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The raw materials conundrum of the energy transition : an energy and building sectors approach

Hugo Le Boulzec

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THÈSE

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**Le défi des matières premières dans la transition énergétique :
modélisation des secteurs de la production d'énergie et du bâtiment**

**The raw materials conundrum of the energy transition: an energy and
building sectors approach**

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Invités :



"Une dictature c'est quand les gens sont communistes, déjà. Qu'ils ont froid, avec des chapeaux gris et des chaussures à fermeture éclair."

- OSS117

"All models are wrong, but some are useful."

- George E. P. Box

Abstract

Our society relies on a wide range of facilities, which provide goods and services. They carry significant amounts of embedded materials, and their intensity and complexity has been increasing over the years. The metals and minerals demand has been widely assessed within the industrial ecology field, and conceptual and transdisciplinary approaches of materials have emerged from the rise of material use (e.g. the nexus behavior of resources and the social metabolism). They aim at deepening the understanding of the interactions between nature and society, as well as within our society. The ongoing energy transition has a significant material challenge in this transdisciplinary research field. It carries changes for all sectors, and a potential shift from an energy materials dependency to a minerals and metals dependency. The material basis of our society is addressed in a growing number of studies. A critical literature review allows to identify the main insights and gaps in a panel of publications displaying material flow analysis of base materials between 2000 and 2021. This work aims at providing further insights on four specific gaps: (1) a lack of prospective studies in a low-carbon context, (2) a lack of analysis of the energy-material nexus, (3) a lack of modeling of some sectors and (4) a limited number of solution-oriented and political-oriented studies. This thesis is included in a larger project of multi-sector material modeling: the Dynamic Modeling of Energy, Materials Demand and Supply (DyMEMDS) model.

In a first published article, Olivier Vidal, Cyril François and myself show that the pace of the development and the short lifetimes of renewable technologies creates a substantial increase of the materials demand. It would likely rely on primary materials, as the recycling potential remains limited. In a second article, (Le Boulzec et al., submitted), we conduct the first dynamic modeling of the fossil fuels supply chain and estimate the material requirements and associated energy demand and CO₂ emissions from 1950 to 2050 in two transition and baseline scenarios. We find that gas is the main driver of material demand and that recycled steel from decommissioned fossil fuel infrastructures could meet the cumulative need of future low-carbon technologies in some scenarios. Ambitious decommissioning strategies are necessary, in parallel to building the infrastructure of renewable technologies. In a third article, (Le Boulzec et al., submitted) we present the results of a dynamic and multi-regional modeling of the building sector from 1950 to 2100 in seven transition and baseline scenarios. The originality of this work relies on both the estimation of the material weight of thermal renovation, and the analysis of the potential of material engineering to reduce energy demand and environmental impact. We show that thermal renovation would represent a small share of the overall increase of material demand, and the energy to produce renovation materials would amount to about 1% of the energy savings. The energy consumption of base material demand could question the feasibility of some low-energy demand scenario, but enhanced recycling of concrete wastes and low carbon materials could provide solutions.

The three sector studies highlight the significant increase of material demand in the building and energy sectors due to the combination of the low-carbon transition and potentially surging population and GDP per capita. It could translate into growing energy demand and environmental impact of material production. This thesis outlines the role of (1) collect and recycling and (2) low-carbon materials to improve the sustainability of material use. However, local and ambitious policies are urgently required to successfully implement the solutions.

Keywords: Raw materials, recycling, low-carbon transition, nexus, dynamic modeling

Résumé

Notre société repose sur un large éventail d'installations fournissant des biens et des services. Elles sont composées d'importantes quantités de matériaux, utilisés avec une intensité et une complexité croissantes. La demande en métaux et minéraux de notre société est étudiée dans le domaine de l'écologie industrielle, au sein duquel de nouvelles approches ont émergé, tels que le nexus des ressources et le métabolisme social. La transition énergétique actuelle représente un défi important au sein de ce champ de recherche. Synonyme de changements sectoriels, elle pourrait se traduire par le passage d'une dépendance aux matériaux énergétiques à celle aux minéraux et aux métaux. La dépendance en matériaux de notre société est abordée dans un nombre croissant d'études. Une revue de la littérature a permis d'identifier les principaux enseignements et lacunes dans une sélection d'études publiées entre 2000 et 2021. Cette thèse propose une approche s'inscrivant dans quatre lacunes identifiées: (1) le manque d'études prospectives dans un contexte de transition bas carbone, (2) le manque d'analyse du lien entre énergie et matériaux, (3) le manque de modélisation de certains secteurs et (4) le nombre limité d'études proposant des solutions afin de diminuer les impacts des matériaux. Ce travail s'inscrit dans un projet plus large de modélisation multisectorielle des matériaux : le modèle DyMEMDS (Dynamic Modeling of Energy, Materials Demand and Supply).

Dans un premier article publié, nous montrons que le rythme de développement et la faible durée de vie des technologies renouvelables entraînent une augmentation substantielle de la demande en matériaux. Celle-ci reposerait sur des matériaux primaires, le potentiel de recyclage restant limité. Dans un second article soumis, nous réalisons la première modélisation dynamique de la chaîne d'approvisionnement en combustibles fossiles. Nous estimons les besoins en matériaux ainsi que la demande énergétique et les émissions de CO₂ associées à leur production de 1950 à 2050 dans deux scénarios. Nous constatons que le gaz est le principal moteur de la demande de matériaux et que l'acier recyclé provenant des infrastructures de combustibles fossiles démantelées pourrait répondre aux besoins cumulés des futures technologies de production d'énergie renouvelable dans certains scénarios. Pour cela, des stratégies ambitieuses de démantèlement sont nécessaires. Dans un troisième article soumis, nous présentons les résultats d'une modélisation dynamique et multirégionale du secteur du bâtiment de 1950 à 2100 dans sept scénarios. L'originalité de ce travail repose à la fois sur l'estimation de la demande en matériaux dans la rénovation thermique, et sur l'analyse du potentiel des matériaux bas-carbone pour réduire la demande énergétique et l'impact environnemental. Nous montrons que la rénovation thermique représenterait une faible part de la croissance de la demande en matériaux, et que l'énergie nécessaire à la production des matériaux de rénovation s'élèverait à environ 1% des économies d'énergie. La consommation d'énergie de la demande de matériaux pourrait remettre en question la faisabilité de certains scénarios, mais le recyclage des déchets de béton et des matériaux bas-carbone pourrait apporter des solutions.

Les trois études sectorielles mettent en évidence l'augmentation significative de la demande en matériaux dans les secteurs du bâtiment et de l'énergie en raison de la combinaison de la transition bas-carbone et de la croissance de la population et du PIB par habitant. Cela pourrait se traduire par une augmentation de la demande énergétique et de l'impact environnemental de la production de matériaux. Cette thèse souligne le rôle (1) de la collecte et du recyclage et (2) des matériaux bas-carbone pour améliorer la durabilité de l'utilisation des matériaux. Cependant, des politiques locales et ambitieuses sont nécessaires de toute urgence pour mettre en œuvre ces solutions avec succès.

Keywords: Matières premières, recyclage, transition énergétique, nexus, modélisation dynamique

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¹ Dans le cru 2022, "En fait dis rie danc cette phraset. Peut etre dire que l'évolution future si exponentielle est un matter of concern? Especially si le prix des ressources augmente de manière signicative as well" (Vidal, 2022). Une compilation des meilleures remarques est à l'étude.

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Chapter 1

Introduction

1.1 A new era: the Anthropocene

1.1.1 Definition and the Great Acceleration

In the second half of the 19th century, [Marsh \(1864\)](#) proposed the first extensive description of a man-made earth through his own observations. George P. Marsh eventually emphasized the need to acknowledge human effects, despite the incapability of assessing the short to long-term impacts of human development on nature and of explaining the origin of the Earth systems changes. Since then, the exponential development of human demography, activities and their growing effects on Earth led [Crutzen and Stoermer \(2000\)](#) to theoretically define a new concept. Meaning "the age of humans", the Anthropocene marks the extensive and profound footprint of humanity on Earth systems, and was initially set to have begun in the late 18th century. However, the definition of a new Epoch requires criteria to be met and several starting dates could be considered ([Lewis and Maslin, 2015](#)). Under the guidance of the International Commission on Stratigraphy, the Anthropocene Working Group (AWG) was created to assess the "potential addition [of Anthropocene] to the Geological Time Scale". In 2019, the AWG finally recommended the consideration of the Anthropocene as a new geologic area starting in the mid-20th century ([Subcommission on Quaternary Stratigraphy, 2019](#)). As a symbol of this new Epoch, [Steffen et al. \(2007\)](#) described the undergoing rise of human activities as the "Great Acceleration". The authors further proposed 24 graphs of Earth systems and socioeconomic indicators evolution, recently updated in [Steffen et al. \(2015a\)](#) (Figure 1.1). While most of the socioeconomic indicators have experienced a similar rise in the last decade than in the previous period, some recent changes can be observed in the Earth system trends. The authors, however, outlined that this could be explained by different reasons, and that observations over a decade are too short to be extrapolated as long-term trends. For example, the stabilization of methane emissions shows a balance between absorption and emissions, while the marine fish capture decrease could indicate a rise in aquaculture, since fish consumption rose during the period.

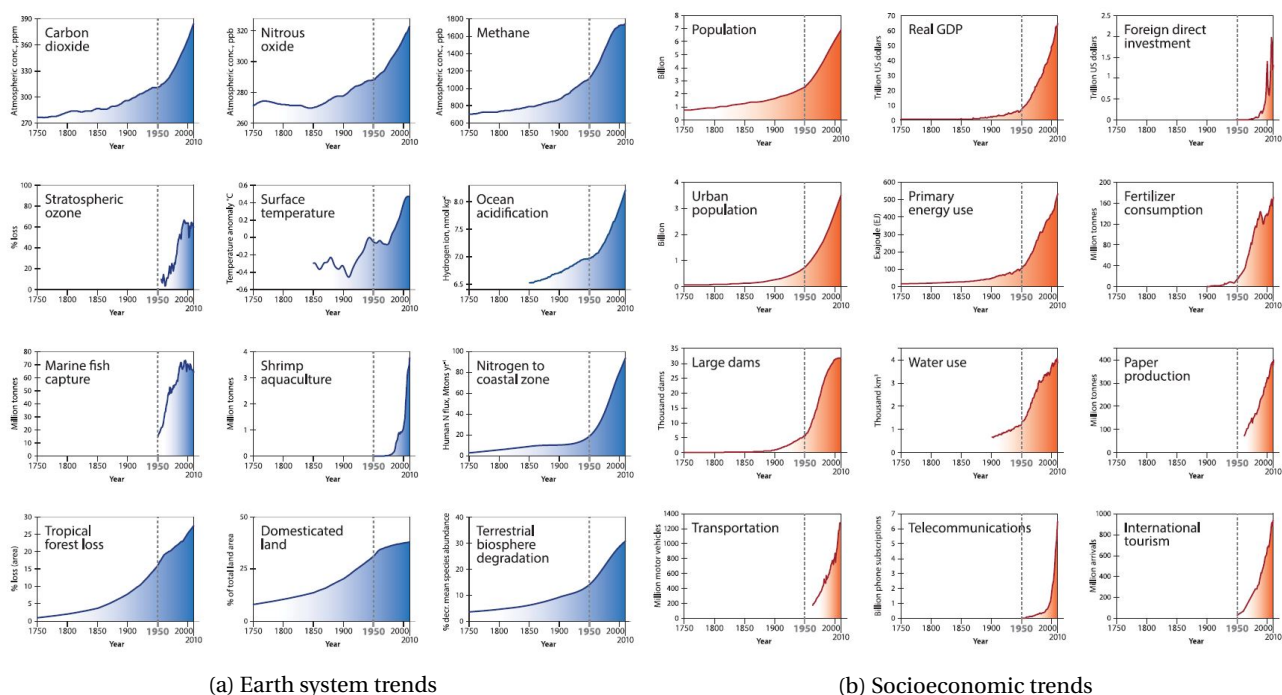


Figure 1.1: Great Acceleration graphs. Source: [Steffen et al. \(2015a\)](#)

1.1.2 Planetary boundaries and climate change impacts

The significant increase of the Earth system and socioeconomic indicators points out the need to estimate the limits to the impacts of human activity for a sustainable development. [Steffen et al. \(2015b\)](#) defined planetary boundaries for Earth-system processes, relying on control variables values¹. The authors considered nine processes and assessed their current levels of risk. Out of seven control variables currently assessed, [Sternier et al. \(2019\)](#) found out that four of them may have already exceeded the authors-defined thresholds (Figure 1.2), which could represent a risk of destabilization of the Earth System². The authors emphasized the complexities of response to those risks, the potential domino effect, and the urging need to design interdisciplinary and multi-variables policies by an extensive collaboration between the academic and the political communities.

