



**HAL**  
open science

## Material requirements and impacts of the building sector in the Shared Socioeconomic Pathways

Hugo Le Boulzec, Sandrine Mathy, François Verzier, Baptiste Andrieu, Daniel Monfort-Climent, Olivier Vidal

### ► To cite this version:

Hugo Le Boulzec, Sandrine Mathy, François Verzier, Baptiste Andrieu, Daniel Monfort-Climent, et al.. Material requirements and impacts of the building sector in the Shared Socioeconomic Pathways. Journal of Cleaner Production, 2023, 428, pp.139117. 10.1016/j.jclepro.2023.139117 . hal-04235239

**HAL Id: hal-04235239**

**<https://brgm.hal.science/hal-04235239>**

Submitted on 23 Nov 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Highlights

### **Material requirements and impacts of the building sector in the Shared Socioeconomic Pathways**

Hugo Le Boulzec, Sandrine Mathy, François Verzier, Baptiste Andrieu, Daniel Monfort-Climent, Olivier Vidal

- The prospective regional building stocks of seven scenarios are compared.
- The regional stocks and flows of base materials are estimated.
- Strong inequalities are observed in the projected in-use stocks per capita of materials.
- The recycled concrete aggregates (RCA) could reduce the landfills stocks if implemented quickly on a large scale.
- The green concrete mixes could allow to significantly decrease the energy demand of concrete production.

# Material requirements and impacts of the building sector in the Shared Socioeconomic Pathways

Hugo Le Boulzec<sup>a,\*</sup>, Sandrine Mathy<sup>a</sup>, François Verzier<sup>b</sup>, Baptiste Andrieu<sup>b,c</sup>, Daniel Monfort-Climent<sup>d</sup> and Olivier Vidal<sup>b</sup>

<sup>a</sup>Univ. Grenoble Alpes, CNRS, INRAE, Grenoble INP, Grenoble Applied Economics Laboratory (GAEL), Grenoble, 38000, France

<sup>b</sup>Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, Univ. Gustave Eiffel, ISTERE, Grenoble, 38000, France

<sup>c</sup>The Shift Project, 16-18, rue de Budapest, Paris, 75009, France

<sup>d</sup>BRGM, 3 Avenue Claude Guillemin, Orléans, 45100, France

## ARTICLE INFO

### Keywords:

Building sector  
Shared Socioeconomic Pathways (SSPs)  
Base materials  
Recycled concrete aggregates  
Green concrete


## ABSTRACT

The significant weight of the building sector in global material demand has been addressed in several publications, but a lack of consideration of the energy-materials nexus was identified. To fill this gap, we developed a stock-flow dynamic model from 1950 to 2100, using scenarios of the International Energy Agency and the Shared Socioeconomic Pathways of the academic literature. We find that (i) the increasing stocks in the less developed countries results in a rise of the inflows; (ii) strong inequalities are observed in the in-use stocks per capita of materials in the SSPs, despite optimistic material intensities projection, (iii) a growing materials demand translates into larger final energy demand of material production, which could question the feasibility of some low-energy demand scenarios, and that (iv) the recycled concrete aggregated display a significant potential to enhance the reduction of accumulated concrete stocks in landfills and green concrete could decrease the energy demand of concrete production. We furthermore highlight the crucial temporal aspect of policies to successfully implement these solutions, as long lifetimes are observed in the building sector.

## 1. Introduction

The conjunction of a soaring human demography over the 20<sup>th</sup> century and a rapid improvement of housing conditions has driven the increase of the final energy demand in the building sector. It grew from 60 EJ in 1973 to more than 121 EJ in 2019 (IEA, 2021), representing approximately 40% of the global final energy demand. In a context of rapid development of emerging countries and of increasing of environmental concerns, a better understanding of the drivers of the energy demand and environmental impacts of the building sector has therefore become a growing topic in the academic and institutional literature<sup>1</sup>. However, the operational phase of building has gathered most of the attention in prospective studies, and we identify a lack of analysis of the energy-raw material nexus in the embodied phase. Industrialization of countries relies on the development of material-intensive infrastructures, which could have an impact on energy availability. We further develop this topic in this section by discussing the embodied phase (Section 1.1), the dynamic and prospective material modeling studies (Section 1.2) and material engineering (Section 1.3).

\*Corresponding author

 hugo.le-boulzec@outlook.fr (H. Le Boulzec)

ORCID(s): 0000-0003-3658-7715 (H. Le Boulzec); 0000-0002-7998-4115 (S. Mathy); 0000-0002-1485-3165 (B. Andrieu)

<sup>1</sup>The development of building energy and infrastructures databases in Europe or the USA shows the growing importance of the understanding of the building sector energy demand.

### 1.1. The need to better evaluate the embodied energy of buildings

The energy demand of the building sector is segmented between the operational phase and the embodied phase, which is defined as "the total energy used to construct, maintain, and finally demolish a building" (Azari and Abbasabadi, 2018). The operational phase has been thoroughly studied over the past decades and has led to a better understanding of the leverages to achieve higher energy efficiency in the building sector, such as the design (Pacheco et al., 2012) or the role of occupants (Yang et al., 2014; Zhang et al., 2018). It has allowed the implementation of energy efficiency policies, such as in the European Union (Economidou et al., 2020), where an improvement of household energy efficiency by 29% has been observed between 2000 and 2019 (Rousselot and Pinto Da Rocha, 2021). The residential segment has received much of the focus, despite the potential for energy efficiency in the non-residential segment (Ruparathna et al., 2016), which explained the increase of the share of the non-residential segment in the building final energy demand over the last two decades (IEA, 2021). With the extensive knowledge on the operational phase of buildings, the embodied phase has progressively gained attention (Chastas et al., 2016; Azari and Abbasabadi, 2018). The bottom-up approach describing the materials and their stocks and flows within the building sector has proven to provide useful results to develop strategies to reduce embodied energy and environmental impacts.

## 1.2. Dynamic materials modeling of the building sector

The analysis of the social metabolism<sup>2</sup> has been a growing research field over the past 20 years. Initial studies developed static top-down approaches of the stocks and flows of materials embedded in human societies<sup>3</sup> and a growing trend for dynamic analysis has rapidly been observed through dynamic material flows analysis (MFA). A special emphasis is placed on the building sector in the literature, as it represents a significant share of base materials demand<sup>4</sup>. Several recent studies have proposed reviews of the materials modeling in the building sector. They allowed a better understanding of the methodological approaches displayed in the literature (Göswein et al., 2019; Nasir et al., 2021), highlighted the substantial role of assumptions on the outcomes (Augiseau and Barles, 2017) and provided a comparison of the methods to quantify the material content of construction and demolition wastes (Wu et al., 2014).

We have identified 21 dynamic MFA studies modelling base materials using a bottom-up approach and focusing on the building sector, on a national, multinational or global scale<sup>5</sup>. The analysis were mainly conducted at a national level, which enables to grasp the specificity of local stock and flow dynamics, and improve data accuracy, especially concerning building lifetime and material intensities (Augiseau and Barles, 2017). Probably due to the low availability of estimates of building surfaces, only three bottom-up studies computed material stocks and flows of materials at regional or multi-regional scale (Mastrucci et al., 2021). They display a focus on materials in a waste framework (Wiedenhofer et al., 2015) and on the prospective materials stocks and flows in a socioeconomic pathways, with a thorough disaggregation of the residential and non-residential buildings types (Marinova et al., 2020; Deetman et al., 2020). However, none of these multi-regional studies provide insights about the analysis of the outcomes in the energy-materials nexus.

## 1.3. The role of materials engineering to reduce energy demand and environmental impacts

The consideration of the stocks and flows within the energy-materials nexus represents a rising topic<sup>6</sup>. Indeed,

<sup>2</sup>The social metabolism-or socioeconomic metabolism-"constitutes the self-reproduction and evolution of the biophysical structures of human society. It comprises those biophysical transformation processes, distribution processes, and flows, which are controlled by humans for their purposes. The biophysical structures of society ('in use stocks') and socioeconomic metabolism together form the biophysical basis of society." (Pauliuk and Hertwich, 2015)

<sup>3</sup>For instance at a regional level in the Stocks and Flows Project (Graedel et al., 2002).

<sup>4</sup>The base materials are defined as the materials used for structural uses, and for which a low substitution potential is observed. It includes aluminum, copper, concrete, iron and the materials mostly used for alloy steel making (manganese, chromium or nickel).

<sup>5</sup>A detail of the identified publications is provided in the Supplementary Information. We observe that the Chinese perimeter represents almost half of these publications.

<sup>6</sup>The reader can refer to recent publications such as Giurco et al. (2014); McLellan (2017); Vidal et al. (2017) or Elshkaki (2019). The inclusion of

the share of GHG emissions from materials production increased from 15% of global GHGs in 1995 to 23% in 2015 (Hertwich et al., 2019). The concrete sector alone represented between 6 and 8% of global energy demand in 2016 (Bataille, 2019; Andrew, 2017). In parallel, the construction and demolition wastes (CDW) accounted for more than 30% of the global produced solid wastes in 2020 (Ginga et al., 2020). In the perspective of reducing the environmental impacts of concrete, new processes of concrete production, through recovery, recycling and the use of other materials in concrete manufacturing are developed and studied.

Japan or the Netherlands achieve close to 100% concrete recycling rate by recycling concrete into new structural applications or in lower grade uses such as road (Tam, 2009; Xicotencatl, 2017). It allows considerable reduction of the environmental impacts of construction and demolition waste (CDW) by lowering their amount in landfills and decreasing the need for production. Concrete is recycled in the form of aggregate by a crushing process, partly replacing natural aggregate content in the concrete production<sup>7</sup>. However, the different types of recycled aggregates suffer from a lack of confidence from construction actors and are rarely used in structural applications (Silva et al., 2019; European Environment Agency, 2021). A growing number of publications focus on the evaluation of mechanical and durability performance of recycled aggregates concrete (RAC) using recycled concrete aggregates (RCA) replacement, showing that several parameters could allow RCA replacement, such as the structure of the aggregates (Silva et al., 2014; Verian et al., 2018; Guo et al., 2018), the process conditions (Thomas et al., 2018) or further enhancement techniques (Verian et al., 2018).

The development of green concrete<sup>8</sup> also aims to reduce the environmental impact. It is a low-carbon concrete, which production mainly relies on industrial or agricultural by-products, nanoparticles and advanced techniques to further understand concrete structures (Vishwakarma and Uthaman, 2020). Given that most of the energy demand and environmental impacts of concrete production occurs during cement production, the replacement of primary materials by waste materials reduces lower impacts of concrete production (Reiners and Palm, 2015). The use of wastes in concrete production has been implemented for decades in the concrete industry through supplementary cementitious materials (SCM)<sup>9</sup>. The most common SCM are coal fly ash (CFA)<sup>10</sup>, blast furnace slags (BFS)<sup>11</sup>, silica fume,

resource studies within a broader nexus has been studied by Bleischwitz et al. (2018a)

<sup>7</sup>Shares of 12% to 29% of recycled concrete were observed in German, the Netherlands and the United Kingdom in 2012 and 2013 (Reiners and Palm, 2015)

<sup>8</sup>"Green concrete" is referred to as green concrete in the text. However, it is a low-carbon concrete and not a carbon-free material.

<sup>9</sup>The Lafarge company defines Supplementary Cementitious Materials (SCMs) as "materials that, when used in conjunction with portland cement, portland limestone cement or blended cements, contribute to the properties of hardened concrete through hydraulic and/or pozzolanic activity".

<sup>10</sup>CFA is a by-product of the combustion of coal to generate electricity.

<sup>11</sup>BFS is produced during the iron-making process.

or metakaolin (Habert, 2014; Holland et al., 2016)<sup>12</sup>. The performance and environmental impacts of green concrete have attracted increasing interest in the literature (Siddique, 2014; Gu and Ozbakkaloglu, 2016; Paris et al., 2016; Jiang et al., 2018; Sandanayake et al., 2020). Despite the extensive research on concrete recovery and recycling, and on green concrete, their implementation has never been conducted in large scale scenarios.

#### 1.4. Scope and objectives of this study

The present study aims at filling the identified gaps by adopting a combined assessment of material requirements, energy-raw materials nexus, and material engineering options to decrease the embodied energy of building infrastructures. These topics are usually considered separately in the literature. It prevents any identification of potential energy availability issues related to an increase in embodied energy. In addition, the scenarios coverage considered in this study is broader than in previous publications, which allows to provide insights in material and embodied energy requirements for the building sectors for various socioeconomic pathways. We (1) estimate the base materials (concrete, aluminum, copper and steel) weight of construction<sup>13</sup> in Shared Socioeconomic Pathways and IEA scenarios, (2) estimate the historical and prospective energy demand of the materials production in the building sector and (3) assess the potential of energy demand reductions of concrete in the building sector through concrete recovery, recycling and green concrete use. This paper is structured as follows. Section 2 details the methods and data. Section 3 describes the results, section 4 discusses them and section 5 concludes.

