruik van bouwzand (voor het maken van beton en glas) tussen 2020 en 2060 met 45% toeneemt. Regionale trends variëren aanzienlijk met bijna 300% toename in regio's met een laag- en onder-middeninkomenen een lichte daling in regio's met hogere inkomens. Toenemende efficiëntie van materiaalgebruik zou de cumulatieve bouwzandbehoefte wereldwijd bijna kunnen halveren. Maar zelfs bij hoge efficiëntie zullen de Afrikaanse regio's met de laagste inkomens hun vraag naar bouwzand in 2060 moeten verdubbelen ten opzichte van 2020.

Internationale samenwerking op het gebied van investeringen, technologie en kennis is van groot belang om deze problemen aan te pakken.

DV2. Hoe kunnen broeikasgasemissies gerelateerd aan bouwmaterialen zich in de toekomst ontwikkelen, hoe kunnen we deze emissies verminderen door middel van materiaal-efficiëntiestrategieën, en wat betekent dit voor wereldwijde klimaatdoelstellingen?

Hoofdstuk 3 onderzoekt de moeilijk te verminderen emissies van de productie van bouwmaterialen. Het beoordeelt de veranderingen in de uitstoot van broeikasgassen (BKG) door de productie van verschillende bouwmaterialen (staal, beton, baksteen, aluminium, koper, glas en hout) in residentiële en commerciële gebouwen in 26 mondiale regio's. De resultaten tonen een continue toename van de uitstoot van 3,5 naar 4,6 Gt CO2eq per jaar tussen 2020-2060 onder een basisscenario, met een verschuiving van regio's met een hoog- en boven-middeninkomen naar regio's met een laag- en onder-middeninkomen, als gevolg van economische, bevolkings- en verstedelijkingstrends. Bijna de helft van deze emissies kan worden vermeden door strategieën voor materiaalefficiëntie op mondiaal niveau op te schalen in een scenario met hoge efficiëntie. Echter, zelfs onder dit scenario zijn de verwachte emissies van bouwmaterialen nog steeds hoger dan wat verenigbaar zou zijn met de klimaatdoelstelling van 1,5 °C (als het resterende wereldwijde koolstofbudget proportioneel over sectoren wordt verdeeld). Bij gebrek aan fundamentele veranderingen in productieprocessen, zullen in de tweede helft van de eeuw waarschijnlijk technologieën voor negatieve emissies nodig zijn om procesgerelateerde emissies die moeilijk te vermijden zijn, te compenseren.

DV3. Wat zijn de wereldwijde trends in de energie-intensiteit van residentiële en commerciële gebouwen in relatie tot economische ontwikkeling en wat zijn de implicaties voor energiebesparing?

Hoofdstuk 4 onderzoekt de trends van energie-intensiteit (energiegebruik per vloeroppervlak) in de wereldwijde gebouwenvoorraad. De resultaten tonen aan dat de energie-intensiteit van woningen wereldwijd aanzienlijk is afgenomen (van 897 naar 476 MJ/m^2 tussen 1971 en 2014), met duidelijke verschillen tussen regio's en inkomensgroepen. Hoewel de meeste regio's met hoge inkomens en boven-middeninkomens een dalende energie-intensiteit en een sterke ontkoppeling met economische groei zien, is het potentieel voor verdere efficiëntieverbetering beperkt als geen verdere sociaaleconomische en technologische verschuivingen plaatsvinden. Regio's met een onder-middeninkomen, die vaak over het hoofd worden gezien in analyses, zullen grote toekomstige potentiële energiebesparingen zien door vermindering van energie-intensiteit van residentiële gebouwen. Hoewel de energie-intensiteit van commerciële gebouwen veel hoger is dan die van residentiële gebouwen, vertoont deze ook wereldwijd een dramatische daling, met grotere verschillen tussen regio's met verschillende inkomens dan die in de residentiële sector. Vanwege het grote potentieel voor vermindering van de energie-intensiteit en de snelle groei van de vloeroppervlakte, zijn commerciële gebouwen steeds belangrijker voor energiebesparing in de toekomst.

DV4. Onder huidige en toekomstige klimatologische omstandigheden, welke voorraden aan gebouwen en materialen lopen een risico op destructie door overstromingen van rivieren hoeveel 'embodied' emissies zijn met dit materiaalverlies gemoeid?