Among environmental issues, climate change (CC) has received considerable attention in recent decades. Climate issues are devastating, cross-cutting to all environmental issues and can generate side benefits on biodiversity, health, etc. Their analysis was undertaken by the academic literature, which led to the creation of the Intergovernmental Panel on Climate Change (IPCC) more than 30 years ago. Following its creation in 1988, the IPCC published its first Assessment Report (AR) in 1990. It indicated an enhancement of the greenhouse effect due to increasing emissions of greenhouse gases (GHG) in human activities, which will induce a rise of the global average temperature. However, the [IPCC \(1990\)](#) stated that uncertainties and natural climate variability could hamper the results, and that "a decade or more" is needed to unequivocally assess the greenhouse effect. The climate change analysis have since become a major research field, with a doubling of the number of publications every 5-6 years between 1980 and 2014 ([Haunschild et al., 2016](#)). The improvements of climate models, methods and data analyses since the AR1 have allowed for an improvement in the variety of results and their reliability. In the last assessment report (AR6), [IPCC \(2021a\)](#) reported that "observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities". The authors further estimated the likeliness³ of human responsibility in the observed higher precipitation over land, retreat of glaciers, warming and acidification of the upper ocean, sea level rise and

¹After evaluating national planetary boundaries, [O'Neill et al. \(2018\)](#) estimated that "no country meets basic needs for its citizens at a globally sustainable level of resource use". The authors showed that the basic physical needs could be fulfilled, but that meeting further qualitative objectives would require crossing planetary boundaries by several times.

²For further readings, an historical review of the conceptual development of the Anthropocene, Great Acceleration and planetary boundaries is offered in [Steffen et al. \(2011\)](#).

³The likeliness is expressed on a scale ranging from exceptionally unlikely (0%-1%) to virtually certain (99%-100%).

changes in the land biosphere. The current climate mitigation policies⁴ would lead to an estimated average global warming of 2.8°C (UNEP, 2021) by 2100 with a 66% probability.

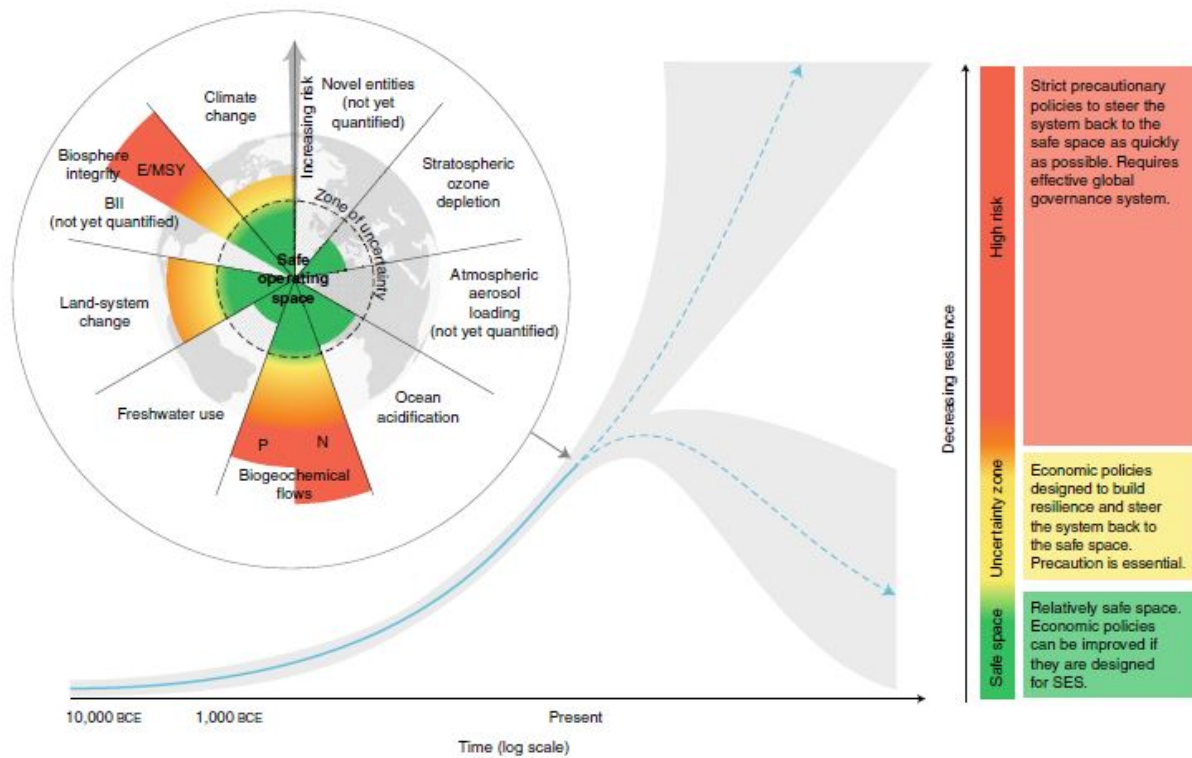


Figure 1.2: Control variables, their current levels of risk and the policies to be implemented. The upper dashed blue line describes a future with risk of control variables and resulting changing Earth conditions while the lower blue dashed line displays a stabilized Earth system. BII, Biodiversity Intactness Index; E/MSY, extinctions per million species per year; P, phosphorus cycle; N, nitrogen cycle; SES, social–ecological systems. Source: Sterner et al. (2019).

The effects of climate change are manifold and display various levels of likelihood. IPCC (2018) described the climate change impacts on three categories of systems: physical systems, biological systems and human and managed systems. The authors pointed out major climate change related impacts in all categories and all global regions with mostly medium to high level of confidence (Figure 1.3). They emphasized the challenge of quantifying the effects of human systems (e.g. health problem attributed to climate change), and their high and uneven vulnerability explained by development inequalities. The increasing collection of data and performance of instrumentation provides deeper understanding on the effects of climate change. While the IPCC assessment reports focus on continents, oceans and the troposphere, recent reports displayed new impacts. For instance, Bailey et al. (2021) showed effects on a middle atmosphere layer: the mesosphere. The authors observed a cooling and a contracting of the mesosphere, which results in a shrinking of the atmosphere⁵.

⁴After the 2030 pledges formulated at the COP26 in Glasgow.

⁵Some effects of this contracting on aerospace technologies are expected, such as a reduction of interferences in satellite communication and "more space junk in low-Earth orbit".

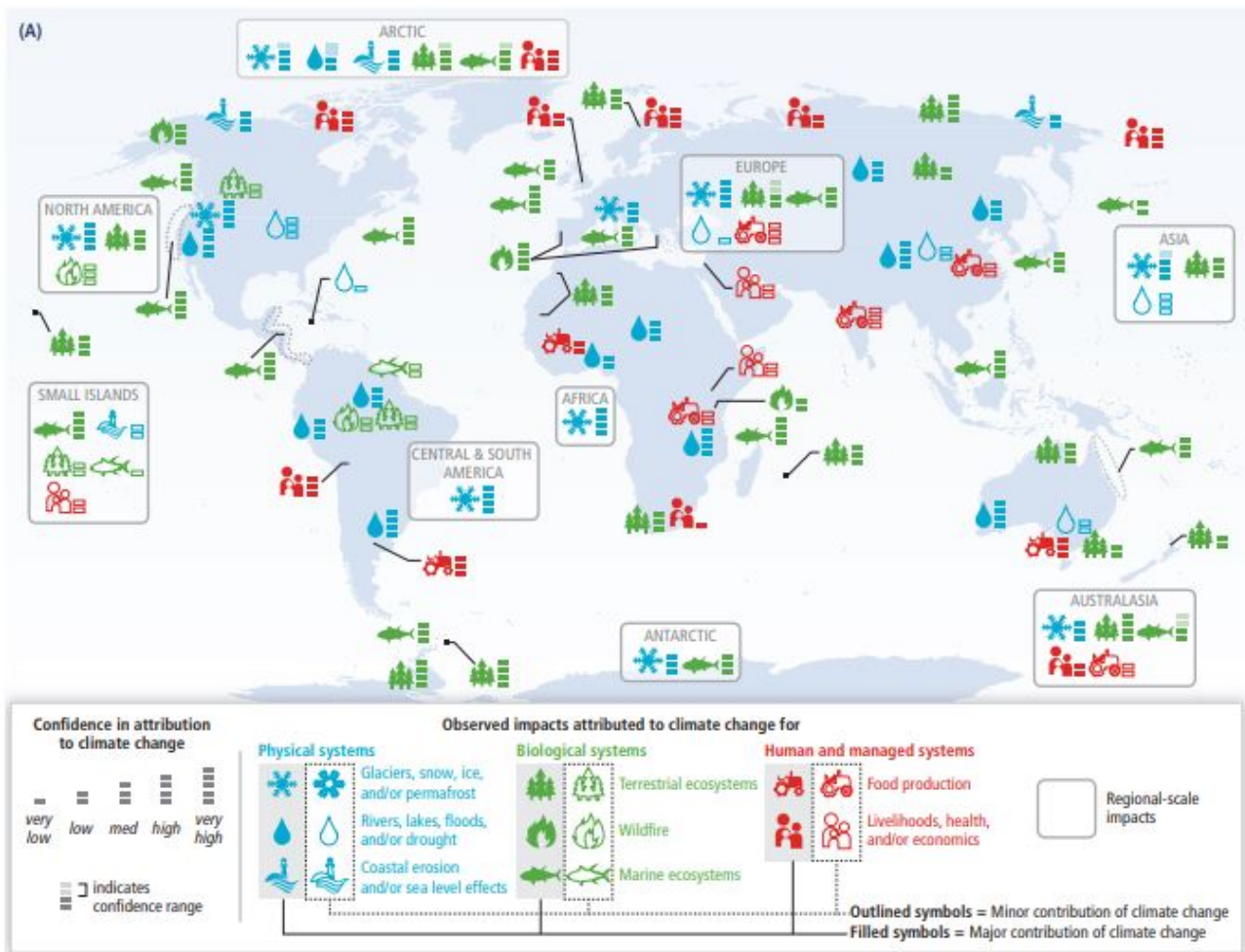


Figure 1.3: Observed regional impacts of climate change in the AR5. Source: IPCC (2018).