## 2. Methods and data

A four-step methodology was developed. First, historical and prospective floor areas were obtained at a regional level. Second, the base material stocks and flows in the building sector were estimated using dynamic and regional material intensities and lifetimes in the MATER model. Both primary and secondary raw materials are estimated. Third, the final energy of material production is estimated and compared to the total final energy in transition scenarios. Lastly, their energy demand was assessed and two solutions were considered for a reduction of concrete demand and impacts: concrete recovery and recycling, and green concrete. Their potential in reducing the embodied energy demand was assessed in the selected scenarios.

### 2.1. Scenarios

Seven scenarios are considered: the Shared Socioeconomic Pathways (SSP) combined with the Representative Concentration Pathways (RCP), the Beyond 2 Degrees Scenario (B2DS) and the Reference Technology Scenario

<sup>12</sup>Many other materials can also be used, such as foundry sand, wood ash, plastic, glass and other ashes (Paris et al., 2016; Sandanayake et al., 2020).

<sup>13</sup>Thermal renovation is related to energy management, and is referred to as renovation in the rest of the study.

(RTS). They provide six socioeconomic futures which corresponds to six projections of the building surfaces. These scenarios were selected for the wide range of socioeconomic and climate pathways they depict and for their broad use in the academic and institutional literature. Their main characteristics are described in this section, and a summary of the scenarios is provided in Table 1.

#### 2.1.1. The Shared Socioeconomic Pathways combined with Representative Concentration Pathways

The Shared Socioeconomic Pathways (SSP) feature multiple baseline (without climate policies) worlds because underlying factors, such as population, economic growth, education, urbanization and the rate of technological development, could lead to very different future emissions and warming outcomes, even without climate policy. They are based on five narratives intended to span the range of plausible futures: *sustainable and inclusive development* in the SSP1, *middle of the road* in the SSP2, *regional rivalry* in the SSP3, *inequality* in the SSP4 and *fossil-fueled development* in the SSP5 (O'Neill et al., 2017). They were developed by the climate change research community in parallel of the Representative Concentration Pathways (RCPs) that set pathways for greenhouse gas concentrations and the amount of warming that could occur by the end of the century (RCP 1.9 to RCP 8.5 W/m<sup>2</sup>)<sup>14</sup> (Moss et al., 2010; van Vuuren et al., 2011). SSPs and RCPs are combined to assess the efforts needed both to reduce GHG emissions and to adapt according to the different levels of global warming of the RCPs and the different socio-economic assumptions of the SSP. Such trajectories are quantified with six Integrated Assessment Models (IAMs) (Riahi et al., 2017). Five of these IAMs are used as markers<sup>15</sup> for a specific SSP<sup>16</sup>.

The SSPs were computed with a climate constraint through the implementation of RCPs. The RCP 2.6 was implemented on the SSP1, SSP2 and SSP3, while the RCP 4.5 was used on the SSP2, SSP3 and SSP4. In order to provide an extreme case, the SSP5 baseline was further selected (Table 1). The computation with the GCAM 5.4 model was selected because in this model, the regional residential and non-residential floor areas are estimated for 32 regions from 1990 to 2100 through a logit approach (Calvin et al., 2017). The building stock and floor areas depend on socioeconomic assumptions (SSPs), but not on the RCP.

#### 2.1.2. The International Energy Agency scenarios

Two scenarios of the International Energy Agency were selected: the Reference Technology Scenario (RTS) and the

<sup>14</sup>The RCP 1.9 translates into a average global warming of about 1.5°C. It reaches at least 4°C in the RCP 8.5 (IPCC, 2021).

<sup>15</sup>A marker consists in a reference modeling of each SSP by an IAM, which is used in climate policies analysis (Riahi et al., 2017). A further computation of the five pathways in several of six selected IAMs allows for a comparative analysis of the results.

<sup>16</sup>AIM/CGE for the SSP1 van Vuuren et al. (2017), MESSAGE-GLOBIOM for the SSP2 (Fricko et al., 2017), IMAGE for the SSP3 (Fujimori et al., 2017), GCAM for the SSP4 (Calvin et al., 2017) and REMIND-MagPIE for the SSP5 (Fricko et al., 2017)



**Table 1**  
Summary of the socioeconomic characteristics of the selected scenarios.

Scenario	Computation model	Population	GDP per capita	Average global warming	References
RTS B2DS	ETP-2017	High	Low	2.7-3°C <2°C	IEA (2017)
SSP1 - RCP 2.6	GCAM 5.4	Low	Medium	1.8°C	Kim et al. (2006) O'Neill et al. (2014)
SSP2 - RCP 2.6	GCAM 5.4	Medium	Medium	1.8°C	Kim et al. (2006) O'Neill et al. (2014)
SSP3 - RCP 4.5	GCAM 5.4	High	Low	2.7°C	Kim et al. (2006) O'Neill et al. (2014)
SSP4 - RCP 4.5	GCAM 5.4	Medium	Low	2.7°C	Kim et al. (2006) O'Neill et al. (2014)
SSP5 baseline	GCAM 5.4	Low	High	4°C	Kim et al. (2006) O'Neill et al. (2014)

Beyond 2°C Scenario (B2DS) (IEA, 2017). The RTS is a baseline scenario that takes into account existing energy-and climate-related commitments by countries, including Nationally Determined Contributions pledged under the Paris Agreement. The average temperature increase would reach 2.7°C to 3°C in 2100 (Table 1). Conversely, the B2DS proposes an ambitious trajectory, with a 50% chance of limiting the temperature increase to 2°C in 2100 by reaching carbon neutrality by 2060 (Table 1). This requires unprecedented efforts in all sectors at the global level, which translates in particular into a drastic reduction in fossil fuel consumption and a massive recourse to renovation (IEA, 2017). Both scenarios display a similar residential and non-residential building stock with different renovation policies, for nine regions up to 2060.

## 2.2. The MATER model

The modeling methodology of this study relies on the *MATER* (Multiregional Assessment of Technology, Energy and Raw material) stocks and flows model (Figure 2) which covers the entire energy chain and three end-use energy sector. A stock-driven approach is considered to estimate the primary and secondary materials requirements, and their associated production energy and CO<sub>2</sub> emissions (Vidal, 2021; Le Boulzec et al., 2022). The *MATER* model is a Python version of the DyMEMDs model (Vidal et al., 2021; Le Boulzec et al., 2022) with new features such as the endogenization of the industry and electricity supply sectors.

### 2.2.1. *MATER* methodology

The building sector was segmented in two segments: residential and non-residential. Historical surfaces data were firstly used to calibrate logistic-based building stocks between 1900 and 2018, for nine multinational areas (Table S1). Secondly, prospective floor areas and renovation strategies were obtained from scenarios to compute the regional

residential and non-residential surfaces up to 2100<sup>17</sup>. Materials intensities, end-of-life collection rate (EOR-CR), recycling process efficiency rate (EOL-PR) and regional building lifetimes distributions are then used to model base material stocks and flows over time. Finally, the indirect energy demand and CO<sub>2</sub> emissions associated with the materials production are estimated. The simplified methodology behind the building module of the *MATER* model is presented in Figure 1. Figure 2 displays more precisely the materials stocks and flows loop used in the model. It was previously described in Le Boulzec et al. (2022), and general model equations are provided in the Supplementary Information.

### 2.2.2. *Historical and prospective regional building stocks*

The stock-driven approach in the *MATER* model requires historical and prospective building stock input data, which were obtained from the literature and from the seven selected scenarios (Section 2.1). The building stock is divided between the residential and non-residential segments. Few historical floor area data are available in the literature at the regional scale. Pan et al. (2020) provided a modelling of Chinese residential and commercial building stocks based on historical data between 1996 and 2014, in accordance with the results of Huo et al. (2019). Some data are available for Europe as well, but the perimeter is usually limited to the European Union countries. IEA (2014) reported residential and services buildings floor areas data in 2000 and 2011, while Harvey et al. (2014) provided insights into regional floor areas per capita and Calvin et al. (2017) displayed national and regional data in the GCAM model. At the prospective level, seven different prospective trends of the building stock evolution are depicted through the computation of seven scenarios: the five Shared Socioeconomic Pathways in the open-source GCAM 5.4 model (Kim et al., 2006) and the

<sup>17</sup>Except in the Low Energy Demand and the International Energy Agency scenarios, see Section 2.1.

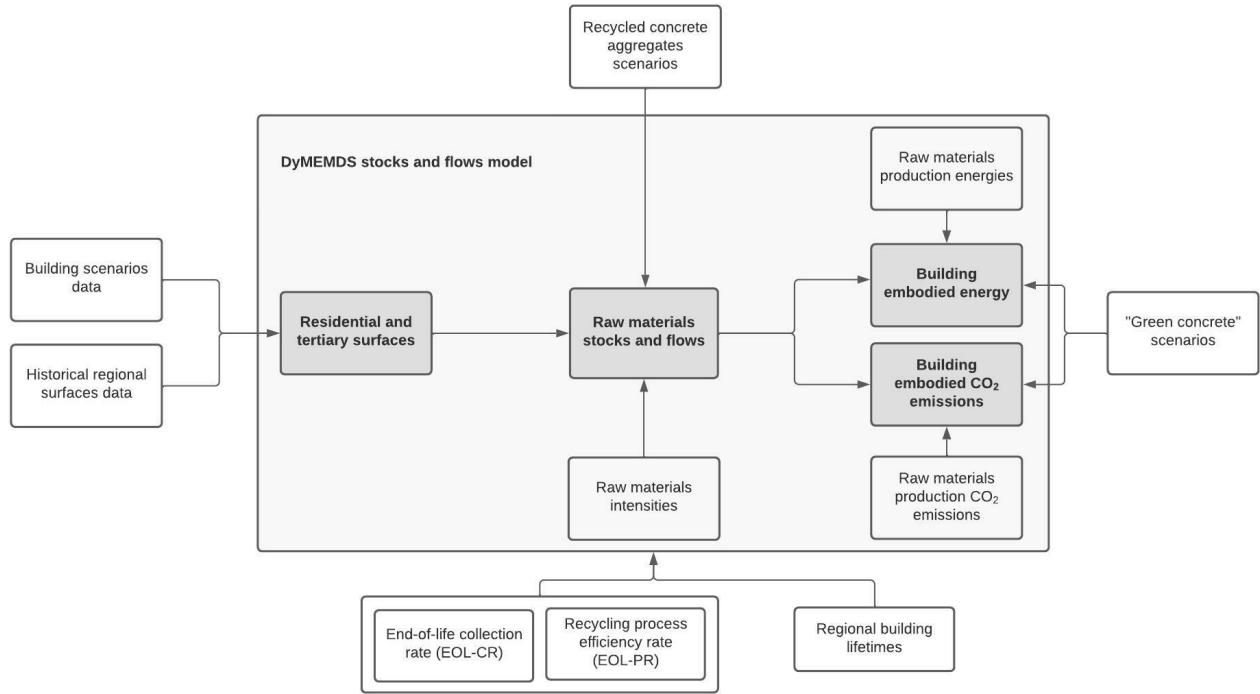


Figure 1: Simplified methodology lying behind the *MATER* model. Adapted from Le Boulzec et al. (2022).

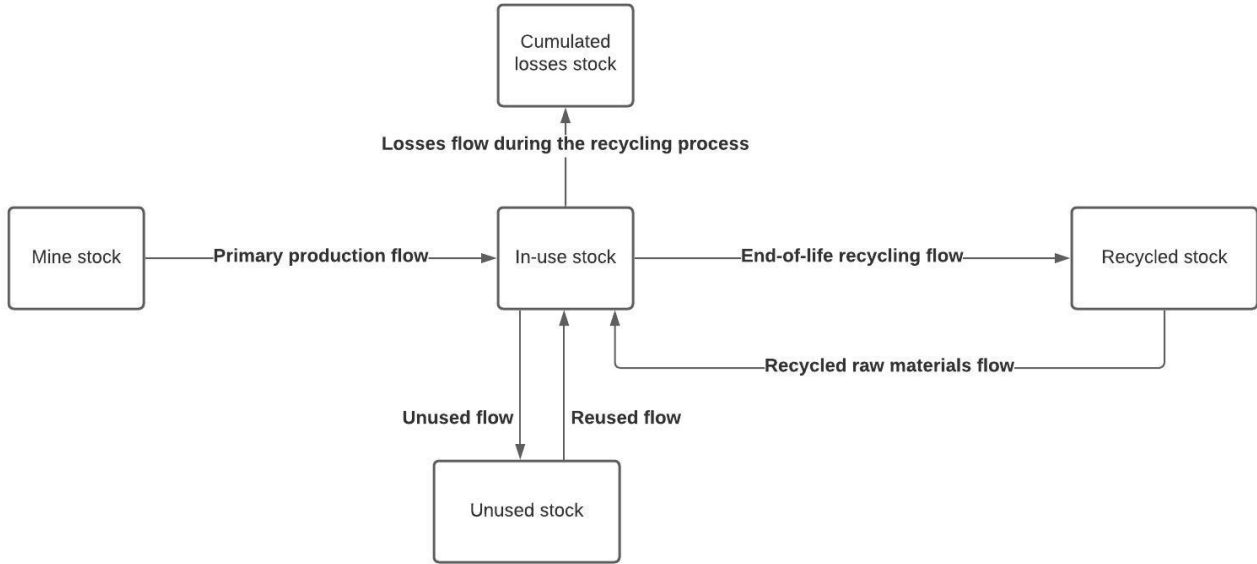


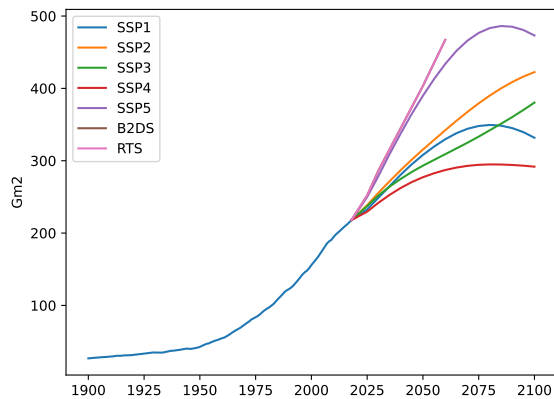
Figure 2: Key loop used in the *MATER* model to estimate the stocks and flows of materials during the construction and maintenance of the infrastructure. Source: Le Boulzec et al. (2022)

RTS/B2DS scenarios modeled in the Energy Technology Perspectives 2017 (ETP-2017) model (IEA, 2017). The scenarios are briefly described in Section 2.1.