Hoofdstuk 5 brengt in kaart hoe verschillende soorten bouwmaterialen (beton, staal, koper, aluminium, hout en glas) in 49 Europese landen/regio's het risico lopen verloren te gaan als gevolg van overstromingen in rivier- en kustgebieden. De resultaten tonen aan dat momenteel bijna 11,7 Gt bouwmaterialen (circa 11,6% van de totale bouwmateriaalvoorraad) is blootgesteld aan een risico op overstromingen die zich gemiddeld eens in de honderd jaar voordoen. Landen die het grootste risico lopen zijn Italië, Frankrijk en Nederland, die over het algemeen grote bouwvoorraden hebben opgebouwd langs lange kustlijnen en rivieroevers of in laaggelegen gebieden. Veranderingen in klimaat en landgebruik kunnen aanzienlijke gevolgen hebben voor de overstromingsrisico's. De Verwachte jaarlijkse schade (VJS) is circa 329 Mt aan verloren materiaal bij afwezigheid van bescherming tegen overstromingen. De vervanging van deze materialen zou ongeveer 106 miljoen ton CO2eq aan broeikasgasemissies veroorzaken. Door potentiële overstromingsbeschermingsnormen in te voeren, zouden deze 'embodied' emissies met ca. 92% of 100 MtCO2eq kunnen worden verminderd, bijna 20% van de huidige jaarlijkse aan bouwmaterialen gerelateerde emissies in

Europa. In een klimaatscenario met hoge koolstofemissies (RCP 8.5, inclusief bodemdaling) zonder rekening te houden met bescherming tegen overstromingen, moet er een hoeveelheid materiaal vervangen worden waarvan de productie gelijk staat aan 180 Mt CO2eq per jaar in 2080 (een toename van 71%). Klimaatmitigatie van RCP 8.5 naar RCP 4.5 vermindert deze ingebedde emissies met 25 Mt CO2eq (14%) tot 147 Mt CO2eq per jaar. Klimaatmitigatie en bescherming tegen overstromingen zijn dus van cruciaal belang voor het verminderen van verliezen aan bouwmateriaal en de hieraan gerelateerde 'embodied' emissies.

Op basis van de antwoorden op de deelvragen kunnen we nu reflecteren op bovenstaande onderzoeksvraag. Door de aanhoudende groei van de bevolking en welvaart zullen we meer woningen en kantoren nodig hebben. Onder andere door de schaarste aan natuurlijke hulpbronnen, vermindering van het budget voor koolstofemissies en verhoging van het risico op natuurrampen worden de randvoorwaarden waaronder wij gebouwen construeren en onderhouden steeds stringenter. We moeten efficiënter en verstandiger materialen produceren, gebouwen construeren en onderhouden. Dit moet met grote urgentie. Daartoe moeten we eerst de belangrijkste uitdagingen in kaart brengen die van invloed kunnen zijn op het zekerstellen van onderdak op mondiale en regionale schaal. Vervolgens moeten we de beschikbare en toekomstige oplossingen voor elk van deze uitdagingen onderzoeken, de kosten en belemmeringen van de implementatie van deze oplossingen in kaart brengen, en de voor- en nadelen van de oplossingen afwegen, en zo bepalen waar investeringen het meest urgent zijn.

Dit proefschrift zet een stap in het begrijpen van een aantal belangrijke mondiale uitdagingen en veelbelovende oplossingen. Het realiseren van een kwalitatief goede huisvesting en gebouwde omgeving voor de gehele wereldbevolking is een grote uitdaging in een wereld die geconfronteerd wordt met problemen als grondstofschaarste en opwarming. Regio's met lagere inkomens hebben te maken met de grootste problemen. Er is vaak al woningnood en economische en bevolkingsgroei leidt tot een toenemende druk de woningvoorraad (fors) uit te breiden. Dit geeft uitdagingen in termen van het vinden van investeringsruimte, het omgaan met grondstofschaarste, en het voorkomen van klimaatschade. Landen met hogere inkomens zullen ook dit soort problemen ervaren, maar waarschijnlijk in mindere mate. Het verbeteren van de efficiëntie van materiaalgebruik bij de constructie en exploitatie van gebouwen kan het probleem van grondstofschaarste en koolstofemissies aanzienlijk verminderen, wereldwijd. Negatieve-emissietechnologieën (NET's) kunnen op de langere termijn nodig zijn om een wereldwijde netto-emissievrije bouwsector te bereiken. Gebouwen moeten op een meer toekomstbestendige manier worden ontworpen en gebouwd, zodat ze langer meegaan, ook bij de meer extreme weersomstandigheden en natuurrampen die verwacht kunnen worden door de klimaatverandering. Normen voor bescherming tegen overstromingen zijn van cruciaal belang om de veiligheid van gebouwen tegen overstromingen te waarborgen en moeten worden aangescherpt. Er moet een alomvattende strategie worden ontwikkeld die ecologische, economische en sociale dimensies integreert, zodat elke wereldburger de verzekerd is van duurzame en goede huisvesting waar ook ter wereld.