1.1.3 Towards catastrophic changes?

The climate change conundrum has progressively outlined the deep interactions between systems and the need to conduct environmental analysis from an "interacting spheres and cycles" perspective (Summerhayes and Zalasiewicz, 2018). The complexity of the nexus approach is further enhanced by the inertial dimension of climate change. A physical delay exists between the GHG emissions and the impacts, and the currently observed effects (heat waves, wildfire...) result of past emissions. The updated future risks have been assessed in IPCC (2021a), and an interactive map displaying regional environmental variables was provided IPCC (2021b). The authors identified five main categories of risks: unique and threatened systems, extreme weather events, distribution of impacts, global aggregate impacts and large-scale singular events. They further emphasized the disproportionate increase of effects as warming rises. Thus, the AR6 depicts higher impacts at every scales (global, regional, sector...) with uneven distribution in space and in time, and potential irreversible changes. The concept of *tipping point* emerged to describe these latter large changes and the potential resulting domino effect. Lenton (2011) defined tipping points as a threshold occurring when "a small change in forcing triggers a strongly nonlinear response in the internal dynamics of part of the climate system, qualitatively changing its future state". The probability of their occurrence has been debated in the literature, as well as the triggering temperature (Lenton et al., 2019). However, the IPCC has been increasing the level of risk of abrupt and irreversible events for low average global warming over time (Figure 1.4) and IPCC (2021a) recently stated that "abrupt responses and tipping points [...] cannot be ruled out (high confidence)". The increasing probability of extreme events has been increasing over time has led the research community to develop the terms "catastrophic climate change" (CCC) and "climate emergency" (CE) to appropriately describe the coming effects of climate change (Moriarty and Honnery, 2021).

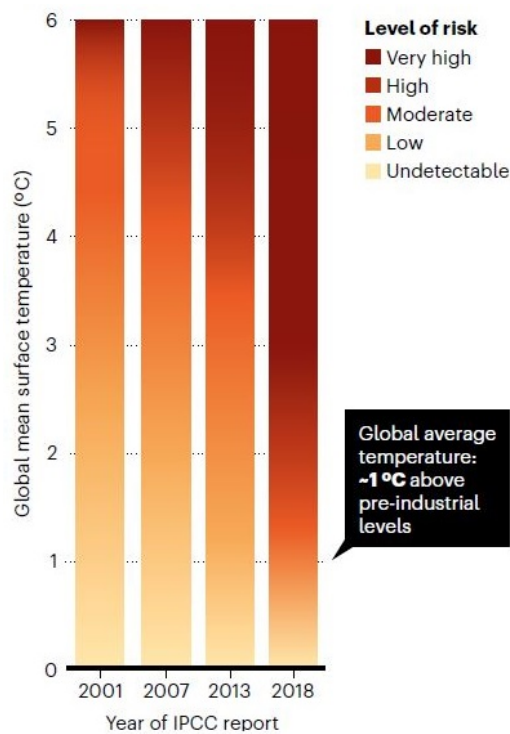


Figure 1.4: Level of risk of abrupt and irreversible changes with average global warming. Source: [Lenton et al. \(2019\)](#)

The tipping points are defined as thresholds for Earth subsystems referred to as *tipping elements* ([Lenton et al., 2008](#)). The authors initially identified 9 tipping elements (the updated list is displayed on Figure 1.5), their main characteristics and finally assessed of their impact depending on their likelihood ([Lenton, 2011](#)). They emphasized their identification could lead to mitigation strategies, but that the intrinsic inertia of some systems could hamper their effectiveness. However, [Lenton et al. \(2019\)](#) prompted for a better assessment of crossed tipping points impacts, as "global cascade" could occur through systems interactions or feedbacks (Figure 1.5). The recent MOSAIC expedition leader Markus Rex reported concerning results on possible Arctic "ice-free summers in just decades", which could be one of the first triggered tipping points, and stated that "one can essentially ask if we haven't already stepped on this mine and already set off the beginning of the explosion"⁶. The literature on the potential implications of triggering tipping points has flourished over the past years, for instance estimating the social cost of deforestation ([Franklin and Pindyck, 2018](#)) or their economic impacts ([Dietz et al., 2021](#))⁷.

⁶The [MOSAIC expedition](#) was a full-year scientific mission in the Arctic Ocean to deepen our understanding on climate change. The main observation were detailed by Markus Rex during a [press conference](#).

⁷The authors conducted a review on 52 publications tackling the economic impacts of tipping point and developed a meta-analytic integrated assessment model. They demonstrated potential economic risk in almost all areas.

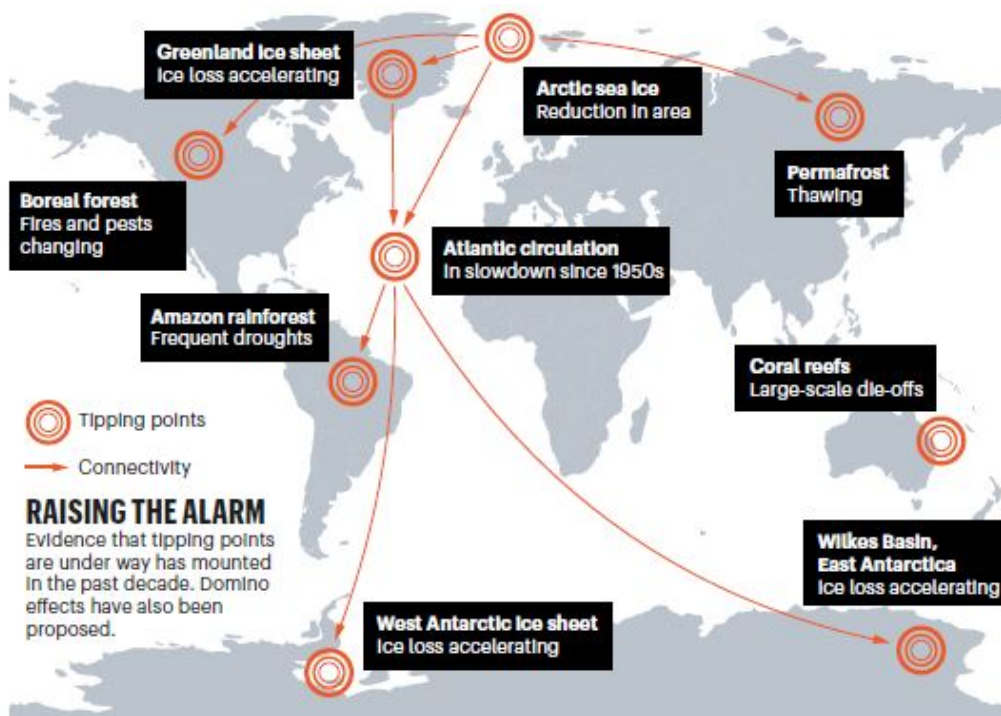


Figure 1.5: Identified tipping elements, and assessment of their relative impact depending on their relative likelihood. Source: [Lenton et al. \(2019\)](#)

1.2 The cause: human development

1.2.1 Link between impacts and resources

The resources consumption is the major source of GHG emissions. Oil, gas and coal have represented most of the CO₂ emissions for a few centuries. Their share have significantly evolved, as coal dominated the early energy mix, while the oil and gas demand increased from the mid-20th (Figure 1.6). An exponential growth in materials production has been observed from the mid-20th century (Figure 1.7), with substantial environmental impacts (Figure 1.8). These impacts have been studied from the late 1960s ([Fischer-Kowalski and Hüttler, 1998](#)), and the effects of metal ore mining and processing were reviewed by [Dudka and Adriano](#) in 1997. The authors emphasized that actual extracted materials quantities are significantly larger than the ore amounts, which induces a waste generation, while melting and refining create gaseous and particulate matter emissions, sewage matter and solid wastes. Moreover, impacts can also be accounted for after the end-of-life of the material-based products: during the recycling process or in landfills storage. At the industrial level, materials production emitted 10 GtCO₂ in 2005, and steel and cement represented about 16% of the global CO₂ emissions. The same levels was observed in 2016. The iron/steel and cement/concrete industries represented both about 6% to 8% of the final energy demand and CO₂ emissions ([Andrew, 2017](#); [Bataille, 2019](#)).

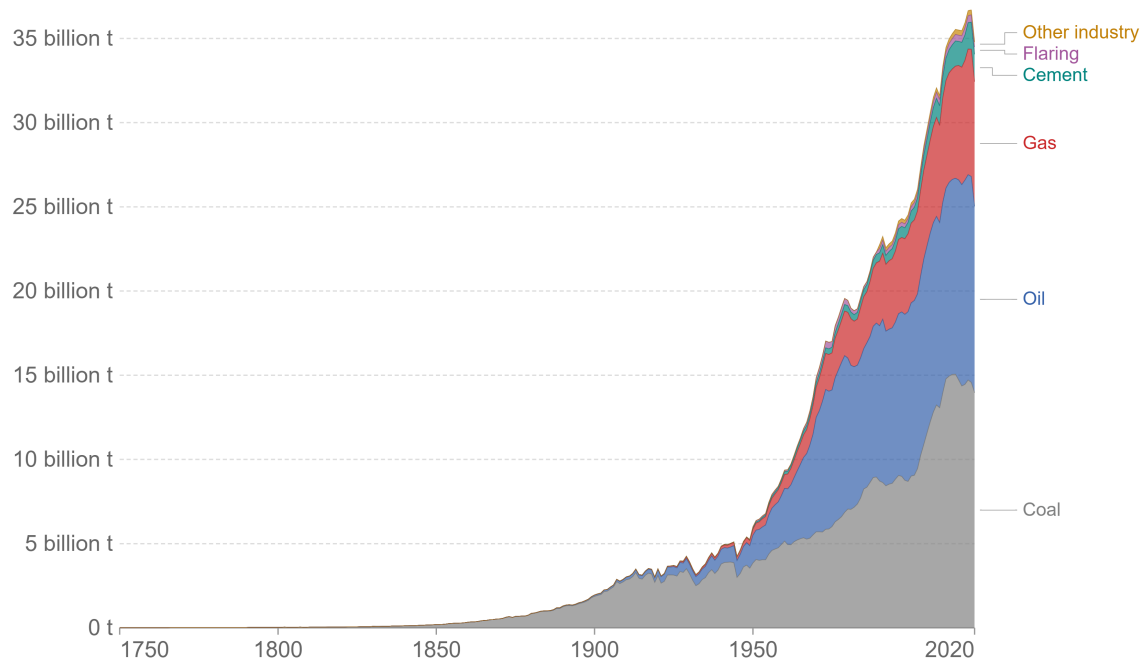


Figure 1.6: CO₂ emissions by source. Source: [Ritchie and Roser \(2020\)](#)