The historical regional residential building floor areas were then extrapolated back to 1900 with a logistic approach

based on GDP per capita<sup>18</sup>. The non-residential stock was assumed to represent a constant share of the total stock from

<sup>18</sup>The logistic curve provides a useful tool to describe the behavior of the infrastructures and materials stock through a three-phase profile: growth, maturation and saturation (Bleischwitz et al., 2018b). It allows to compute the limited "carrying capacity" of a system (Chen and Graedel, 2015). The



**Figure 3:** Global building floor areas in the selected scenarios.

1900 to 1990, and the shares observed in the SSPs from 1991 to 2018. The prospective surfaces were then considered from 2019 to 2100 for the SSPs and 2060 for the IEA scenarios. However, the IEA (2018) showed significant differences in the floor areas in 2017, and the prospective regional surfaces were rescaled to fit the historical building stocks.

### 2.2.3. Intensities and recycling rates

The material scope of this study includes four base materials (aluminum, concrete, copper and steel), which represent most of both the annual demand (USGS, 2021b) and the environmental impacts of material production (Bataille, 2019). The dynamic end-of-life recycling rates from Le Boulzec et al. (2022) were considered for aluminum, copper and steel. The regional recovery and recycling shares of Tam et al. (2018) and Reis et al. (2021) were used for concrete, assuming no concrete was recovered in 1990. In order to estimate materials stocks and the input and output flows of the building sector, regional and dynamic materials intensities were considered. A further distinction was made between residential and non-residential intensities. The residential segment displays various levels of intensities, which is explained by the different constructive modes in the areas. Concrete dominates the mixes ahead of masonry and wood, except in North America and Africa where wood remains the most used materials (IEA, 2018). The non-residential segment encompasses various types of buildings (e.g. hospital, industrial building, school, office, bar and restaurant...) with different functionalities and only few disaggregated material intensities data are available. Therefore, average values were selected for this segment. As for the residential segment, concrete remains dominant in the construction mix ahead of steel, except in the North American segment where the steel intensity is the highest. Dynamic material intensities were considered to model the evolution of both the building

GDP/capita values were obtained from the Maddison historical statistics and the population from the United nations population

materials mix<sup>19</sup> over time and the amounts required. A logit profile based on GDP was used to compute the materials intensities, based on historical data from Müller (2006); Ortlepp et al. (2016); IEA (2018) and Gontia et al. (2018) for steel and concrete and from Ortlepp et al. (2016); Kleemann et al. (2016); Ortlepp et al. (2018); ADEME et al. (2018); Schipper et al. (2018); Dong et al. (2019); Marinova et al. (2020) and Deetman et al. (2020) for aluminum and copper. Given their structural nature in building, different saturation levels were considered for steel and concrete<sup>20</sup>, while the same saturation levels were selected for copper and aluminum.

Finally, primary production energies estimated in Vidal (2021) and Le Boulzec et al. (2022) were selected, as well as the secondary production energies from Le Boulzec et al. (2022). The historical data and the modeled intensities are available the Supplementary Information.

### 2.3. Regional lifetimes

Lifetime represents an influential parameter in material modeling (Hu et al., 2010), and its value carries significant effects on infrastructure stock renewal and outputs (Müller et al., 2014). In spite of this, the parameter is not well known because of a lack of regional and empirical data (Cao et al., 2019). Static values reduce the accuracy and undermine the reach of studies, and dynamic lifetimes are increasingly considered in the literature. Recent researches focus on providing better insights about the lifetime dynamics (Zhou et al., 2019; Cao et al., 2019), studying the impact of the choice of statistical distribution (Miatto et al., 2017) and analysing the impact of lifetime on building LCA results (Aktas and Bilec, 2012; Marsh, 2017). However, the lack of knowledge about the evolution of regional lifespans prevents a correct estimation of dynamic lifespans in multi-regional studies. Therefore, constant and regional mean lifetime were considered, and a normal distribution was used. Due to a lack of data about the non-residential building stocks lifetime characteristics, similar values are considered for residential and non-residential buildings. Current regional lifetimes considered in the literature were used, and normal distributions were considered. A full documentation of the data and the lifetime distributions are available in the Supplementary Information.

### 2.4. Reducing the energy demand of concrete

Two main solutions for a reduction of concrete demand and impacts are considered. Firstly, a growing recovery and recycling of concrete is studied, and the potential reduction of accumulated concrete in landfills is assessed. It allows for a reduction in primary concrete. Then, green concretes

<sup>19</sup>For instance, a rising share of concrete observed in Japan and the Western countries was observed after the Second World War, see Section S2.5 of the Supplementary Information. However, no further evolution of the mix was considered, such as the increasing use of wood.

<sup>20</sup>It is explained by the different materials mixes in building in the considered areas. For example, more steel and wood building are observed in the North American area (IEA, 2018).



mixes based on industrial by-products and recycled aggregates are used in the projected concrete demand, to estimate a potential decrease of the impacts of concrete production. The two solutions are computed in the selected scenarios to estimate the associated energy demand.

#### 2.4.1. Concrete recovery and recycling

The first solution is displayed in two successive steps. The recovery potential (1) is firstly assessed. It then allows for an estimation of a reduction of the landfills burden (2). Few data are available on the regional recovery rates of concrete, and the European Union results on the recovery and recycling of Construction and Demolition Wastes (CDW) are not representative of the global CDW management<sup>21</sup>. The rates displayed in Reis et al. (2021) and Tam et al. (2018) were used to estimate the regional lost and recovered stocks and flows, and were assumed to increase by 20% by 2060. Dynamic rates were used, assuming that no concrete was recovered in 1990.

The concrete is recovered in two types of aggregates. Recycled aggregates (RA) are composed of several materials in significant proportions and represents most of the recovered flow, and recycled concrete aggregates (RCA) are mainly made of concrete waste Marinković and Carević (2019). The RA and RCA replace natural aggregated (NA) to produce recycled aggregated concrete (RAC). Most of the RA and RCA are currently used for non-structural applications (Behera et al., 2014; Silva et al., 2019), but recent studies have shown that high shares of RCA in RAC could be reached under some process conditions (Thomas et al., 2018; Guo et al., 2018; Verian et al., 2018). In order to estimate the reduction of the concrete lost stock, a business-as-usual case and three scenarios of progressive increase of RCA replacement of NA in concrete production are considered (Table 2). No replacement was assumed before 2025, and final replacement share of 20% was assumed to be reached in 2040 or 2060, and 50% in 2060. The 20% replacement hypothesis aims to compute a conservative scenario, in accordance with the current limit in some European countries (Tang et al., 2020), while the 50% scenario displays a more optimistic case. RCA generation is only computed to estimate the reduction of lost stock, and given the lack of consensus, no energy demand and environmental impact reductions were considered<sup>22</sup>. More information about the literature and the methodology is available in the Supplementary Information. The SI further proposes a 50% penetration case to compute RCA replacement on a smaller regional perimeter.

#### 2.4.2. Green concrete

The second solution considered is green concrete, which is defined as low-carbon concrete. Mainly based on industry or agriculture by-products, it allows to reduce the energy

<sup>21</sup>The European Union implemented a Waste Framework Directive, which set quantitative objective by 2020.

<sup>22</sup>The energy demand of concrete production mostly occurs during cement production. The recycling of concrete has therefore little or no impact on the overall concrete energy consumption (World Business Council for and Sustainable Development, 2009).

demand and environmental impact of concrete production. Four green concrete mixes were considered, based on two types of replacements used from 2030 to 2100:

- Replacement of natural aggregates by various types of recycled concrete aggregated<sup>23</sup>, or steel slag<sup>24</sup>;
- Replacement of Ordinary Portland cement, by coal fly ash (CFA)<sup>25</sup> or blast furnace slag (BFS)<sup>26</sup>.

The four mixes were used on a low penetration case (20% of the concrete inflow) and a high penetration case (100% of the concrete inflow). The composition and green concrete environmental impacts were selected from Flower and Sanjayan (2007); Turk et al. (2015) and Kurda et al. (2018). The four mixes and their production energy and emissions reductions are summarized in Table 3.

### 2.5. Sensitivity analysis

Little information on uncertainties were provided with the data used in this study. In order to give insights about main data and modeling choice related variability, a local sensitivity analysis was conducted. Since material intensities and energy intensities of material production have linear effects in the computation, the analysis focuses on the mean lifetime value in the normal distribution, for which both variations of  $\pm 20\%$  were computed (Le Boulzec et al., 2022) and a logit-based evolution was considered. Material intensities and energy intensities of base material production have linear effect throughout the calculation. We find that the logit-based evolution has little impacts on the material inflows. Conversely, we observe significant differences for  $\pm 20\%$  variations of the mean lifetime, which is explained by the combined effects of different material intensities among regions with various socioeconomic dynamics and the larger inflow required to feed the in-use stock in a stock-driven model.

## 3. Results

The stock-driven flow modeling approach conducted offers a regional and dynamic analysis of materials, and their production energy between 1950 and 2100 for the SSPs, and 2060 for the RTS and B2DS. The results are depicted in this section. The global and regional level results are presented. The SSP2 2p6 is referred to as SSP2, and the SSP3 4p5 is referred to as SSP3 in this section.

<sup>23</sup>It includes fine RCA, coarse RCA and a mix of fine and coarse RCA. Coarse and fine aggregates are defined by the size of their particles.

<sup>24</sup>Steel slag is a byproducts of steel manufacturing. The natural aggregates are sometimes replaced by electric arc furnace steel slag (EAFSS), which is produced during the electric arc furnace (EAF) steel manufacturing process.

<sup>25</sup>Coal fly ash (CFA) is a by-products of coal combustion for power generation.

<sup>26</sup>Blast furnace slag is a by-products of iron or steel during the blast furnace manufacturing process.

Scenario	Replacement
RS1	Progressive increase from 0% in 2025 to 20% of RCA replacement in 2060
RS2	Progressive increase from 0% in 2025 to 50% of RCA replacement in 2060
RS3	Progressive increase from 0% in 2025 to 20% of RCA replacement in 2040
BAU	No RCA replacement from 2025 to 2060

**Table 2**

Replacement scenarios of natural aggregates by recycled concrete aggregates.

Green concrete	Replacement	Production energy reduction	Emissions reduction
GC1	30% CFA	19%	26%
GC2	60% CFA	38%	51%
GC3	60% CFA and 100% coarse RCA	60%	60%
GC4	40% BFS		22%

**Table 3**

Considered replacements in green concretes, using coal fly ash (CFA), recycled concrete aggregates (RCA) and blast furnace slag (BFS). Sources : Flower and Sanjayan (2007); Turk et al. (2015) and Kurda et al. (2018)

### 3.1. Global in-use stocks and inflows of materials

#### 3.1.1. Materials in-use stocks

The significant increase observed in the building stock (Figure 3) has a direct impact on the materials embedded in residential and non-residential buildings between 1950 and 2018. The concrete in-use stock grew from 9.7 to 211 Gt in the period, while the steel in-use stock increased from 0.3 Gt to 8.5 Gt, the aluminum in-use stock from 4.9 Mt to 375 Mt and the copper in-use stock from 4.9 Mt to 266 Mt (Figure 4). The global building surface experiences an upward trend in all the selected scenarios. Different profiles are however observed. Monotonic growth is observed in the RTS, B2DS, and SSP2-3 for all base materials, while non-monotonic growth is shown in the SSP1 and SSP4-5. The in-use stocks displays substantial differences among the scenarios. The concrete stock reaches between 332 Gt (SSP4) and 546 Gt (SSP5) in 2100, while the steel stock grows between 14 Gt (SSP4) and 23 Gt (SSP5), the copper stock between 527 Gt (SSP4) and 900 Gt (SSP5) and the aluminum stock between 628 Gt (SSP4) and 1,070 Gt (SSP5). The SSP4 is the less material-intensive scenario, and the SSP5, RTS and B2DS consumes the most materials. As the assumptions of the IEA scenarios are very high in terms of floor area, they lead to the highest weight of materials until 2060. In-use stocks profiles vary among materials as well. The SSP5 displays a reduction of the concrete in-use stock from 2085, while the copper stock increases up to 2100 (Figure 4). This outcome is explained by the logistic behavior of the materials intensities and the regional building hypothesis.