Dit proefschrift heeft verschillende wetenschappelijke en beleidsmatige implicaties. Vanuit wetenschappelijk perspectief bieden we eerst een geïntegreerd raamwerk dat de wereldwijde behoefte aan kwalitatief goede huisvesting verbindt met milieu-uitdagingen. Hierbij verbeteren we diverse modelmatige aanpakken. De modellen die we hebben ontwikkeld kunnen eenvoudig worden toegepast voor een breed scala aan onderzoeksdoeleinden. Als voorbeeld: het dynamische bouwzandmodel (Hoofdstuk 2) kan, als eerste in zijn soort, bijvoorbeeld worden gebruikt om inzicht te krijgen in de ontwikkeling van de zandcrisis en andere problemen met grondstoffenschaarste in verschillende mondiale regio's en sectoren.

Dit proefschrift bevat ook belangrijke informatie voor beleid vanuit regionaal en mondiaal perspectief. Op regionaal niveau bevelen wij aan dat beleidsmakers duurzaamheid integreren in het hele proces van de ontwikkeling van de gebouwde omgeving, van investeringsbeslissingen in stedelijk gebied tot het ontwerp en de constructie van gebouwen, van onderhoud en renovatie tot het beheer van gebouwen, en het management aan het einde van de levensduur van componenten en materialen. Vanuit een mondiaal perspectief laten we eerst zien dat de inzet van negatieve-emissietechnologieën waarschijnlijk nodig is om emissiereducties in de moeilijk koolstofneutraal te maken materiaalsector te compenseren om de klimaatdoelstelling van 1,5 °C te bereiken. Vervolgens laten we zien dat er behoefte is aan meer internationale samenwerking ten aanzien van kennis, technologie, en onderlinge financiële ondersteuning om de regionale ongelijkheden in de mogelijkheden om problemen op te lossen. Hierbij kunnen handelsovereenkomsten een belangrijke rol spelen.

De modellen in dit onderzoek kunnen breder worden toegepast of uitgebreid. Ze kunnen ook worden toegepast voor andere economische hulpbronnen (zoals landgebruik en inzet van arbeid) en voor andere milieu-uitdagingen (zoals klimaatmigratie en biodiversiteitsproblemen). Andere verbeteringen kunnen betrekking hebben op modellering en gegevens. Nieuwe modellen zouden bijvoorbeeld renovatie kunnen integreren in dynamische modellen voor de toekomstige bouw- en renovatiebehoefte. Dit resulteert in een breder spectrum aan scenario's voor de toekomst. Daarnaast is het nodig de beschikbaarheid en robuustheid van gegevens voor wereldwijde en regionale analyse te verbeteren.

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Curriculum Vitae

Xiaoyang Zhong was born in 1992 in Heze, Shandong province, China. After graduating from No.1 High School of Heze Shandong, he studied Engineering Management and obtained his bachelor’s degree at Ocean University of China. Xiaoyang continued to study Management Science and Engineering at Chongqing University where he obtained his master’s degree in 2018 with a thesis on assessing the water and energy use efficiency of the construction industry in provinces of China. Later that year, Xiaoyang joined the Institute of Environmental Sciences (CML) at Leiden University to work on his PhD research about the environmental challenges of sheltering a growing global population. Before finishing his PhD, Xiaoyang commenced a postdoctoral research position at the same institute, where he joined the Future Availability of Secondary Raw Materials (FutuRaM) project with a focus on scenario analysis of future availability of second raw materials in Europe. Coming April, Xiaoyang will join the Energy, Climate, and Environment (ECE) program of the International Institute for Applied Systems Analysis (IIASA) as a research scholar.

Publication list

Publications related to this thesis

1. **Zhong X**, Deetman S, Tukker A, Behrens P. Increasing material efficiencies of buildings to address the global sand crisis. *Nature Sustainability* 2022: 1-4.
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Additional publications

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