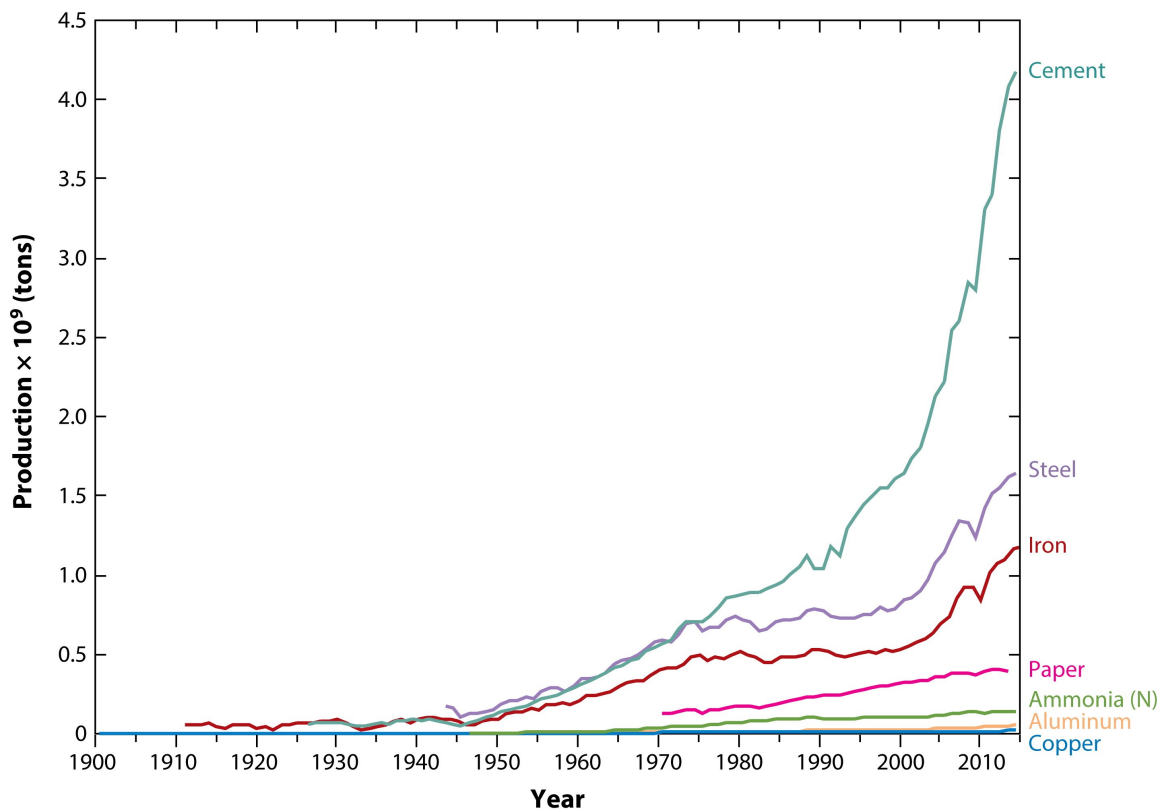


Figure 1.7: Global resources production. Source: [Worrell et al. \(2016\)](#)

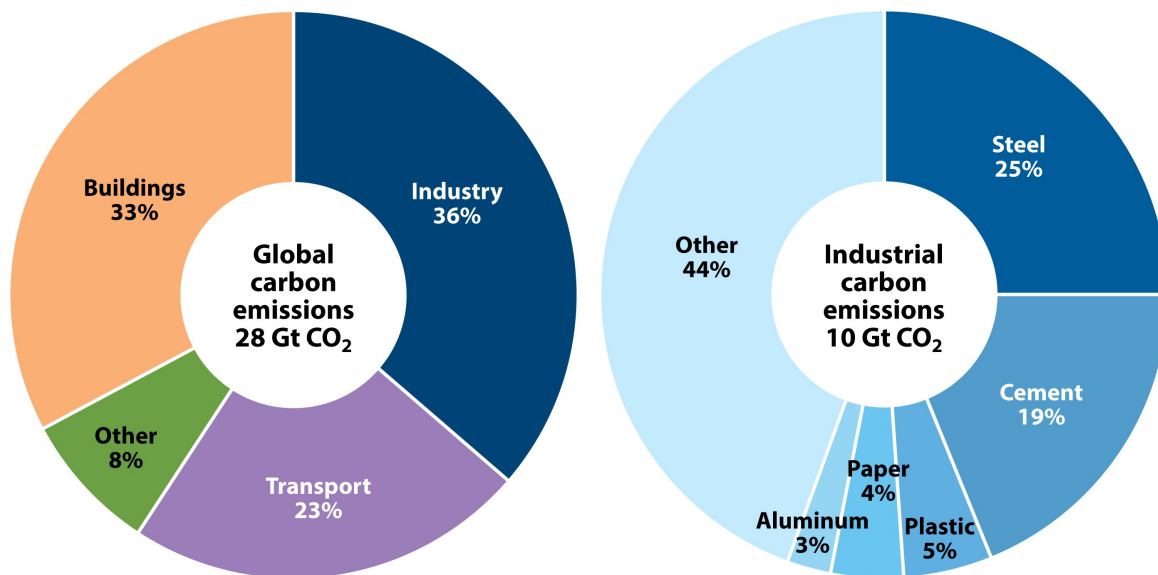


Figure 1.8: Global total and industrial CO₂ emissions. Source: [Worrell et al. \(2016\)](#)

1.2.2 Link between resources and human development

The access to abundant and cheap energy has enabled an industrial society to emerge, with an extensive reliance on more complex technologies. Its combination with a soaring human demography and economic growth⁸ over the 20th century has driven an exponential growth of resources use. Demand for materials has grown faster than population growth. An evolution of the annual material demand per capita from 25 t/cap in 1970 to 37 t/cap in 2019 has been observed⁹. In contrast, per capita water use has remained stable, due to lower availability, which has led to an increase in the share of the population experiencing water shortages ([Kummu et al., 2016](#)). Demography and economic growth partially explain the increase in resources, and other factors such as industrialization and urbanization play an important role. The growing organization of human society in the form of cities has created a new pattern of resource consumption, which is studied in urban metabolism. It aims at analyzing the flows and stocks of resources and people of a society on a territory ([Galychyn et al., 2020](#)). In contrast with agrarian metabolism, a higher density of flows, larger stocks and a partial externalization of urban metabolism are observed. In Paris, France, the average supply distance of food and energy significantly increased between the 20th and the 21st century ([Billen et al., 2012](#); [Barles, 2021](#))¹⁰. A better knowledge of local metabolism characteristics would allow more accurate estimations of local resource use.

Despite the complexity of resources growth patterns, several theories emerged. They rely on analyses of the link between resources use and GDP/capita. [Bleischwitz and Nechifor \(2016\)](#) proposed a short review of the resources growth theories. The authors identified four phases in the literature:

- The emergence of resources growth theories in the 1950s.
- The Intensity-of-Use (IoU) hypothesis was developed in the late 20th century. [Malenbaum \(1973\)](#) identified a potential inverted U-shaped form of demand with economic growth, which was ultimately validated for steel, only in the middle-income countries ([Wårell, 2014](#)).
- A lack of interest for the topic in the 1980s and 1990s, as the materials prices were lowering and the globalization was observed.
- The emergence of the decoupling debate in the context of environmental concerns.

[Bleischwitz et al. \(2018b\)](#) recently emphasized the need of a "greater demand on the underlying assumptions and the

⁸The GDP per capita (in \$ppp 2011) increased from \$9,677 per capita to more than \$16,897 per capita between 1990 and 2019. The GDP per capita data were retrieved from the [World Bank database](#).

⁹The [United Nations Environment Programme International Resource Panel Global Material Flows Database](#) provides annual material data between 1970 and 2019. The scope includes biomass, excavated earthen materials, fossil fuels, metal ores, mixed and complex products and non-metallic minerals.

¹⁰Particular attention should also be paid to the effects of policies and changes in the energy mix on the average supply distance.

possibility of long-term changes". The authors proposed a three-stage profile of the in-use stock per capita evolution. At first, a growth stage occurs, during which the industrialization of a society leads to a rapid accumulation. This stage explains the progressive shifting of materials demand towards emerging countries as they are building their infrastructures (Pothen, 2017). Secondly, a maturing stage is reached when the stock growth slows down, before a final saturation stage with a stabilization of the stock. The empirical data further suggested saturation values for steel and cement at \$12,000 GDP/capita and for copper at \$20,000 GDP/capita (Bleischwitz et al., 2018b).

1.2.3 GDP: a very imperfect indicator

The International Monetary Fund defines Gross Domestic Product (GDP) as "the monetary value of final goods and services - that is, those purchased by the end user - produced in a country over a given period of time (e.g., a quarter or a year)¹¹. The "basic" idea of GDP appeared in the 17th century, but it was not until the 1930s that the modern concept as we know it today was developed with Simon Kuznets (Secretary of Commerce, 1934). Following the Bretton Woods conference in 1944, GDP became the main tool for measuring the economic development of a country. Its adoption on a global scale made it possible to compare economic growth between countries, and many derivatives were derived from it, such as GDP per capita, often considered as an indicator of the standard of living. However, standard of living is not synonymous with quality of life and well-being. There is a divide in this distinction that seems to be becoming more and more pronounced, as already attested to in 1968 by Robert F. Kennedy's remark in a speech at the University of Kansas: "it [GDP] measures everything in short, except that which makes life worthwhile."

This position is seen by some as the beginning of the "Beyond GDP" movement. The latter is defined by the European Commission as the initiative that "aims to develop indicators that are as clear and attractive as GDP, but that take greater account of the environmental and social aspects of progress". Although GDP remains the dominant tool for measuring a country's economic development and productivity, the search for more inclusive and comprehensive indicators appeared from the 70s in France, Japan and the USA, in parallel of the critics to growth. They focused on the opposition between this production indicator and the supposed measure of economic well-being, and the exclusive process of addition to evaluate it (Méda, 2020). Meda (1999) later highlighted the need for the GDP index to evolve from its exclusive quantitative to fit a changing worldview, and the "wealth" of our natural heritage and our social cohesion. In the 2000s, the questioning of GDP gradually evolved from the academic spheres to the political world (e.g. the Stiglitz-Sen-Fitoussi report commissioned by the French President (Stiglitz et al., 2009)).

GDP critics have focused on several aspects. First, from an economic and social perspective, a growing GDP in a country does not necessarily reflect sustainable development or development without inequalities (Piketty and Goldhammer, 2014). Moreover, by definition, this indicator only integrates the monetary value of goods and services, and not the informal economy, domestic labour and the externalities, which are defined as the positive and negative effects generated during their creation process¹². Currently, a growing GDP generally translates into more goods and services produced but at the expense of the environment (Kapoor and Debroy, 2019). The environmental impacts of economic activity is neglected by GDP, while the expenses of restoration of natural environments or depollution contribute to increase it.

Integrating the externalities into decision-making and measurement/study processes will help reconcile human and economic development in more concrete and constructive ways. For example, the Genuine Progress Indicator (GPI) is an alternative indicator that attempts to measure the real impacts of economic activity on the economic well-being of populations (Kubiszewski et al., 2013). In this study, the authors reveal that, although differences can be observed for each country, a generalized divergence appears between GDP and GPI after 1978. Indeed, if from 1950 to 1978 the two indicators are clearly positively correlated, a reversal of trend occurs around 1978 at the global level, with a correlation that becomes negative (GDP rising while the GPI stagnates and then falls)¹³. This reflects the rising environmental

¹¹The IMF further describe the real GDP and its limitations.

¹²The total subsidies to fossil fuels were estimated to about \$5.9 trillion in 2020, which represented about 6.8% of global GDP (Parry et al., 2021). The authors outlined that only 8% of the subsidies are direct, i.e. for supply costs, and "92 percent for undercharging for environmental costs and foregone consumption taxes".

¹³More indicators have been proposed over the years (Gadrey and Jany-Catrice, 2006; Smits and Steendijk, 2015)

costs and social inequalities in most countries since that time, outweighing the economic benefits of GDP growth. However, the GPI is not a perfect indicator, just as any indicator used individually. This is why many researchers agree on the importance of a "dashboard" approach with the joint use of several indicators, such as Ecological Footprint, Biocapacity, Human Development Index, Life Satisfaction, Gini coefficient, Social Progress Index, etc¹⁴.