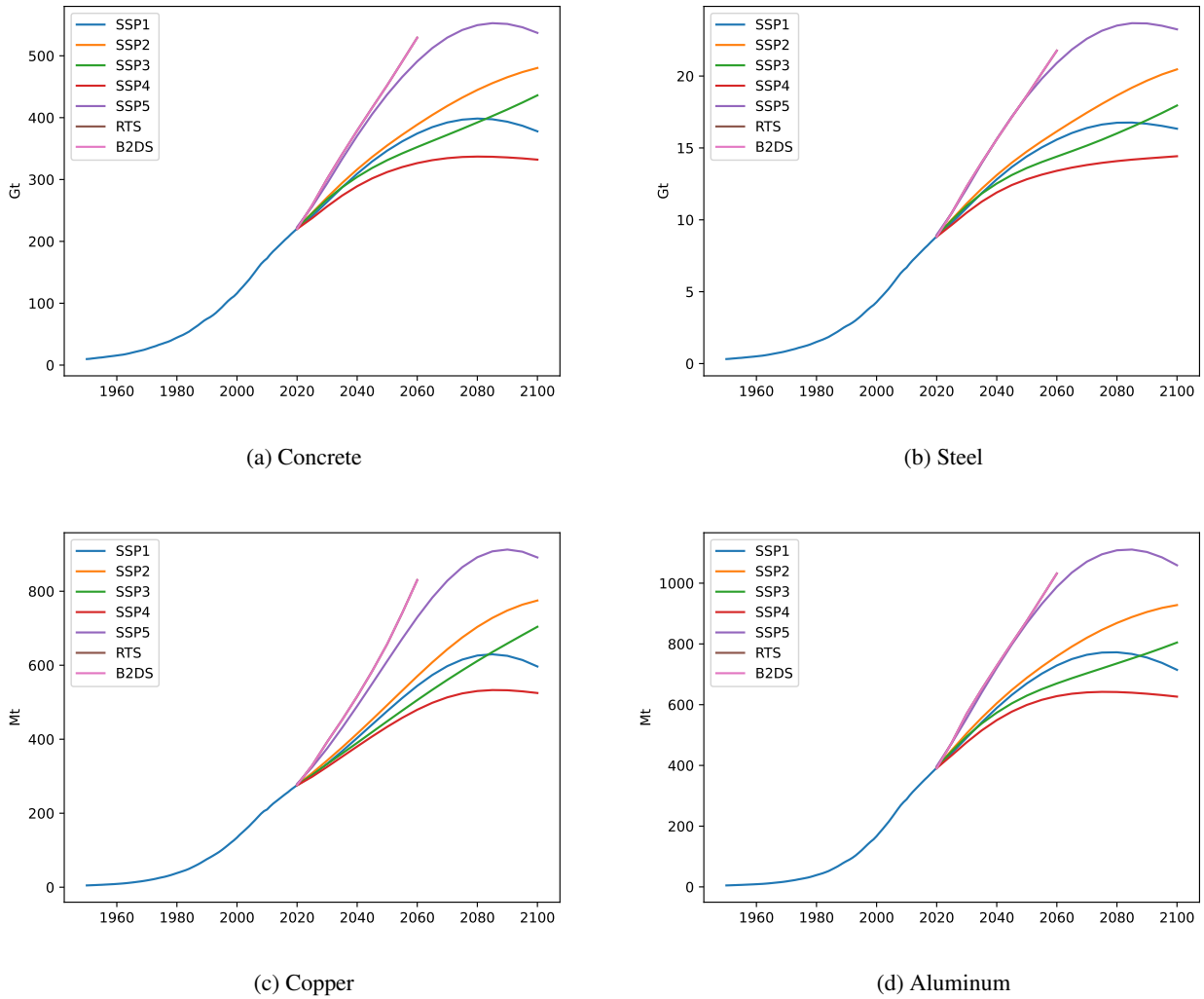
#### 3.1.2. Global materials inflows

The depicted stocks and their associated lifetimes create a dynamic of input and output flows. The historical reduction of the growth rate of materials in-use stock between 2008

and 2018 induces a stabilization of the annual inflows<sup>27</sup> (Figure 5). The variations between 2018 and 2030 result of the transition from the historical modeled surfaces to the prospective scenarios hypothesis and the historical behavior is explained by the choice of a GDP-based logit curve. Despite similar values of the inflows in 2100 for some scenarios, they all display significant differences in their profiles. In the SSP5, the flows experience a substantial rise until 2035 before stabilizing for concrete, steel and aluminum. The SSP5 flows peak to about 14 Gt/yr for concrete, 0.5 Gt/yr for steel, 27 Mt/yr for aluminum and 22 Mt/yr for copper. We also find that the SSP1 and the SSP4 present monotonic decreasing profiles and similar values in 2100. However, while the SSP1 flows show an increase in the rate of decline from 2055 to 2100, the SSP4 flows exhibit a reduction of this rate from 2060 to 2100. In the same vein, the SSP2 and SSP3 reaches comparable flows values in 2100, and are the only scenarios with upward phases. Finally, the RTS and B2DS display higher flows values than other scenarios. The linear growth of the surfaces in the two scenarios creates large required inflows, estimated to 17 Gt/yr of concrete, 0.6 Gt/yr of steel, 32 Mt/yr of aluminum and 30 Mt/yr of copper in 2060. Regional materials stocks and flows were obtained for the nine regions.

The building stock was segmented between the residential and the non-residential surfaces. The residential segment represents most of the global floor area, but displays lower concrete, steel and aluminum intensities. We therefore observe a high share of the non-residential segment in the materials stocks and flows. It reaches 33% of the concrete stock, 44% of the steel stock, 51% of the aluminum stock and 16% of the copper stock in 2018, for only 26% of the total floor areas. The share of the non-residential buildings

<sup>27</sup>We refer to the inflow as the sum of both the primary flow and the recycled flow.



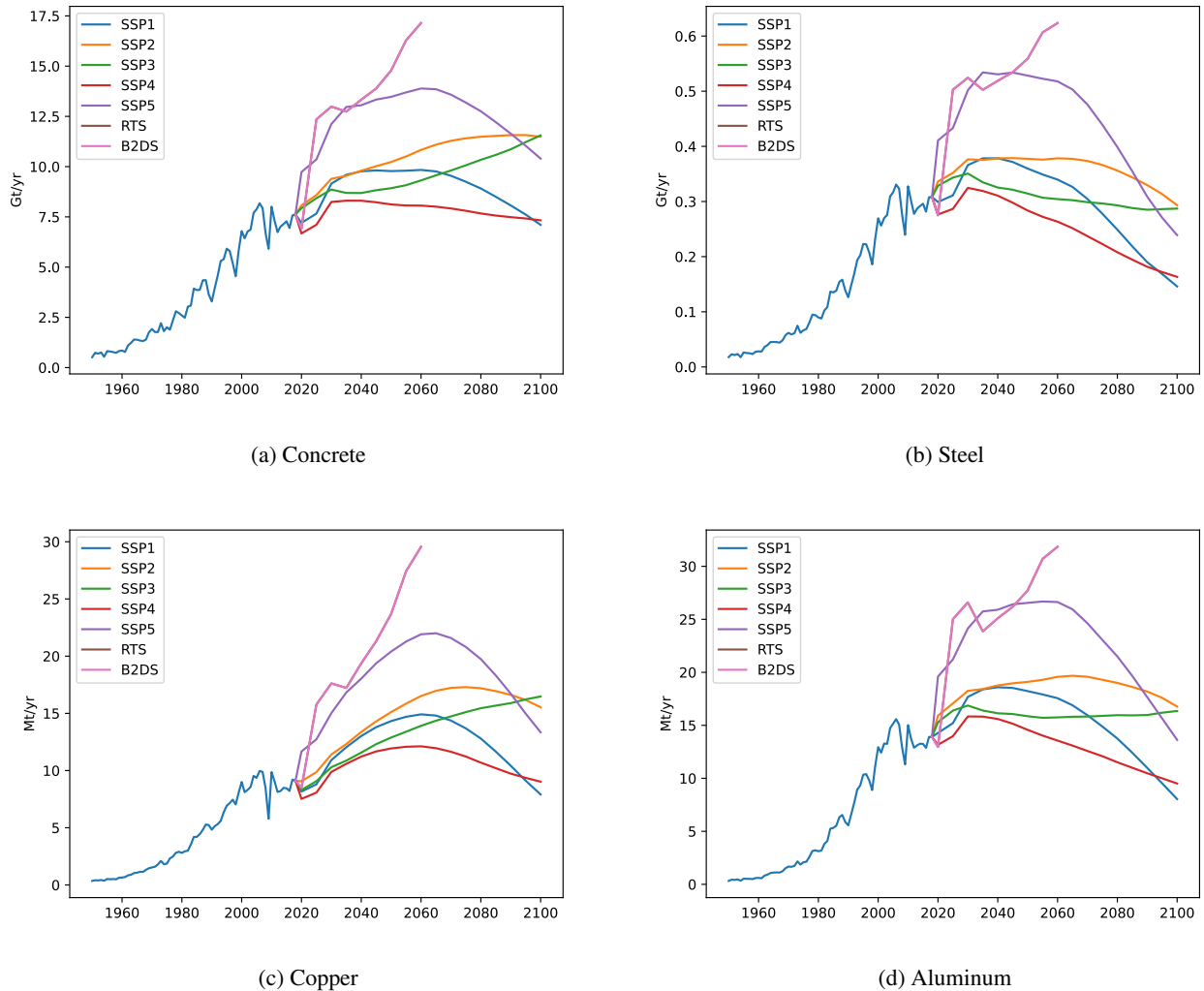
**Figure 4:** In-use stocks of concrete, steel, copper and aluminum in the global building sector. The RTS and B2DS results are almost similar because of their similar building stock.

in the annual inflows increases over time in the SSPs, and remains steady in the RTS and B2DS. The inflow was further segmented between primary and secondary materials, and no secondary concrete was assumed in the study. The recycled steel reaches 15% of the annual flow in 2018, while secondary aluminum and copper respectively represent 5.7% and 4.3% of the inflow. The projected surfaces behavior has a significant impact on the secondary share, since a decreasing floor area allows for a higher share of recycled materials in the inflow. We therefore observe substantial differences between scenarios, and the SSP1 displays twice the share of secondary materials compared to the SSP3, with 78% of recycled steel, 41% of recycled aluminum and 30% of recycled copper.

### 3.1.3. Regional in-use stocks and inflows of materials

The global evolution of raw material in the building sector hinders regional disparities. The areas considered

present different socioeconomic trajectories and construction characteristics (lifespan, materials intensity), resulting in heterogeneous regional demand. While developed areas display more mature building stocks and slow increase of material intensities, developing areas present lower lifetimes, rapidly increasing population, GDP/capita and material intensities. The stock of basic raw materials in use in Europe, North America and the OECD-Pacific region represent just 23% of the global stock by 2100 in the SSP2 (Figure S17), compared with 47% in 1950. It translates into a larger reduction of share in the inflow because of lower lifetimes in developing areas than in developed areas. Moreover, a few areas represent most of future demand of base raw materials. Africa, China, India and Other Asia account for 63% to 67% of the total cumulative inflow between 2025 and 2100 in the SSPs. Moreover, the in-use stocks per capita shows many disparities between scenarios (Figure 6). In particular, there are major differences in the levels reached by industrialising countries by the end of the century. The inequalities between



**Figure 5:** Annual inflows of concrete, steel, copper and aluminum in the global building sector.

the regional in-use stocks per capita of aluminum and copper display an increase in the two decades before decreasing by the end of the century (Figure 7). This results is explained by the assumptions on material intensities.

### 3.2. Materials production energy

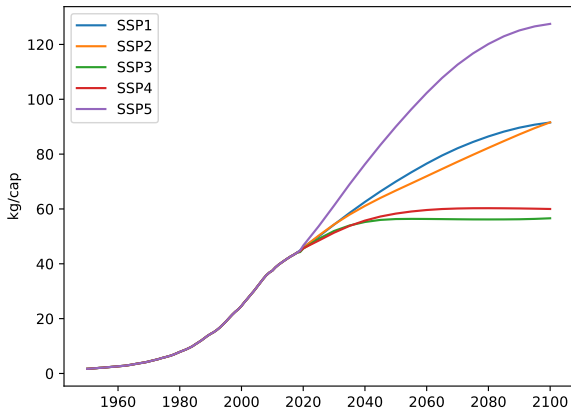
The energy and environmental cost of extracting and transforming the base materials experienced a significant rise during the historical period. The production energy of raw materials increased from 3,100 PJ/yr in 1950 to nearly 29,800 PJ/yr in 2006, before dropping to 22,600 PJ/yr in 2018, as a direct effect of the 2007-2008 financial crisis. It represents about 4% of the global final energy demand (Table 6). The energy consumed for materials production finally reaches between 6,670 PJ/yr and 12,600 PJ/yr in 2100 in the SSPs, which corresponds to 1960-1970 levels. The required energy remains higher in the RTS and B2DS than in the SSPs in 2060.

### 3.3. Impacts reduction potential

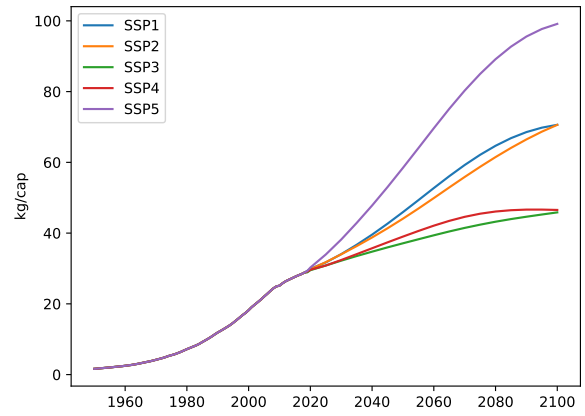
#### 3.3.1. Concrete recovery

The assumed growing share of recovery of concrete leads to a rise of recovered flow of concrete from 0.1 Gt/yr in 1993 to more than 1.2 Gt/yr in 2018, with a recovered stock amounting to 16 Gt. The recovered stock then displays little differences between scenarios, due to the time-delay effect of long lifetime in the building sector. The recovered flow finally reaches between 2.9 Gt/yr and 4.5 Gt/yr in 2100, and the recovered stock grows to more than 200 Gt in all the scenarios (Figure S18). A noteworthy result is the evolution of the lost stock with the assumed growing concrete recovery compared to constant 2020 regional shares until 2100. The Figure S18 shows the comparison for the lowest lost stock (SSP4) and the highest value (SSP5). We observe differences amounting to about 65 Gt between the two scenarios, which represents between 18% and 20% of concrete lost stock reduction in landfills.

Material requirements and impacts of the building sector in the Shared Socioeconomic Pathways

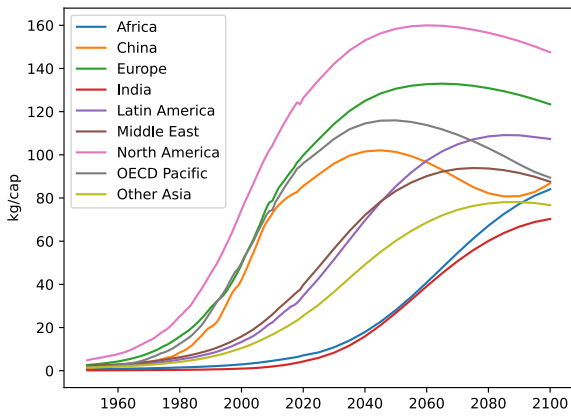


(a) Aluminum

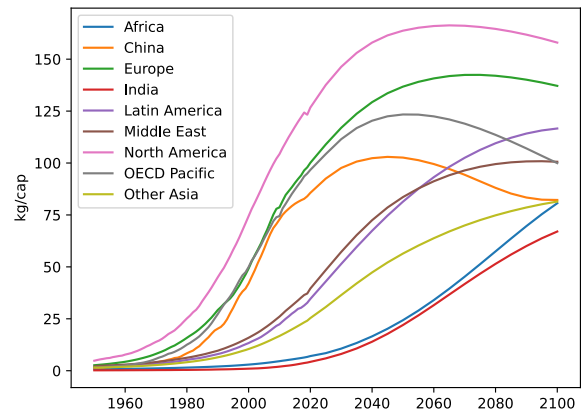


(b) Copper

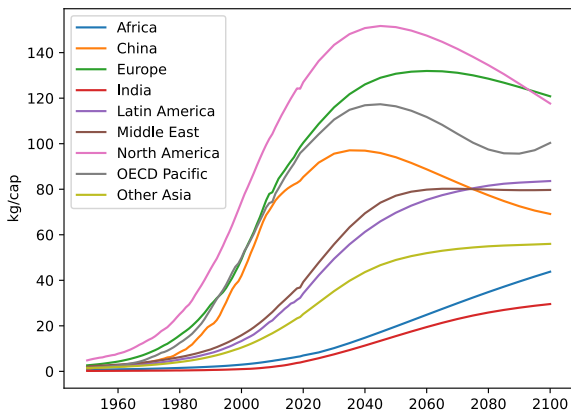
Figure 6: Stock per capita by scenarios in the building sector.



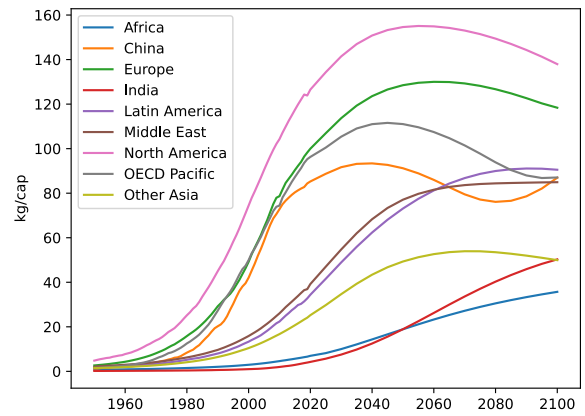
(a) SSP1



(b) SSP2



(c) SSP3



(d) SSP4

Figure 7: Stock per capita of aluminum by scenarios and areas in the building sector. Further regional results are available in the Supplementary Information.



Green concrete reduction	Production energy reduction
GC1	4%
GC2	8%
GC3	12%
GC4	4%

**Table 4**

Energy demand reductions in the scenarios in 2100 for a use of green concretes on 20% of the concrete inflow.

### 3.3.2. Concrete recycling

Three cases of RCA replacement are considered. The conservative scenarios assume a 20% RCA replacement of NA in concrete by 2040 or 2060. Both scenarios require maximum annual RCA processing between 0.7 Gt/yr and 1.7 Gt/yr depending on the prospective building stock. The S1 scenario allows for a reduction of the concrete lost stock reaching 16% to 24% in 2100. The 20-year delay observed between the S1 and the S3 creates a higher RCA demand peak in the S3, as the building stocks rise in the early prospective period. It further allows for an average 4% larger lost stock reduction by 2100 in the S3. However, even the most ambitious RCA replacement scenario, assuming a 50% level, does not allow for a depletion of the lost stock, which decreases by 41% to 59% in 2100 in the seven selected building surfaces scenarios.

### 3.3.3. Green concrete

The computation of the four green concrete mixes shows that their use could reduce the energy demand and the CO<sub>2</sub> emissions of concrete production between 4% and 12% by 2060 for a 20% penetration scenario (Table 4). A full penetration of green concrete in the inflow of the building sectors shows significant reduction of concrete impacts. The energy demand drops between 19% and 60% depending on the concrete mix considered, as expected by the design of the green concrete mixes. The CFA and BFS demand display the same profile in the scenarios as the concrete inflows in Figure 5a. The CFA requirements could reach more than 700 Mt/yr between 2030 and 2040 in the 100% penetration scenario for the GC2 and GC3 mixes, and more than 140 Mt/yr in the 20% penetration case. For the GC4 mix, the BFS needs reach more than 70 Mt in the 20% case and almost 500 Mt in the 100% case in the early 2030s.

## 4. Discussion

### 4.1. Saturation levels of per-capita surface

The per-capita floor areas display high final levels in the B2DS and RTS of the IEA (2017) and show steep rises until 2060. Considering the medium population scenario of the United Nations et al. (2019), the per-capita floor area reaches 102 m<sup>2</sup>/capita in Europe, 117 m<sup>2</sup>/capita in North America and 127 m<sup>2</sup>/capita in the OECD Pacific area in

2060<sup>28</sup>. The global average per-capita floor area finally raises from 32 m<sup>2</sup>/cap in 2017 to 48 m<sup>2</sup>/cap in 2050 and 53 m<sup>2</sup>/cap in 2060. The RTS and B2DS final per-capita floor areas were not designed with saturation level, and the total floor area displays a linear profile. We consider this linear assumption to be unrealistic<sup>29</sup>, and the final levels are not in line with the few prospective estimation available in the literature. The SSPs display substantially lower per-capita stock values, estimated between 54 and 66 m<sup>2</sup>/cap in Europe, 66 and 83 m<sup>2</sup>/cap in North America and 53 to 66 m<sup>2</sup>/cap in the OECD Pacific. Deetman et al. (2020) and Marinova et al. (2020) estimated a global value of about 38 m<sup>2</sup>/cap in 2050 in the SSP2 scenario, which is 24% lower than in the IEA (2017) study. In a normative 1.5°C scenario, Grubler et al. (2018) estimated a global convergence to 30 m<sup>2</sup>/cap. In China, Hong et al. (2016, 2014) and Cao et al. (2018) depicted potential saturation levels of 46 m<sup>2</sup>/capita to 50 m<sup>2</sup>/capita for the Chinese residential sector in 2050. Considering the historical share of non-residential surfaces in the global stock of 16% (Pan et al., 2020), the saturation level of the global stock could amount to 53 to 58 m<sup>2</sup>/capita in 2050, in line with the SSPs, but significantly lower than the RTS and B2DS. Given the impact of floor area per capita assumption in the total floor area projections, an in-depth analysis of their future regional saturation levels has yet to be conducted to assess the consistency of scenarios.

### 4.2. Material weight of the building sector and comparison with previous studies

The results reflect a significant share of the building sector in the global materials consumption. The global total demand for concrete was estimated to about 24 Gt/yr in 2020 (USGS, 2021a)<sup>30</sup>. The calculated demand in the building sector reaches 8 Gt/yr in 2018, which represents about 40% this global consumption. The steel inflow of 2019 amounts to 18% of the global steel demand. It remains low in comparison to the 50% estimate of Worldsteel (2021). The construction sector however also includes infrastructures and networks, which could partially explain this difference. The copper demand estimated exceeds 40% of the global refined consumption, which is above the 30% common estimated of the building share in the global demand, with regional disparities (Schipper et al., 2018; Dong et al., 2019; Institute, 2021; ICSG, 2014). It indicates lower actual copper intensities to the selected values. The aluminum consumption of buildings was evaluated to 56% of the global demand in 2018, which is larger than in the estimates<sup>31</sup>.

Finally, the results were compared with previous prospective studies focusing on the SSPs. Greater use of industrial ecology tools in integrated assessment models (IAMs)

<sup>28</sup>In relative terms, the higher increase is observed in India, Other Asia and OECD Pacific, with floor area per capita increasing by 125% to 167% between 2017 and 2060.

<sup>29</sup>A saturation level is already observed in France. Insee (2017) reported an almost steady residential floor area per capita of 40 m<sup>2</sup>/capita since 2006.

<sup>30</sup>We considered a 20% share of cement in concrete.

<sup>31</sup>A 25% to 37% share of building and construction in aluminum demand is observed.

has been identified as a potential avenue for improvement towards more coherent scenarios (Pauliuk et al., 2017). Over the past years, several studies have proposed ex-post estimations of material requirements in SSPs. Marinova et al. (2020) and Deetman et al. (2020) analyzed the regional need for base materials for residential and service buildings in the SSP2, Pedneault et al. (2022) estimated global future aluminum stocks and flows for six sectors and all SPPs while Klose and Pauliuk (2023) studied the global copper requirements in the SSP2. The estimation in this study align well with Pedneault et al. (2022) for aluminum, with Deetman et al. (2020) for steel, concrete and copper and are higher than in Klose and Pauliuk (2023) for copper. The authors estimated an increase of the in-use stock of copper per capita in a building sector from about 28 kg/cap to 37 kg/cap between 2015 and 2050. In this study, we observe a similar result in 2015, but a significantly larger stock per capita in 2050 (Figure 6b). This could be explained by the rapid increase in the material intensity of copper in the industrialising regions considered in this study. The Table S12 summarizes the results of the different studies.

### 4.3. Increasing materials demand and the potential of RCA

The results show an increase of the building stock until 2060 or 2100 with various paces for the selected materials. It is explained by both new construction and renovation. We firstly observe increasing population and GDP per capita in most of the scenarios, and rising base materials intensities in the less developed areas. Moreover, a growing development of renovation policies is observed in the scenarios to tackle the environmental impact of the building sector. We estimated that the aluminum weight of renovated surfaces could be significant in Europe, North America and China, while both concrete and steel display low amount in the renovation process. The regional policies could therefore carry a substantial impact on the aluminum demand.