This short review of the GDP-resources-impacts nexus introduces the current research field on the sustainability of our human society. The assessment of environmental impacts and their mitigation could involve a wide range of tools such as an overhaul of the energy system, geoengineering, a large scale development of carbon capture and storage/use but also a change of the current growth model. In the next section, two of the main current topics on sustainability are discussed: "our" relationship to growth and the feasibility of the energy transition.

1.3 Are there any solutions? Questioning our relationship to growth and the feasibility of the energy transition.

1.3.1 The *Limits to Growth*

Despite the common belief in the benefits of economic growth (Thomas, 2000), numerical or modelling works have highlighted the unsustainability of development methods based on the search for strong economic growth, and the contradiction between continued economic growth and planetary limits¹⁵. In 1966, Kenneth Boulding described the lack of understanding of the closed system concept of Earth by Economists, and its consequences for inputs and outputs (Boulding, 1966). In 1973, continuing this reasoning, he stated before the US Congress that "anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist." (Boulding, 1973). However, in a review of the contributions of economics to the effort to combat climate change, Criqui and Mathy (2022) showed that economists have long identified the potential limits to economic development imposed by natural resources and environment. Economics has always been concerned with the relationship between human activities, natural resources and the environment. Among the classical economists (F. Quesnay, A. Smith), natural resources were seen as a source of wealth. At the beginning of the 19th century, the English classical economists (Smith, Ricardo, Mills) nevertheless identified the problem of potential limits to human activities: man does not destroy nature; nature imposes its own rhythm of exploitation and promises only a stationary state as a horizon. The neoclassicals integrated the impact of human economic activities on exhaustible natural resources. Thus Arthur Pigou in 1920 introduced the notion of negative environmental externality and the principle of environmental tax to achieve the social optimum. At the beginning of the 20th century, economic science had fully integrated the issue of resource scarcity and the ecological damage caused by capitalist development. But the solutions it proposed reinforced the existing economic system more than they worried it...Aiming at better understanding the ultimate consequences of the biophysical limits to growth¹⁶, new approaches emerged, such as steady-state economics (Daly, 1973), early ecological economics and the degrowth current (Georgescu-Roegen, 1971, 1979)¹⁷.

In an implicit coherence with ecological economics, the Club of Rome was created to "discuss the present and future predicament of man" (Meadows et al., 1972). The emergence of systems dynamics allowed for the computation of a global model—World3—analyzing human society development through five factors: population, agricultural production, natural resources, industrial production, and pollution (Meadows et al., 1972). The results were published in the *Limits to Growth* (LtG) report. Twelve scenarios were computed, describing several development profiles up to 2100. After observing "overshoot and collapse" in most of them, the authors showed that the stabilization of both population and industrial capital¹⁸ could prevent "overshoot and collapse", but that natural resources would be depleted,

¹⁴For instance (Laurent, 2020) and (Laurent, 2021) in the French literature.

¹⁵A detailed examination of the critics to growth is provided in Markantonatou (2016).

¹⁶Daly (1973) distinguished the moral and the biophysical critics to growth.

¹⁷Georgescu-Roegen was an initial member of the Club of Rome but finally became a critic as their vision of the possibility of sustainable growth diverged.

¹⁸The authors identified two positive loops in the model, leading to population growth and capita growth. They stated that the loops were not coherent with a limited resources world, and thus calibrated negative feedback loops (e.g death rate) to counteract the positive loops.

except in case of favorable technological policies¹⁹. The study led to three main conclusions. Under unchanged trends in the five considered factors, the World3 model forecasted that our society will experience the limits to growth within a century [1]²⁰. This result could however be prevented by the implementation of policies, which could lead to an inclusive and sustainable equilibrium [2]. However, the authors emphasized that reaching this sustainable state will strongly depend on the pace of the human reaction [3]. The LtG report triggered numerous reactions, summarized in [Bardi \(2011\)](#) and [Jackson and Webster \(2016\)](#). The results were eventually confronted to recent empirical data ([Turner, 2014](#); [Herrington, 2021](#)). In the most recent study, Herrington focused on four scenarios (Business-as-usual (BAU), Business-as-usual 2 (BAU2), Comprehensive Technology (CT) and Stabilized World (SW)) and showed the best fit with empirical data for BAU2 and CT, which indicates "a slowdown and eventual halt in growth within the next decade", and the worst fit for the SW scenario, which results in a population and human welfare stabilization. As depicted in the conclusion of the LtG report, Herrington finally concludes on the possibility to alter this trajectory and on the urgent need for action ([Herrington, 2021](#)).

1.3.2 What evolution for the growth paradigm?

The strategy to reduce the depicted human impact on Earth systems requires to revisit our definition of prosperity and its relationship with economic growth ([Jackson, 2016](#)). Infinite growth has been strived for decades and its relevance in solving the current social and environmental crisis is advocated by the political world in the form of *Green Growth*. It refers to the enhancement of economic growth while ensuring a better use of resources and a reduction of the impacts of human activity ([OECD, 2011](#)), despite various definition displaying different levels of environmental commitment ([Hickel and Kallis, 2020](#)). The concept was initially born under the *Green Economy* etiquette in the 1989 UK Government commissioned report "Blueprint for a Green Economy" ([David W Pearce, 1989](#)), a year before the first occurrence of the expression of green growth in a World Bank working paper ([Colby, 1989](#)). A decline of reference to the green growth term was then observed after the Earth Summit of 1992, since the concept of *Sustainable Development*²¹ became predominant in the sustainability debate ([Brown et al., 2014](#)). The concept was re-introduced after the 2008 financial crisis, for its potential to revitalize the economy while coping with environmental issues ([Georgeson et al., 2017](#)). Green economy and green growth progressively gained momentum as the United Nations Environment Programme (UNEP) launched the Green Economy initiative in 2008, and the Organisation for Economic Co-operation and Development (OECD) published the "Green Growth Strategy Package" (OECD 2011) defining green growth as "fostering economic growth and development, while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies". It relies on the concept of decoupling between economic growth, resources use and impacts. This option requires rapid technological improvements to achieve an energy transition with for instance negative emissions technologies. Green growth is currently considered as the main option to tackle the social and environmental conundrum, as shown in the 8th Sustainable Development Goal of the United Nations ([United Nations, 2015](#)).

However, there have been critics of an impossibility to achieve exponential growth with limited resources since the 1970s ([Boulding, 1973](#); [Meadows et al., 1972](#)). Moreover, the GDP level has shown an absence of correlation with social welfare beyond some level ([Hickel et al., 2021](#)) and the green growth strategy requires an absolute decoupling between economic growth, resource use and environmental impacts, which has rarely been observed over the past decades ([Parrique et al., 2019](#); [Haberl et al., 2020](#)). The decoupling options such as biofuels or carbon capture and storage (CCS) have high uncertainties about their scalability, their impacts and their limited effect on emissions ([Hickel et al., 2021](#)). The identification of these contradiction led the ecological economists to propose new options aside of the decoupling approach. Several approaches have emerged over the past decades, providing new alternatives in the debate on the future of human economic development and its sustainability. In the early 2000s, [Latouche \(2004\)](#) re-

¹⁹The authors emphasized that technology could be a solution but that "Faith in technology as the ultimate solution to all problems can thus divert our attention from the most fundamental problem - the problem of growth in a finite system and prevent us from taking effective action to solve it".

²⁰The authors further stated that "the most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity".

²¹Sustainable is defined as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" ([World Commission on Environment and et al., 1987](#))

introduced the *degrowth* alternative to the common growth model²². Acknowledging an "addiction to growth" in the Western culture and its devastating effects on equality and sustainability, the author proposed the implementation of degrowth to tackle the entropic nature of the current economic growth and to cope with the limited capacity of Earth resources. He further insisted on the importance to envision this term within a "degrowth society" and its cultural and socioeconomic specificities²³, i.e. outside the scope of a growth-centered system in which degrowth would be comparable to a destructive "negative growth". The notion was further developed in [Latouche et al. \(2009\)](#), with the definition of a theoretical framework of 8 stages leading to degrowth through a virtuous circle²⁴, and a preliminary political program with an emphasis on job and work hours. The author however outlined the difficult uniform implementation of the notion at a global scale - considering the heterogeneity of development and cultures - and the need to assess its potential at every levels. The sustainable coherence of degrowth was further defended in [Martínez-Alier \(2009\)](#) and [Martínez-Alier et al. \(2010\)](#) with the introduction of the sustainable degrowth concept, and in [Kallis \(2011\)](#), who defined degrowth as the "socially sustainable and equitable reduction of society's throughput"²⁵. Some critics however emerged from the manichean aspect of degrowth, which fully reject the concept of growth. [van den Bergh \(2011\)](#) emphasized the absurdity of the growth quest and the uselessness of the GDP indicator in measuring social welfare, but acknowledged that growth can have positive effects in some development context. The author therefore proposed the *a-growth* notion, which is indifferent to GDP growth, and focuses on social and environmental policies whatever their impacts on growth. The sectoral disaggregation of a-growth can result in degrowth, but van den Bergh outlined it would become a mean, and not an objective²⁶. A third alternative option considers the *post-growth* approach. It acknowledges that economic growth has had positive effects on the development of human societies, but that new paradigms are required to achieve further social and environmental goals ([Jackson, 2016](#)). Moreover, post-growth policies are differentiated between countries, because the development without growth is "desirable" for various reasons ([Jackson, 2019](#)). The post-growth topic has displayed flourishing interest in ecological economy, with concerns about the role of "work in a post-growth world" ([Mair et al., 2020](#)) or the post-growth strategy in the Global South ([Gerber and Raina, 2018](#)).

Degrowth, agrowth or post-growth could therefore provide policies framework for a more sustainable and inclusive society [Parrique \(2019\)](#). However, [van den Bergh and Kallis \(2012\)](#) outlined that the past link between growth and environmental impact was criticized in a context of no environmental policies. Future efficient policies implementation could provide more insights in the growth debate. Given the current pursuit of economic growth as a human development objective (SdG), its decoupling with resource use and impacts is crucial ([United Nations, 2015](#)). A recent comprehensive review of the decoupling between GDP, resource use and GHG emissions was conducted in [Wiedenhofer et al. \(2020\)](#) and [Haberl et al. \(2020\)](#). They focused on two decoupling axis: resources decoupling and impact decoupling. While resource decoupling is defined as a reduction of resource use per unit of GDP, impact decoupling is defined as the decline of environmental impact per unit of GDP. The targeted decoupling can be relative in case of a better efficiency, or absolute in case of a decrease of resources use or impact while the economy grows. The authors showed that relative resource decoupling (material use) has been observed, as well as relative impact decoupling (GHG and CO₂ emissions). They further emphasized that few absolute decoupling were achieved mainly in crisis or slow growth context, and that "a potentially fundamental incompatibility between economic growth and systemic societal changes to address the climate crisis is rarely considered" ([Wiedenhofer et al., 2020](#)).

1.3.3 The energy transition

The depicted economic options of green growth, degrowth, agrowth and post-growth all rely on a sustainable approach of energy, which is currently achieved through an energy transition from fossil fuels to renewable energies. Despite being currently closely linked with environmental challenges, several energy transitions have occurred in

²²The term comes from the French word *décroissance*. Previous work already considered similar notion in the late 19th century. [Parrique \(2019\)](#) and [Martínez-Alier et al. \(2010\)](#) provided thorough historical reviews and detailed origins of the approach.

²³Such as a drop of work hours, an evolution in the role of states, or a greater emphasis on social relationships over material consumption.

²⁴The 8 stages are re-evaluate, reconceptualize, restructure, redistribute, relocalize, reduce, re-use and recycle.

²⁵The throughput are defined as the flow in the socio-economic metabolism, i.e. the resource inflow and outflow between nature and society, as well as between societies.

²⁶A comparison of the growth, degrowth and a-growth notions is provided in [van den Bergh and Kallis \(2012\)](#).

human history, at various scales and paces, and for diverse reasons. Smil (2010) identified two main global energy transitions, which allowed a rapid industrial and economic development: the transition from animal - initially human - force to mechanical force, and the transition from biomass to fossil fuels, with a massive reliance on electricity as a secondary energy²⁷. The triggers of these transitions are manifold. In the first transition, the limited productivity of human and domesticated animals led to the development of "inanimate prime movers", such as windmills or watermills. The second transition is explained by the rapid industrial and city development, as Smil (2010) explained it: "growing cities, expanding manufactures, and increasing iron production led to the demise of surrounding forests, and affordable availability of nearby wood or charcoal supplies (as long-distance land transport using pack or draft animals was usually prohibitively expensive) became a key factor limiting the size of preindustrial cities and the level of iron output". It is still ongoing in many rural regions (sub-Saharan Africa, Asia, Latin America), and its past timing displayed significant disparities among countries. While some areas used coal as a new major energy source, other regions could not rely on domestic coal reserves, and operated a direct transition from biomass to oil and natural gas. The related reliance on electricity is explained by Smil by a triptych of economic benefits: efficiency, productivity and flexibility, as well as more technological aspects (easy to use, multi-scale applications, accuracy of delivery...). These successive transitions have catalyzed the human society development. In order to better perceive the magnitude of the evolution that has taken place over the past several centuries, the concept of *energy slave* has been developed. It is defined as the number of human slaves - based on the average energy a person can produce - needed to provide the equivalent energy use of our modern lifestyle (Mouhot, 2011), and Jancovici (2013) estimated the current French energy consumption per capita to be equivalent to about 400 slaves.

General aspects of the ongoing energy transition

The ongoing energy transition is part of a larger ecological transition, and it displays new challenges compared to the previously depicted examples. Under its current meaning, the term *energy transition* was firstly used in 1980 in Germany by Krause et al. (1980). It aims at achieving a shift from fossil fuels to renewable energies, an increasing share of electricity in the energy mix, and additional measures (e.g. CCS, demand efficiency...). The need for a transition is explained by the conjunction of the oil and gas supply/demand peak perspective (Murphy and Hall, 2010; Delannoy et al., 2021a,b) with the environmental stakes to reach a full decarbonation of the energy sector by 2050. The global primary energy mix remains largely dominated by fossil fuels (Figure 5.1) and energy currently represents about 90% of the global CO₂ emissions (IEA, 2019a), of which 40% are emitted to generate power (Figure 1.10).

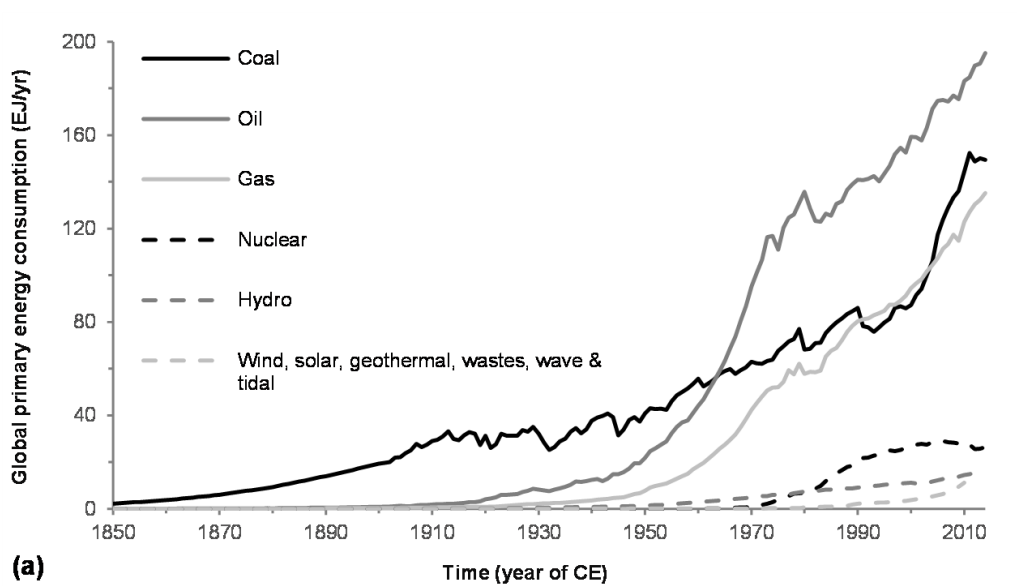


Figure 1.9: Global primary energy supply by sources from 1850 to 2014. Source: Court (2016)

²⁷ Duruisseau (2014) further proposed to segment these transitions in two categories: disruptive (e.g. the two identified by Smil (2010)), and substitution (e.g. the ongoing replacement of oil by natural gas, or the nuclear industry development in France).

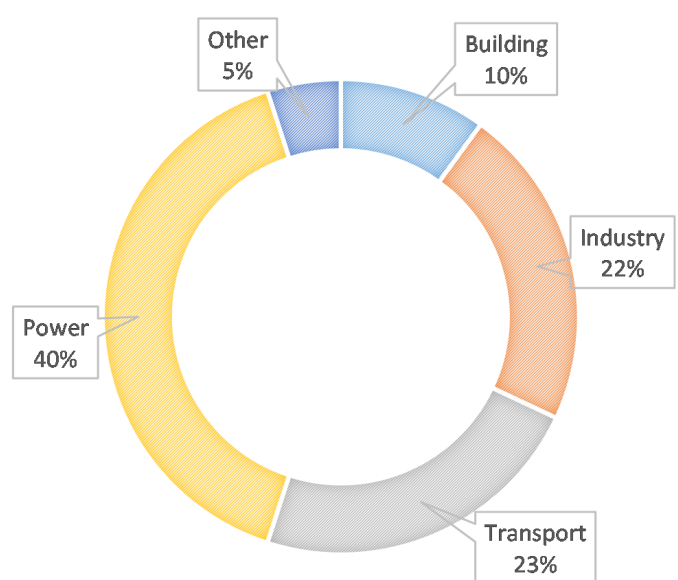


Figure 1.10: Global energy-related CO₂ emissions by sector. Source: IEA (2021b)

The process to politically assess the link between the energy system and the greenhouse gases emissions and aiming at providing global measures to decarbonate our economy has been undergone through international climate negotiations for almost 30 years. The United Nations Framework Convention on Climate Change (UNFCCC) was signed in 1992 with the objective of "[stabilizing] greenhouse gas (GHG) concentrations in the atmosphere at a level that will prevent dangerous human interference with the climate system, in a time frame which allows ecosystems to adapt naturally and enables sustainable development" (UNFCCC, 2021a). It gathers 197 parties, which meet annually in the Conferences of Parties (COP). Several major steps resulting from the COP can be outlined. The Kyoto Protocol was established during COP1 in 1997, with the objective to reduce GHG emissions in 36 developed countries—thus acknowledging the impact of development level on the capacity to tackle climate change through the “common but differentiated responsibility and respective capabilities”—over two periods, to implement emission market mechanisms, and to monitor national emissions inventories (UNFCCC, 2021d). In 2015, the COP21 held in Paris resulted in the Paris agreement, which is a binding treaty adopted by 196 parties. It aims at limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C through Nationally Determined Contributions (NDC). These pledges consist of comprehensive national climate action plans (UNFCCC, 2021c), with an emphasis of renewable energy development and energy efficiency (UNFCCC, 2021b). In order to reach the climate objective of the COP21—and potentially go even further—significant measures were expected at the COP26 in Glasgow, such as a reinforcement of the NDC announced at the COP21. Worth noticing are the expected initiatives to phase-out of coal (e.g. [Powering Past Coal Alliance](#)) but also of oil and gas (e.g. [Beyond Oil & Gas Alliance](#)), which remains a first step as the main oil and gas producers are not part of the alliance, and the commitment to halt financing new energy-related project from 2022 by 39 parties²⁸), or the [non-binding agreement](#) to foster the shift to zero emissions vehicles in sales and owned/leased fleet by both a set of countries and automotive manufacturers. However, the COP26 measures and pledges remain unambitious in terms of scale and pace in relation to the climate emergency raised by the IPCC (IPCC, 2022).

This international negotiations and initiatives conceal strong regional and sector disparities, as agendas vary. The European Union is at the forefront on the transition with a rising share of renewable energy in the energy mix from 9.6% in 2004 to 19.7% in 2019 (European Commission, 2020), but displays a low share of battery-electric vehicles (BEV) despite a significant increase and great ambitions (ACEA, 2020) and a current low level of 1% of annual building renovations (European Commission, 2021). The USA has experienced a two-fold raise of the share of renewables in the energy to more than 12% in 2020 (EIA, 2020) and a tenfold increase of electric vehicle²⁹ share in the stock between

²⁸The 39 parties agreed to "end new direct support for the international unabated fossil fuel energy sector by the end of 2022, except in limited and clearly defined circumstances that are consistent with a 1.5°C warming limit and the goals of the Paris Agreement.

²⁹Only battery-electric vehicles are considered in these figures, plug-in hybrid electric vehicles are not accounted for.

2013 and 2020, which represented only 0.35% of the total fleet in 2020 (IEA, 2021c). Finally, China displays a peculiar situation. The country strongly relies on coal and further coal power plants projects are planned, while being the leader in installed solar capacity and electric vehicle manufacturing (IEA, 2021a). The Chinese BEV number raised by 35 times between 2014 and 2020, but only represented about 1% of the car fleet in 2020 (IEA, 2021c). These low figures show that the energy transition remains at an early stage and that further ambitious measures are needed to achieve the announced objectives. For example, the European Union established a *Green Deal* aiming at ensuring "no net emissions of greenhouse gases by 2050, economic growth decoupled from resource use and no person and no place left behind" through multi-sector actions (European Commission, 2019), while the US President Joe Biden is currently experiencing internal struggle to implement his Climate Plan aiming in particular at cleaning the electricity system and fostering domestic industries (Davenport, 2021). The means to reach the full decarbonation of the energy system remains a highly researched topic, as manifold pathways exist. For several decades, institutions and the academic world have been developing models and scenarios to provide insights and influence the previously depicted governmental transition plans.

A field of scenarios

Achieving the energy transition could materialize through numerous technological and regional paths. To provide insights to the policy-makers on the requirements and consequences of the paths, energy transitions scenarios have been extensively constructed by Non-Governmental Organization (NGO), private firms, charities, governmental or intergovernmental organizations, think tanks and the academic world over the past decades. However, the variety of methods and philosophies hamper the possibility of comparing scenarios. Therefore, several authors have progressively identified a classification to analyze scenarios (IPCC, 2001; Börjeson et al., 2006; van Vuuren et al., 2012; Dagnachew et al., 2019) which led WEC (2019a) and Skea et al. (2021) to propose three types of scenarios:

- Outlooks, with the purpose to answer the question "what will happen?" (Börjeson et al., 2006). These scenarios consider a business-as-usual case or planned policies (e.g. the Intended Nationally Determined Contributions of the COP21 in the Stated Policies Scenario).
- Exploratory scenarios, with the purpose to answer the question "what can happen?" (Börjeson et al., 2006). They aim at describing futures under a set of socio-economic hypothesis.
- Normative scenarios, with the purpose to answer the question "how a predefined target can be achieved?" (Börjeson et al., 2006). In these scenarios, the technical path towards a predetermined target is assessed.