The increase of the materials in-use stock will create outflows of construction and demolition wastes, which could ultimately translate into a growing landfills burden. The potential of higher share of concrete recovery was showed to reduce the concrete lost stock, and it is crucial to quickly develop recovery strategies, because of the time-delay effect on outflows of long lifetimes in the building sector. The RCA replacement could further allows to use CDW as a "secondary mine". However, we estimated that no depletion of the concrete in landfills could occur in case of a late and low-scale use of RCA. In a very ambitious scenario, the lost stock could be depleted between 2047 and 2060 in all the scenarios for a 100% RCA replacement on 100% of the inflow. The RCA demand could reach 3.5 Gt/yr to 8.6 Gt/yr. It shows the magnitude of the lost stock, and the importance of policies in the feasibility of quickly initiating a RCA processing industry.

### 4.4. Impacts of materials production and the significant role of green concrete in reducing concrete impacts

The base materials demand estimated in the study represents about 4% of the final energy consumption in 2018. It was estimated that concrete had the most impact, with 2.7% of the final energy demand. Given the shares of the global materials demands evaluated in Section 4.2, the global concrete and steel industries represent between 11% and 13% of the final energy consumption in 2018, in line with Bataille (2019) and Andrew (2017). The prospective shares were estimated for the RTS, B2DS and two different RCP<sup>32</sup> applied on the SSP1, SSP2 and SSP3 (Table 6). We observe lower shares of production energy of materials in final energy demand than the 2018 level, except for the B2DS. It is explained by the significant reduction in final energy demand, and similar socioeconomic assumptions to the RTS. Moreover, the more stringent the RCP, the higher the share of production energy of materials in total final energy demand. It is explained by a substantial decrease of energy demand at the end of the century to reach a lower radiative forcing. Our results further show that the production energy of materials is substantial when compared to the final energy demand of the building sector. It could amount to about 10% of the cumulative final energy demand of the building sector between 2015 and 2100 in the SSP2 2p6, and 32% in the B2DS between 2015 and 2060 (Table 5).

Therefore, despite a context of growing demography and GDP per capita, the final energy demand of producing base raw materials could decrease. In order to reach stringent climate objectives, low-energy demand scenarios are considered, despite still displaying medium to high assumptions of socioeconomic parameters. However, accounting for the final energy demand of the production phase of infrastructures and the impacts of a decline of ore grade could show a growing share of future total final energy demand.

The rising shares of the production energy of materials in final energy demand between 2060 and 2100 unveil the issue of the feasibility of ambitious scenarios with medium or high socioeconomic assumptions. Accounting for the final energy demand of the production phase of infrastructures and the impacts of a decline of ore grade could show a growing share of future total final energy demand. The share of the base materials production for the building sector increases in 2060 compared to the historical level, and could reach 7.3% of the final energy demand in the B2DS. A similar trend in others sectors-such as the development of renewable energies (Vidal et al., 2017, 2018) or storage devices (Deetman et al., 2021)-could create a substantial energy constraint due to the materials production. Concrete represents most of the energy demand among the four selected base materials. The implementation of a higher share of green concrete depicted in Section 2.4 could provide an option to actually reduce the energy and environmental impacts of concrete production

<sup>32</sup>The Representative Concentration Pathways are scenarios of radiative forcing, as previously presented in Section 2.1. It acts as a climate policy in the SSP.

Scenario	Final energy of materials production (EJ)	Final energy in the building sector (EJ)	Total final energy demand (EJ)
SSP1 2p6	1,350	14,100	47,430
SSP2 2p6	1,560	15,100	52,200
SSP3 4p5	1,410	14,000	51,400
SSP4 4p5	1,190	14,100	52,150
SSP5 baseline	1,890	22,400	73,980
B2DS	1,390	4,300	15,480
RTS	1,390	6,300	24,130

**Table 5**

Estimations of cumulative production energy of materials in new buildings and comparison with the final energy demand between 2015 and 2100 for SSPs and between 2015 and 2060 for RTS and B2DS.

Scenario	Final energy of material production (EJ)				
	1950	2018	2040	2060	2100
SSP1 2p6			20	18	6.7
SSP2 2p6			24	19	12
SSP3 4p5	3.1	23	24	16	12
SSP4 4p5			20	14	7.4
SSP5 baseline			32	25	10
B2DS			33	31	
RTS			33	31	
SSP2 2p6 with GC2-20%			23	19	11
SSP2 2p6 with GC3-20%			22	17	11
SSP2 2p6 with GC2-100%	3.1	23	18	12	7.9
SSP2 2p6 with GC3-100%			15	8.4	5.4
B2DS with GC2-20%			31	29	
B2DS with GC3-20%			30	28	
B2DS with GC2-100%			25	20	
B2DS with GC3-100%			20	13	

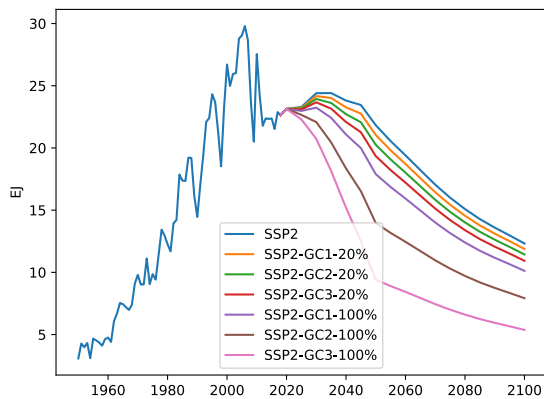
**Table 6**

Final energy demand of the base materials production in the selected scenarios. The results of the SSP2 and B2DS are further displayed with the green concrete scenarios on 20% or 100% of the inflow.

while considering higher socioeconomic pathways. We observed in Section 3.3.3 the energy reduction potential when green concrete mixes were used on 20% or 100% of the flow. In the most optimistic case, the GC3 used on 100% of the B2DS concrete inflow would allow to reduce the building materials share of the energy demand below the level of the RTS, and the GC2 induces intermediate results. When applied on the SSP2 2p6, it the GC mixes allow substantial energy savings in the peak demand years. In 2040, between 1 and 9 EJ could thus be saved in the SSP2 in comparison with a BAU case, and it could reach 0.4 to 6.9 EJ in 2100 (Figure 8). The GC mixes could therefore provide a significant tool

to further decrease the impact of concrete while consuming industrial or agriculture by-products.

The rise in green concrete demand induces a growing by-products demand. The feasibility of a large development of some green concrete mixes could therefore be hampered by a decrease in the main products demand, and our model shows that a penetration of CFA on 100% of the concrete inflow could create shortage in most of the scenarios at a global level. The development of various low carbon concrete mixes could prevent dependency to one materials, and rely on regional by-products availability. Further assessments of the dynamic between the industrial by-products generation, their stocks, the penetration rate



**Figure 8:** Comparison of final energy for base material production in the building sector.

of green concretes and their composition would allow to identify the opportunities and the constraints of a large use of green concrete to decrease the energy demand of materials in the building sector. Further implementation of material efficiency strategies (Allwood et al., 2013; Shanks et al., 2019; Pauliuk et al., 2021) are not considered and could provide additional tools in a further analyses.

#### 4.5. Limitations

This study proposes a regional approach of the building sector, modeling raw materials as well as their embodied energy. Several limitations to a more accurate modeling were however identified. Firstly, as emphasized in Augiseau and Barles (2017) and Müller et al. (2014), data intensity and data quality significantly undermine construction materials modeling studies, and induce strong impact on outputs. In this bottom-up study, the difficulty to assess materials intensities was observed, and revealed significant errors in the copper demand results. Few analysis tackle the regional disparities in both construction mixes (concrete and steel) and other material uses (copper and aluminum), their evolution over time and the uncertainties. If the selected level of concrete consumption in buildings is in accordance to common values of the literature, the estimated copper and aluminum regional material intensities suffer of significant uncertainties. This issue could benefit from lower scale studies assessing the local intensities. We believe that both household and multi-regional level studies could be complementary to further understand the local materials cycle dynamics while providing input for more accurate large-scale analysis and allowing a better understanding of building life cycle management.

Secondly, the overall building life span is considered, without distinctions on the incorporated devices. Given the structural nature of concrete and steel, this assumption is reliable. It could however induce uncertainties for copper and aluminum, if mainly incorporated in less structural devices such as electrical applications (Schipper et al., 2018).

Further studying on the specific uses of materials in construction is needed to assess the impact of this overall life span assumption. Thirdly, the considered collect rates are not specific to the building sector, which is not a physical reality.

## 5. Conclusion

Human demography is a growing concern in current environmental studies. It carries crucial impacts on residential and non-residential building stock growth over the coming decades, and was analyzed through six socioeconomic pathways combined with climate scenarios. Firstly, the base materials stocks and flows of the building sector was estimated, as well as the final energy of raw materials production. Secondly, the results were confronted to the prospective energy of the selected scenarios, and two solutions were implemented to reduce the impacts of concrete.

We firstly find that (i) the material dependency of the building sector could create a massive rise of the inflows, further enhanced by two aspects: the considered increase of the materials intensities in the less developed areas. We further show that (ii) strong inequalities are observed in the in-use stocks per capita of materials in the SSPs, despite optimistic material intensities projection, (iii) a growing materials demand translates into larger final energy demand of material production, which could question the feasibility of some low-energy demand scenarios, and that (iv) the recycled concrete aggregated display a significant potential to enhance the reduction of accumulated concrete stocks in landfills and green concrete could decrease the energy demand of concrete production.

We furthermore highlight the crucial temporal aspect of the RCA and green concrete implementation, as it requires the development of industries to tackle the large concrete demand of the building sector. These strategies remain however insufficient to limit human impact within planetary boundaries. They should be used in conjunction with other measures (e.g. material efficiency), and as part of an in-depth review of uses, with the broader aim of achieving a decent standard of living for as many people as possible while limiting the impact on the environment.

## CRedit authorship contribution statement

**Hugo Le Boulzec:** Conceptualization, Methodology, Software, Data Curation, Writing - Original Draft, Writing - Review & Editing. **Sandrine Mathy:** Methodology, Writing - Review & Editing, Supervision. **François Verzier:** Visualization, Software, Writing - Review & Editing. **Baptiste Andrieu:** Visualization, Software, Writing - Review & Editing. **Daniel Monfort-Climent:** Writing - Review & Editing. **Olivier Vidal:** Software, Writing - Review & Editing, Supervision, Funding acquisition.



## Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

## Acknowledgments

We would like to thank the two anonymous reviewers for their comments that helped improving our manuscript, as well as Francesco Ricci and Ester van der Voet for reviewing an earlier version of this manuscript.

## Funding

This work was supported by the project SURFER financed by the French Environment and Energy Management Agency (ADEME) and the grant ANR-21-CE03-0012 SCARCYCLET, without any involvement in the conduct of the research and the preparation of the article.