Depending on their typology, the scenarios propose different philosophies to policy makers. While the outlooks validate or invalidate the current measures, the exploratory scenarios highlight what might happen if a specific set of actions were taken. The normative scenario can help design policies, as they provide insights in what should be done to achieve a specific target. Some of the existing scenarios can be listed following this classification, as presented in Tables 1.1 and 1.2. Their number has been increasing over the past years, and more organisms have been developing their own scenarios. Most of them are carried out by private firms or intergovernmental organizations, and very few scenarios were carried out by researchers. Among the research community scenarios, the Shared Socioeconomic Pathways (SSP) hold a peculiar place. Five plausible socioeconomic future have been designed by the climate change community in parallel of a set of GHG trajectories in the Representative Concentration Pathways (RCP) to create a new generation of scenarios computed in Integrated Assessment Models (IAM) (Moss et al., 2010). In the scenarios presented in Tables 1.1 and 1.2, the projected CO₂ emissions display numerous futures within each category (Figures 1.11, 1.12 and 1.13). In their comparison of global energy scenarios, Skea et al. (2021) showed that some trends are envisioned in every scenarios, however at various scales. They highlighted patterns in three similarities: an increase of primary energy demand [1], a rise of the share of electricity in the energy mix [2] and of the share of solar and PV [3]. Similarly, the authors identified patterns of differences. They firstly outlined the increasing demand of coal and oil in outlooks, while stabilizing or dropping in most of exploratory and normative scenarios. Secondly, the observed development of wind and solar energies displays various range of penetration. Thirdly, the authors showed that the future role of hydropower in the energy mix could depend on the consideration of environmental constraints in project development. The distribution of scenarios by type allows us to characterize the validity of the current

measures, in particular through the evolution of CO₂ emissions. We observe that the projected CO₂ emissions range of outlooks remains higher than in 1.5/2°C normative scenarios (Figures 1.11 and 1.13), which indicates that limiting global warming to between 1.5°C and 2°C seems currently unrealistic.

Scenario	Year (last update)	Organisation	Type of body	Reference	Global warming
Outlook					
Reference	2017	CEPSA	Private firm	CEPSA (2017)	4°C
International energy outlook	2019	US EIA	Governmental organization	EIA (2021)	
Reference	2019	ExxonMobil	Private firm	ExxonMobil (2019)	
Current policies	2019	IEA	Intergovernmental organization	IEA (2019b)	
Stated policies	2019	IEA	Intergovernmental organization	IEA (2019b)	3°C
Reference	2020	IEEJ	Think tank	IEEJ (2020)	
Business-as-usual	2020	BP	Private firm	BP (2020)	
Announced Pledges Scenario	2021	IEA	Intergovernmental organization	IEA (2021e)	
Ener Base	2021	Enerdata	Private firm	Enerdata (2021)	
Ener Blue	2021	Enerdata	Private firm	Enerdata (2021)	
Reform	2021	Equinor	Private firm	Equinor (2021)	> 2°C
Energy Transition Outlook	2021	DNV GL	Private firm	DNV (2021)	
World Oil Outlook	2021	OPEC	Intergovernmental organization	OPEC (2021)	
Planned Energy Scenario	2021	IRENA	Intergovernmental organization	IRENA (2021)	
Exploratory					
Modern Jazz	2019	WEC	Charity	WEC (2019b)	2.5°C
Unfinished Symphony	2019	WEC	Charity	WEC (2019b)	2°C
Hard Rock	2019	WEC	Charity	WEC (2019b)	> 3°C
Mountain	2019	Shell	Private firm	Shell (2019)	2.5°C
Ocean	2019	Shell	Private firm	Shell (2019)	2.6°C
Advanced Technology	2020	IEEJ	Think tank	IEEJ (2020)	> 2°C
Waves	2021	Shell	Private firm	Shell (2021)	
Islands	2021	Shell	Private firm	Shell (2021)	
Momentum	2021	Total Energies	Private firm	TotalEnergies (2021)	2.2/2.4°C
Rupture	2021	Total Energies	Private firm	TotalEnergies (2021)	1.7°C
Rivalry	2021	Equinor	Private firm	Equinor (2021)	

Table 1.1: Outlooks and exploratory global energy scenarios. The list is not exhaustive. Adapted from [Skea et al. \(2021\)](#) and [WEC \(2019a\)](#)

Scenario	Year (last update)	Organisation	Type of body	Reference	Global warming
Normative					
SSPs RCP1.9 to 8.5	2011,2017	Researchers	Academic community	van Vuuren et al. (2011) Riahi et al. (2017) van Vuuren et al. (2017) Fricko et al. (2017) Fujimori et al. (2017) Calvin et al. (2017) Kriegler et al. (2017)	1.5°C in RCP1.9 and 2°C in RCP2.6
Low Energy Demand	2018	Researchers	Academic community	Grubler et al. (2018)	1.5°C
Sky	2019	Shell	Private firm	Shell (2019)	1.7°C
Sustainable development	2019	IEA	Intergovernmental organization	IEA (2019a)	1.65°C
Rapid transition	2020	BP	Private firm	BP (2020)	< 2°C
Net Zero	2020	BP	Private firm	BP (2020)	1.5°C
Net Zero Emissions	2021	IEA	Intergovernmental organization	IEA (2021d)	1.5°C
Sky 1.5	2021	Shell	Private firm	Shell (2021)	1.5°C
Ener Green	2021	Enerdata	Private firm	Enerdata (2021)	
Rebalance	2021	Equinor	Private firm	Equinor (2021)	2°C
1.5°C Scenario	2021	IRENA	Intergovernmental organization	IRENA (2021)	1.5°C

Table 1.2: Normative global energy scenarios. The list is not exhaustive. Adapted from Skea et al. (2021) and WEC (2019a)

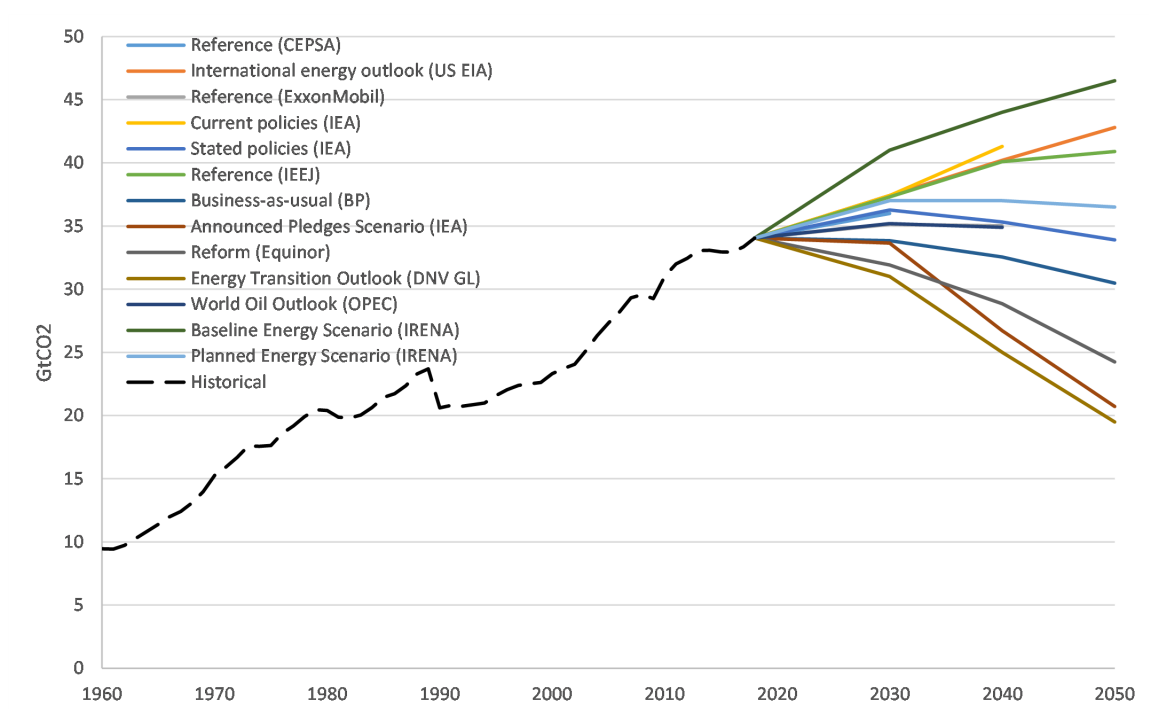


Figure 1.11: Global energy-related CO₂ emissions in outlooks. Sources: Various

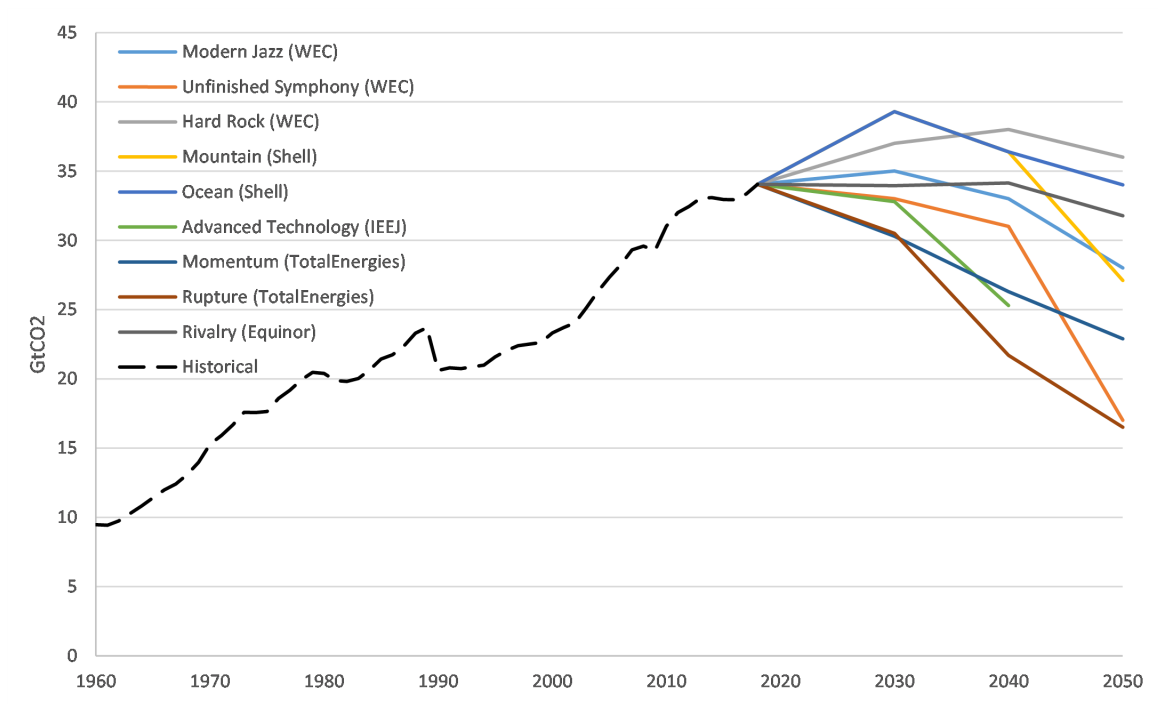


Figure 1.12: Global energy-related CO₂ emissions in exploratory scenarios. Sources: Various