## References

- ADEME, Leonardon, P., CSTB, Laurenceau, S., Louerat, M., 2018. Prospective de consommation de matière pour les bâtiments neufs aux horizons 2035 et 2050. Technical Report. ADEME, CSTB.
- Aktas, C.B., Bilec, M.M., 2012. Impact of lifetime on US residential building LCA results. *The International Journal of Life Cycle Assessment* 17, 337–349. URL: <http://link.springer.com/10.1007/s11367-011-0363-x>, doi:10.1007/s11367-011-0363-x.
- Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2013. Material efficiency: providing material services with less material production. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 371, 20120496. URL: <https://royalsocietypublishing.org/doi/10.1098/rsta.2012.0496>, doi:10.1098/rsta.2012.0496.
- Andrew, R., 2017. Global CO2 Emissions From Cement Production. URL: <https://zenodo.org/record/831455>, doi:10.5281/ZENODO.831455. type: dataset.
- Augiseau, V., Barles, S., 2017. Studying construction materials flows and stock: A review. *Resources, Conservation and Recycling* 123, 153–164. URL: <http://linkinghub.elsevier.com/retrieve/pii/S092134491630235X>, doi:10.1016/j.resconrec.2016.09.002.
- Azari, R., Abbasabadi, N., 2018. Embodied energy of buildings: A review of data, methods, challenges, and research trends. *Energy and Buildings* 168, 225–235. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0378778817327937>, doi:10.1016/j.enbuild.2018.03.003.
- Bataille, C., 2019. Low and zero emissions in the steel and cement industries. Barriers, technologies and policies. Technical Report. OECD.
- Behera, M., Bhattacharyya, S., Minocha, A., Deoliya, R., Maiti, S., 2014. Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review. *Construction and Building Materials* 68, 501–516. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0950061814007181>, doi:10.1016/j.conbuildmat.2014.07.003.
- Bleichschwitz, R., Hoff, H., Spataru, C., van der Voet, E., VanDeveer, S.D., 2018a. *Routledge Handbook of the Resource Nexus*. Routledge. URL: <https://www.routledge.com/Routledge-Handbook-of-the-Resource-Nexus/Bleichschwitz-Hoff-Spataru-Voet-VanDeveer/p/book/9780367505288>.
- Bleichschwitz, R., Nechifor, V., Winning, M., Huang, B., Geng, Y., 2018b. Extrapolation or saturation – Revisiting growth patterns, development stages and decoupling. *Global Environmental Change* 48, 86–96. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959378016306550>, doi:10.1016/j.gloenvcha.2017.11.008.
- Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., Kim, S., Kyle, P., Link, R., Moss, R., McJeon, H., Patel, P., Smith, S., Waldhoff, S., Wise, M., 2017. The SSP4: A world of deepening inequality. *Global Environmental Change* 42, 284–296. doi:10.1016/j.gloenvcha.2016.06.010.
- Cao, Z., Liu, G., Duan, H., Xi, F., Liu, G., Yang, W., 2019. Unraveling the mystery of Chinese building lifetime: A calibration and verification based on dynamic material flow analysis. *Applied Energy* 238, 442–452. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0306261919301072>, doi:10.1016/j.apenergy.2019.01.106.
- Cao, Z., Shen, L., Zhong, S., Liu, L., Kong, H., Sun, Y., 2018. A Probabilistic Dynamic Material Flow Analysis Model for Chinese Urban Housing Stock: A Probabilistic Dynamic MFA Model. *Journal of Industrial Ecology* 22, 377–391. URL: <https://onlinelibrary.wiley.com/doi/10.1111/jiec.12579>, doi:10.1111/jiec.12579.
- Chastas, P., Theodosiou, T., Bikas, D., 2016. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment* 105, 267–282. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360132316301986>, doi:10.1016/j.buildenv.2016.05.040.
- Chen, W.Q., Graedel, T.E., 2015. In-use product stocks link manufactured capital to natural capital. *Proceedings of the National Academy of Sciences* 112, 6265–6270. URL: <http://www.pnas.org/lookup/doi/10.1073/pnas.1406866112>, doi:10.1073/pnas.1406866112.
- Deetman, S., de Boer, H., Van Engelenburg, M., van der Voet, E., van Vuuren, D., 2021. Projected material requirements for the global electricity infrastructure – generation, transmission and storage. *Resources, Conservation and Recycling* 164, 105200. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344920305176>, doi:10.1016/j.resconrec.2020.105200.
- Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D.P., Edelenbosch, O., Heijungs, R., 2020. Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production* 245, 118658. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959652619335280>, doi:10.1016/j.jclepro.2019.118658.
- Dong, D., Tukker, A., Van der Voet, E., 2019. Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis. *Journal of Industrial Ecology* 23, 1363–1380. doi:10.1111/jiec.12926.
- Economidou, M., Todeschi, V., Bertoldi, P., D’Agostino, D., Zangheri, P., Castellazzi, L., 2020. Review of 50 years of EU energy efficiency policies for buildings. *Energy and Buildings* 225, 110322. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0378778820317229>, doi:10.1016/j.enbuild.2020.110322.
- Elshkaki, A., 2019. Materials, energy, water, and emissions nexus impacts on the future contribution of PV solar technologies to global energy scenarios. *Scientific Reports* 9, 19238. URL: <http://www.nature.com/articles/s41598-019-55853-w>, doi:10.1038/s41598-019-55853-w.
- European Environment Agency, 2021. Construction and demolition waste: challenges and opportunities in a circular economy. URL: <https://www.eea.europa.eu/publications/construction-and-demolition-waste-challenges>.
- Flower, D.J.M., Sanjayan, J.G., 2007. Green house gas emissions due to concrete manufacture. *The International Journal of Life Cycle Assessment* 12, 282–288. URL: <http://link.springer.com/10.1065/lca2007.05.327>, doi:10.1065/lca2007.05.327.
- Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D.L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W., Riahi, K., 2017. The marker quantification of the shared socioeconomic pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change* 42, 251–267. doi:10.1016/j.gloenvcha.2016.06.004.
- Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D.S., Dai, H., Hijioka, Y., Kainuma, M., 2017. SSP3: AIM implementation of shared socioeconomic pathways. *Global Environmental Change* 42, 268–283. doi:10.1016/j.gloenvcha.2016.06.009.



- Ginga, C.P., Ongpeng, J.M.C., Daly, M.K.M., 2020. Circular Economy on Construction and Demolition Waste: A Literature Review on Material Recovery and Production. *Materials* 13, 2970. URL: <https://www.mdpi.com/1996-1944/13/13/2970>, doi:10.3390/ma13132970.
- Giurco, D., McLellan, B., Franks, D.M., Nansai, K., Prior, T., 2014. Responsible mineral and energy futures: views at the nexus. *Journal of Cleaner Production* 84, 322–338. URL: <http://linkinghub.elsevier.com/retrieve/pii/S0959652614006805>, doi:10.1016/j.jclepro.2014.05.102.
- Gontia, P., Nägeli, C., Rosado, L., Kalmykova, Y., Österbring, M., 2018. Material-intensity database of residential buildings: A case-study of Sweden in the international context. *Resources, Conservation and Recycling* 130, 228–239. doi:10.1016/j.resconrec.2017.11.022.
- Graedel, T., Bertram, M., Fuse, K., Gordon, R., Lifset, R., Rechberger, H., Spataro, S., 2002. The contemporary European copper cycle: The characterization of technological copper cycles. *Ecological Economics* 42, 9–26. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921800902001015>, doi:10.1016/S0921-8009(02)00101-5.
- Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy* 3, 515–527. URL: <http://www.nature.com/articles/s41560-018-0172-6>, doi:10.1038/s41560-018-0172-6.
- Gu, L., Ozbakkaloglu, T., 2016. Use of recycled plastics in concrete: A critical review. *Waste Management* 51, 19–42. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0956053X16300915>, doi:10.1016/j.wasman.2016.03.005.
- Guo, H., Shi, C., Guan, X., Zhu, J., Ding, Y., Ling, T.C., Zhang, H., Wang, Y., 2018. Durability of recycled aggregate concrete – A review. *Cement and Concrete Composites* 89, 251–259. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0958946517310958>, doi:10.1016/j.cemconcomp.2018.03.008.
- Göswein, V., Silvestre, J.D., Habert, G., Freire, F., 2019. Dynamic Assessment of Construction Materials in Urban Building Stocks: A Critical Review. *Environmental Science & Technology* 53, 9992–10006. URL: <https://pubs.acs.org/doi/10.1021/acs.est.9b01952>, doi:10.1021/acs.est.9b01952.
- Habert, G., 2014. Assessing the environmental impact of conventional and ‘green’ cement production, in: *Eco-efficient Construction and Building Materials*. Elsevier, pp. 199–238. URL: <https://linkinghub.elsevier.com/retrieve/pii/B9780857097675500108>, doi:10.1533/9780857097729.2.199.
- Harvey, L.D., Korytarova, K., Lucon, O., Roshchanka, V., 2014. Construction of a global disaggregated dataset of building energy use and floor area in 2010. *Energy and Buildings* 76, 488–496. URL: <https://linkinghub.elsevier.com/retrieve/pii/S037877881400231X>, doi:10.1016/j.enbuild.2014.03.011.
- Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N., Ali, S., Tu, Q., Ardente, F., Berrill, P., Fishman, T., Kanaoka, K., Kulczycka, J., Makov, T., Masanet, E., Wolfram, P., 2019. Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Technical Report. Zenodo. URL: <https://zenodo.org/record/3542680>, doi:10.5281/ZENODO.3542680. ISBN: 9789280737714.
- Holland, R., Kurtis, K., Kahn, L., 2016. Effect of different concrete materials on the corrosion of the embedded reinforcing steel, in: *Corrosion of Steel in Concrete Structures*. Elsevier, pp. 131–147. URL: <https://linkinghub.elsevier.com/retrieve/pii/B9781782423812000079>, doi:10.1016/B978-1-78242-381-2.00007-9.
- Hong, L., Zhou, N., Feng, W., Khanna, N., Fridley, D., Zhao, Y., Sandholt, K., 2016. Building stock dynamics and its impacts on materials and energy demand in China. *Energy Policy* 94, 47–55. doi:10.1016/j.enpol.2016.03.024.
- Hong, L., Zhou, N., Fridley, D., Feng, W., Khanna, N., 2014. Modeling China’s Building Floor-Area Growth and the Implications for Building Materials and Energy Demand. ACEEE Summer Study on Energy Efficiency in Buildings , 12.
- Hu, M., Pauliuk, S., Wang, T., Huppes, G., van der Voet, E., Müller, D.B., 2010. Iron and steel in Chinese residential buildings: A dynamic analysis. *Resources, Conservation and Recycling* 54, 591–600. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344909002407>, doi:10.1016/j.resconrec.2009.10.016.
- Huo, T., Cai, W., Ren, H., Feng, W., Zhu, M., Lang, N., Gao, J., 2019. China’s building stock estimation and energy intensity analysis. *Journal of Cleaner Production* 207, 801–813. doi:10.1016/j.jclepro.2018.10.060.
- ICSG, 2014. The World Copper Factbook 2014. Technical Report. ICSG. URL: <https://copperalliance.org/wp-content/uploads/2012/01/ICSG-Factbook-2014.pdf>.
- IEA, 2014. Energy Technology Perspectives 2014. Technical Report. IEA.
- IEA, 2017. Energy Technology Perspectives 2017. Technical Report. IEA.
- IEA, 2018. Global Status Report 2018. Technical Report. IEA. URL: <https://www.worldgbc.org/sites/default/files/2018%20GlobalABC%20Global%20Status%20Report.pdf>.
- IEA, 2021. IEA Sankey Diagram. URL: <https://www.iea.org/sankey/>.
- Insee, 2017. Les conditions de logement en France. Technical Report. Insee.
- Institute, E.C., 2021. Europe’s Copper Industry - How Copper is Produced and Where It’s Used. URL: <https://copperalliance.eu/about-us/europes-copper-industry/>. publisher: European Copper Institute.
- IPCC, 2021. Climate Change 2021 : The physical science basis. Technical Report IPCC AR6 WGI. IPCC. URL: [https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC\\_AR6\\_WGI\\_SPM.pdf](https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf).
- Jiang, Y., Ling, T.C., Shi, C., Pan, S.Y., 2018. Characteristics of steel slags and their use in cement and concrete—A review. *Resources, Conservation and Recycling* 136, 187–197. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344918301617>, doi:10.1016/j.resconrec.2018.04.023.
- Kim, S.H., Edmonds, J., Lurz, J., Smith, S.J., Wise, M., 2006. The O bj ECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation. *The Energy Journal* 27, 63–91. URL: <http://www.jstor.org/stable/23297046>.
- Kleemann, F., Lederer, J., Aschenbrenner, P., Rechberger, H., Fellner, J., 2016. A method for determining buildings’ material composition prior to demolition. *Building Research & Information* 44, 51–62. doi:10.1080/09613218.2014.979029.
- Klose, S., Pauliuk, S., 2023. Sector-level estimates for global future copper demand and the potential for resource efficiency. *Resources, Conservation and Recycling* 193, 106941. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344923000782>, doi:10.1016/j.resconrec.2023.106941.
- Kurda, R., Silvestre, J.D., de Brito, J., 2018. Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash. *Resources, Conservation and Recycling* 139, 407–417. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344918302490>, doi:10.1016/j.resconrec.2018.07.004.
- Le Boulzec, H., Delannoy, L., Andrieu, B., Verzier, F., Vidal, O., Mathy, S., 2022. Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data. *Applied Energy* 326, 119871. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0306261922011369>, doi:10.1016/j.apenergy.2022.119871.
- Marinković, S., Carević, V., 2019. Comparative studies of the life cycle analysis between conventional and recycled aggregate concrete, in: *New Trends in Eco-efficient and Recycled Concrete*. Elsevier, pp. 257–291. URL: <https://linkinghub.elsevier.com/retrieve/pii/B978081024805000105>, doi:10.1016/B978-0-08-102480-5.00010-5.
- Marinova, S., Deetman, S., van der Voet, E., Daioglou, V., 2020. Global construction materials database and stock analysis of residential buildings between 1970–2050. *Journal of Cleaner Production* 247, 119146. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959652619340168>, doi:10.1016/j.jclepro.2019.119146.
- Marsh, R., 2017. Building lifespan: effect on the environmental impact of building components in a Danish perspective. *Architectural Engineering and Design Management* 13, 80–100. URL: <https://www>.

- andfonline.com/doi/full/10.1080/17452007.2016.1205471, doi:10.1080/17452007.2016.1205471.
- Mastrucci, A., van Ruijven, B., Byers, E., Poblete-Cazenave, M., Pachauri, S., 2021. Global scenarios of residential heating and cooling energy demand and CO<sub>2</sub> emissions. *Climatic Change* 168, 14. URL: <https://link.springer.com/10.1007/s10584-021-03229-3>, doi:10.1007/s10584-021-03229-3.
- McLellan, B.C., 2017. The Minerals-Energy Nexus: Past, Present and Future, in: Matsumoto, M., Masui, K., Fukushima, S., Kondoh, S. (Eds.), *Sustainability Through Innovation in Product Life Cycle Design*. Springer Singapore, Singapore, pp. 619–631. URL: [http://link.springer.com/10.1007/978-981-10-0471-1\\_42](http://link.springer.com/10.1007/978-981-10-0471-1_42), doi:10.1007/978-981-10-0471-1\_42. series Title: EcoProduction.
- Miatto, A., Schandl, H., Tanikawa, H., 2017. How important are realistic building lifespan assumptions for material stock and demolition waste accounts? *Resources, Conservation and Recycling* 122, 143–154. URL: <http://linkinghub.elsevier.com/retrieve/pii/S0921344917300265>, doi:10.1016/j.resconrec.2017.01.015.
- Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. *Nature* 463, 747–756. URL: <http://www.nature.com/articles/nature08823>, doi:10.1038/nature08823.
- Müller, D., 2006. Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. *Ecological Economics* 59, 142–156. doi:10.1016/j.ecolecon.2005.09.025.
- Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environmental Science & Technology* 48, 2102–2113. URL: <http://pubs.acs.org/doi/abs/10.1021/es403506a>, doi:10.1021/es403506a.
- Nasir, U., Chang, R., Omrany, H., 2021. Calculation Methods for Construction Material Stocks: A Systematic Review. *Applied Sciences* 11, 6612. URL: <https://www.mdpi.com/2076-3417/11/14/6612>, doi:10.3390/app11146612.
- Ortlepp, R., Gruhler, K., Schiller, G., 2016. Material stocks in Germany's non-domestic buildings: a new quantification method. *Building Research & Information* 44, 840–862. doi:10.1080/09613218.2016.1112096.
- Ortlepp, R., Gruhler, K., Schiller, G., 2018. Materials in Germany's domestic building stock: calculation model and uncertainties. *Building Research & Information* 46, 164–178. doi:10.1080/09613218.2016.1264121.
- O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* 42, 169–180. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959378015000060>, doi:10.1016/j.gloenvcha.2015.01.004.
- O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* 122, 387–400. URL: <http://link.springer.com/10.1007/s10584-013-0905-2>, doi:10.1007/s10584-013-0905-2.
- Pacheco, R., Ordóñez, J., Martínez, G., 2012. Energy efficient design of building: A review. *Renewable and Sustainable Energy Reviews* 16, 3559–3573. URL: <https://linkinghub.elsevier.com/retrieve/pii/S1364032112002286>, doi:10.1016/j.rser.2012.03.045.
- Pan, L., Zhu, M., Lang, N., Huo, T., 2020. What Is the Amount of China's Building Floor Space from 1996 to 2014? *International Journal of Environmental Research and Public Health* 17, 5967. URL: <https://www.mdpi.com/1660-4601/17/16/5967>, doi:10.3390/ijerph17165967.
- Paris, J.M., Roessler, J.G., Ferraro, C.C., DeFord, H.D., Townsend, T.G., 2016. A review of waste products utilized as supplements to Portland cement in concrete. *Journal of Cleaner Production* 121, 1–18. URL: <https://linkinghub.elsevier.com/retrieve/pii/S095965261600158X>, doi:10.1016/j.jclepro.2016.02.013.
- Pauliuk, S., Arvesen, A., Stadler, K., Hertwich, E.G., 2017. Industrial ecology in integrated assessment models. *Nature Climate Change* 7, 13–20. URL: <http://www.nature.com/articles/nclimate3148>, doi:10.1038/nclimate3148.
- Pauliuk, S., Heeren, N., Berrill, P., Fishman, T., Nistad, A., Tu, Q., Wolfram, P., Hertwich, E.G., 2021. Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. *Nature Communications* 12, 5097. URL: <https://www.nature.com/articles/s41467-021-25300-4>, doi:10.1038/s41467-021-25300-4.
- Pauliuk, S., Hertwich, E.G., 2015. Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies. *Ecological Economics* 119, 83–93. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921800915003481>, doi:10.1016/j.ecolecon.2015.08.012.
- Pedneault, J., Majeau-Bettez, G., Pauliuk, S., Margni, M., 2022. Sector-specific scenarios for future stocks and flows of aluminum: An analysis based on shared socioeconomic pathways. *Journal of Industrial Ecology* 26, 1728–1746. URL: <https://onlinelibrary.wiley.com/doi/10.1111/jiec.13321>, doi:10.1111/jiec.13321.
- Reiners, J., Palm, S., 2015. Technical report - Closing the loop: what type of concrete re-use if the most sustainable option? Technical Report. European Cement Research Academy. Düsseldorf.
- Reis, G.S.d., Quattrone, M., Ambrós, W.M., Grigore Cazacliu, B., Hoffmann Sampaio, C., 2021. Current Applications of Recycled Aggregates from Construction and Demolition: A Review. *Materials* 14, 1700. URL: <https://www.mdpi.com/1996-1944/14/7/1700>, doi:10.3390/ma14071700.
- Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., HumpenÄnder, F., Silva, L.A.D., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42, 153–168. doi:10.1016/j.gloenvcha.2016.05.009.
- Rousselot, M., Pinto Da Rocha, F., 2021. Energy efficiency trends in buildings in the EU. Technical Report. ODYSSEE-MURE project.
- Ruparathna, R., Hewage, K., Sadiq, R., 2016. Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews* 53, 1032–1045. URL: <https://linkinghub.elsevier.com/retrieve/pii/S1364032115010540>, doi:10.1016/j.rser.2015.09.084.
- Sandanayake, M., Bouras, Y., Haigh, R., Vrcelj, Z., 2020. Current Sustainable Trends of Using Waste Materials in Concrete—A Decade Review. *Sustainability* 12, 9622. URL: <https://www.mdpi.com/2071-1050/12/22/9622>, doi:10.3390/su12229622.
- Schipper, B.W., Lin, H.C., Meloni, M.A., Wansleben, K., Heijungs, R., van der Voet, E., 2018. Estimating global copper demand until 2100 with regression and stock dynamics. *Resources, Conservation and Recycling* 132, 28–36. doi:10.1016/j.resconrec.2018.01.004.
- Shanks, W., Dunant, C., Drewniok, M.P., Lupton, R., Serrenho, A., Allwood, J.M., 2019. How much cement can we do without? Lessons from cement material flows in the UK. *Resources, Conservation and Recycling* 141, 441–454. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344918304191>, doi:10.1016/j.resconrec.2018.11.002.
- Siddique, R., 2014. Utilization of Industrial By-products in Concrete. *Procedia Engineering* 95, 335–347. URL: <https://linkinghub.elsevier.com/retrieve/pii/S1877705814032512>, doi:10.1016/j.proeng.2014.12.192.
- Silva, R., de Brito, J., Dhir, R., 2014. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials* 65, 201–217. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0950061814004437>, doi:10.1016/j.conbuildmat.2014.04.117.

- Silva, R., de Brito, J., Dhir, R., 2019. Use of recycled aggregates arising from construction and demolition waste in new construction applications. *Journal of Cleaner Production* 236, 117629. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959652619324795>, doi:10.1016/j.jclepro.2019.117629.
- Tam, V.W., 2009. Comparing the implementation of concrete recycling in the Australian and Japanese construction industries. *Journal of Cleaner Production* 17, 688–702. URL: <https://linkinghub.elsevier.com/retrieve/pii/S095965260802904>, doi:10.1016/j.jclepro.2008.11.015.
- Tam, V.W., Soomro, M., Evangelista, A.C.J., 2018. A review of recycled aggregate in concrete applications (2000–2017). *Construction and Building Materials* 172, 272–292. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0950061818307451>, doi:10.1016/j.conbuildmat.2018.03.240.
- Tang, W., Khavarian, M., Yousefi, A., Cui, H., 2020. Properties of self-compacting concrete with recycled concrete aggregates, in: *Self-Compacting Concrete: Materials, Properties and Applications*. Elsevier, pp. 219–248. URL: <https://linkinghub.elsevier.com/retrieve/pii/B978012817369500009X>, doi:10.1016/B978-0-12-817369-5.00009-X.
- Thomas, J., Thaikavil, N.N., Wilson, P., 2018. Strength and durability of concrete containing recycled concrete aggregates. *Journal of Building Engineering* 19, 349–365. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2352710218302511>, doi:10.1016/j.job.2018.05.007.
- Turk, J., Cotič, Z., Mladenović, A., Šajna, A., 2015. Environmental evaluation of green concretes versus conventional concrete by means of LCA. *Waste Management* 45, 194–205. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0950653X15300064>, doi:10.1016/j.wasman.2015.06.035.
- United Nations, Department of Economic and Social Affairs, Population Division, 2019. *World population prospects Highlights, 2019 revision Highlights, 2019 revision*. OCLC: 1142478963.
- USGS, 2021a. *Cement, annual publication. Technical Report*. USGS. URL: <https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf>.
- USGS, 2021b. *Mineral Commodity Summaries. Technical Report*. USGS.
- Verian, K.P., Ashraf, W., Cao, Y., 2018. Properties of recycled concrete aggregate and their influence in new concrete production. *Resources, Conservation and Recycling* 133, 30–49. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344918300430>, doi:10.1016/j.resconrec.2018.02.005.
- Vidal, O., 2021. Modeling the Long-Term Evolution of Primary Production Energy and Metal Prices, in: *Mineral Resources Economics 1: Context and Issues*. fizaïne, f.; galiègue, x. ed.. Wiley, pp. 95–118. doi:10.1002/9781119850861.
- Vidal, O., Boulzec, H.L., François, C., 2018. Modelling the material and energy costs of the transition to low-carbon energy. *EPJ Web of Conferences* 189, 00018. doi:10.1051/epjconf/201818900018. publisher: EDP Sciences.
- Vidal, O., Le Boulzec, H., Andrieu, B., Verzier, F., 2021. Modelling the Demand and Access of Mineral Resources in a Changing World. *Sustainability* 14, 11. URL: <https://www.mdpi.com/2071-1050/14/1/11>, doi:10.3390/su14010011.
- Vidal, O., Rostom, F., François, C., Giraud, G., 2017. Global Trends in Metal Consumption and Supply: The Raw Material–Energy Nexus. *Elements* 13, 319–324.
- Vishwakarma, V., Uthaman, S., 2020. Environmental impact of sustainable green concrete, in: *Smart Nanoconcretes and Cement-Based Materials*. Elsevier, pp. 241–255. URL: <https://linkinghub.elsevier.com/retrieve/pii/B978012817854600009X>, doi:10.1016/B978-0-12-817854-6.00009-X.
- van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. *Climatic Change* 109, 5–31. URL: <http://link.springer.com/10.1007/s10584-011-0148-z>, doi:10.1007/s10584-011-0148-z.
- van Vuuren, D.P., Stehfest, E., Gernaat, D.E., Doelman, J.C., van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., van Meijl, H., Måller, C., van Ruijven, B.J., van der Sluis, S., Tabeau, A., 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change* 42, 237–250. doi:10.1016/j.gloenvcha.2016.05.008.
- Wiedenhofer, D., Steinberger, J.K., Eisenmenger, N., Haas, W., 2015. Maintenance and Expansion: Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25. *Journal of Industrial Ecology* 19, 538–551. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12216>, doi:10.1111/jiec.12216. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12216>.
- World Business Council for Sustainable Development, 2009. *The Cement Sustainability Initiative - Recycling concrete. Technical Report*. World Business Council for Sustainable Development.
- Worldsteel, 2021. *Buildings and infrastructure*. URL: <http://www.worldsteel.org/steel-by-topic/steel-markets/buildings-and-infrastructure.html>.
- Wu, Z., Yu, A.T., Shen, L., Liu, G., 2014. Quantifying construction and demolition waste: An analytical review. *Waste Management* 34, 1683–1692. URL: <http://linkinghub.elsevier.com/retrieve/pii/S0950653X14002104>, doi:10.1016/j.wasman.2014.05.010.
- Xicotencatl, B.M., 2017. *Scenarios for concrete-rubble recycling in the Netherlands. Technical Report*. Leiden University.
- Yang, L., Yan, H., Lam, J.C., 2014. Thermal comfort and building energy consumption implications – A review. *Applied Energy* 115, 164–173. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0306261913008921>, doi:10.1016/j.apenergy.2013.10.062.
- Zhang, Y., Bai, X., Mills, F.P., Pezzey, J.C., 2018. Rethinking the role of occupant behavior in building energy performance: A review. *Energy and Buildings* 172, 279–294. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0378778818307576>, doi:10.1016/j.enbuild.2018.05.017.
- Zhou, W., Moncaster, A., Reiner, D.M., Guthrie, P., 2019. Estimating Lifetimes and Stock Turnover Dynamics of Urban Residential Buildings in China. *Sustainability* 11, 3720. URL: <https://www.mdpi.com/2071-1050/11/13/3720>, doi:10.3390/su11133720.