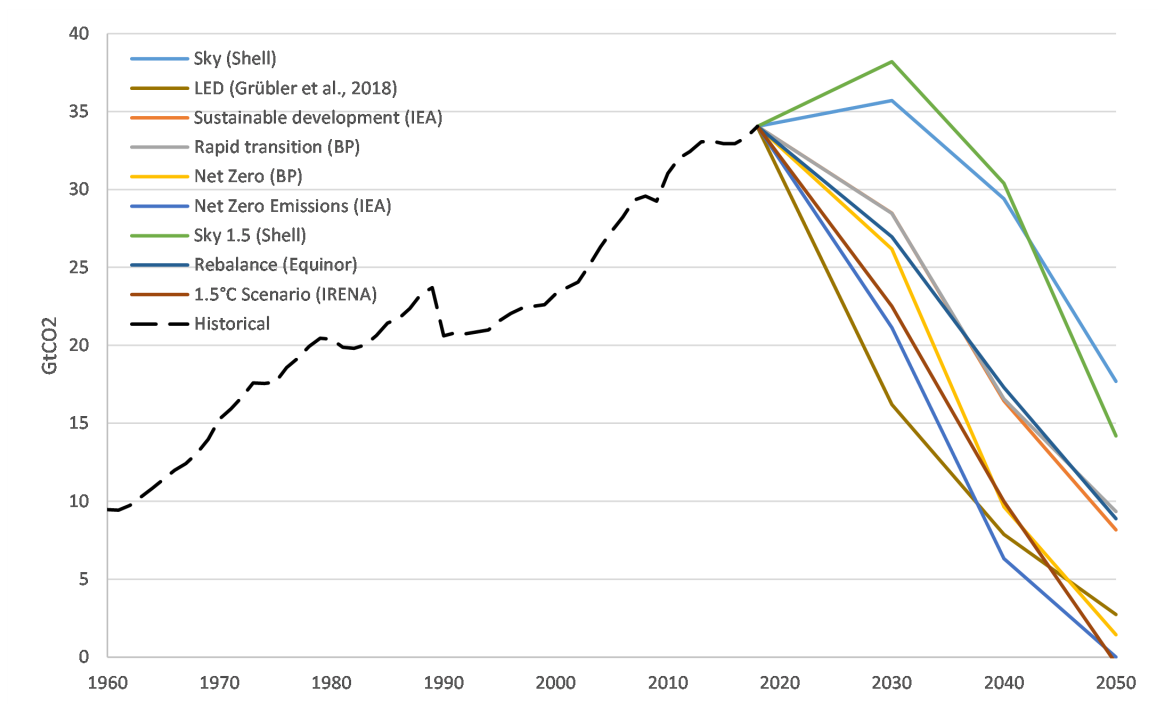


Figure 1.13: Global energy-related CO₂ emissions in normative scenarios. Sources: Various

Criticisms and analysis

The scenarios analysis displays the current high range trajectory of global CO₂ emissions, and therefore the need to implement additional and more drastic energy transition measures—assuming the validity of the green growth paradigm. It could represent a significant feasibility challenge. Over the past decades, numerous studies have conducted analysis to assess the achievability of the energy transition and its impacts from a wide panel of topics, providing insights about the current and upcoming difficulties. Several aspects have particularly concentrated criticisms and analysis, and are briefly explicated thereafter. It is not the purpose of this introduction to thoroughly review the existing analysis of the feasibility of the energy transition, the literature being wide. I intend to provide a brief overview

of some of the most challenging technical and biophysical topics, with a special emphasis on both the needed adaptation of the power system and the net energy constraints as major sources of concern on our society development. Among the analyzed topics, the temporal feasibility has been debated from technological and historical perspectives, as numerous past energy transitions can provide case studies. In 2009, [Kramer and Haigh \(2009\)](#) stated that "cost is less important than the rate at which existing low-carbon energy technologies can be physically deployed". The authors argued about the role of industrial capacity in limiting the minimum time needed for a technology to reach a significant share of the energy mix. The energy transition could therefore be a very long process, taking decades to complete. This statement is in accordance with historical examples of large scale transitions ([Fouquet, 2016](#); [Grubler et al., 2016](#); [Smil, 2016](#))³⁰. We can observe that the lack of coordination between nations has already significantly delayed the potential transition, as international discussion have been carried out for more than 30 years³¹. The resulting time frame could therefore already exceed the mid-century, which is currently targeted in most scenarios. The historical examples provide further insights about the feasibility of government-led energy transition, which has proven difficult to realize. [Solomon and Krishna \(2011\)](#) depicted the historical success of transitions for one sector in country (e.g. in France and Brazil), and identified the novelty of the current global and multi-sector situation. The authors also highlighted the challenge to implement a global "supply side energy transition", and the easier and quicker potential on the demand side.

The ongoing energy transition has also raised concerns about its biophysical aspect, which is commonly measured through the Energy Return On Investment (EROI)³². It is defined as the ratio of energy output on energy input³³. It has a direct link with net energy, which is defined as the energy output minus the energy input. The EROI was firstly introduced by Charles A.S. Hall in a biological approach for fish migration ([Hall, 1972](#)) and later adapted to fossil fuels in a biophysical approach ([Cleveland et al., 1984](#)). The ratio compares the production to the energy cost and indicates the quality of an energy source ([Hall et al., 2014](#)). For an energy source to be energetically viable, a minimum EROI of 1:1 is needed. From a technological perspective, the EROI provides a powerful tool to assess of the energetic viability of a technology - from both static and dynamic approaches - as it "integrates the counteracting effects of depletion and technological improvements" ([Hall, 2017](#)). Fossil fuels values of EROI amounted to about 80:1 in mid-1950s for coal, and decreased in the last decades ([Murphy and Hall, 2010](#)), while it fell from 140:1 in 1950 to about 20:1 in 2020 for natural gas ([Delannoy et al., 2021a](#)) and from 45:1 in 1950 to less than 10:1 in 2020 for oil ([Delannoy et al., 2021b](#))³⁴, with significant disparities between conventional and non-conventional sources, and geography. Conversely, standard EROI³⁵ of power generation technologies values are much lower (Figure 1.14)³⁶. Decreasing EROI are observed for renewables, which is explained by the use of the most "suitable" sites first for renewables [Moriarty and Honnery \(2021\)](#) and for fossil fuels, because of the depletion of the most easily accessible resources for fossil fuels and lower non-conventional EROI ([Court and Fizaine, 2017](#); [Dale et al., 2011](#); [Delannoy et al., 2021b](#); [Murphy, 2014](#); [Gupta and Hall, 2011](#)). However, recent literature showed the difficulty to compare fossil fuels and renewable energy EROI at the primary energy stage, and the need to consider the point-of-use EROI (at the final energy stage) ([Brockway et al., 2019](#)). The authors concluded that fossil fuels is significantly lower than standard EROI and could display closer value to EROI_{pu} of renewable energy.

³⁰Comparing transitions requires an apple to apple basis, as stated in [Grubler et al. \(2016\)](#). The authors issued a criticism of [Sovacool \(2016\)](#), who estimated a potential low transition period from the recent incremental technological changes (e.g. air conditioning, improved cookstoves...).

³¹As presented in Section 1.3.3.

³²Sometimes referred to as Energy Return On Energy Invested (EROEI), e.g. in [Režný and Bureš \(2019\)](#)

³³The EROI is expressed as $X : 1$, with X indicating the normalized energy output from the energy input.

³⁴The decrease of fossil fuel EROI is explained by the production of less accessible deposits (e.g. deep offshore).

³⁵Standard EROI is estimated at the primary energy stage.

³⁶Which is explained by the lower density of renewable energy technologies.

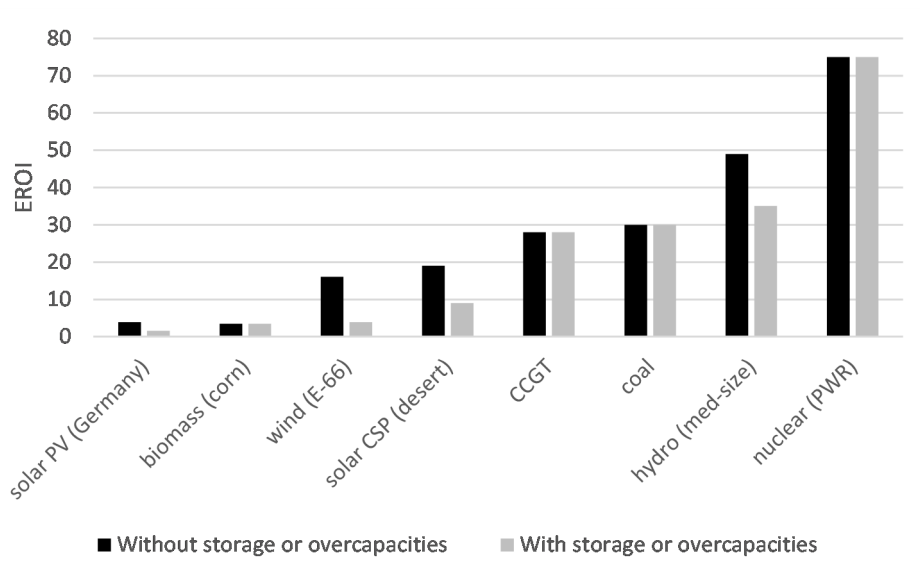


Figure 1.14: Energy Return on Investment (EROI) for the main power generation technologies. The EROI are differentiated for the use of storage and over-capacities needed for the solar, wind and hydro energy. Static values are described to give an indication of the magnitude of EROI by technology. Present values may be different. Source: (Weißbach et al., 2013)

As the EROI decreases below 10:1, a *net energy cliff* is observed³⁷ (Murphy and Hall, 2010). The net energy exponentially drops, decreasing the energetic viability of the technology. From an energy perspective, the lower the EROI, the more energy is needed to produce energy. It represents a major concern for the energy transition, since most of new energy sources display lower EROI values than fossil fuels³⁸. Several studies proposed estimations of the EROI evolution in a low-carbon transition. In the power systems, Trainer (2018) estimated the EROI of a 100% renewable Australian energy system to be around 5.9:1 - while currently about 40:1 - and Fabre (2019) predicted a global EROI of 6:1 in 2050 for electricity in case of a 100% renewable system, and 12:1 in a BAU scenario³⁹. King and van den Bergh (2018) further showed a decrease of the global EROI by 24 to 31% by 2050 in two low-carbon scenario, and Capellán-Pérez et al. (2019) concluded on a global energy system EROI between 3:1 and 5:1 in 2060. Therefore, from an economic perspective, the more renewables in the energy mix, the more economic activity is allocated to energy production, which could hamper the current "growth quest". The initial high EROI of fossil fuels resources has been a catalyst for the economic development observed in the last decades (Hall et al., 2014; Hall, 2017), which is explained by the productivity raise (Jackson, 2019). The expected decrease of EROI could create a divergence between primary energy and net energy (Moriarty and Honnery, 2019). The usable energy would significantly decrease⁴⁰, which could have devastating consequences on the economy⁴¹, as a recession and a "below trend growth" could occur if energy costs rise⁴² (Hall, 2017; Hamilton, 2009; Sers and Victor, 2018; Jackson and Jackson, 2021). Reviewing previous studies arguing of a link between economic growth and energy supply, Murphy and Hall (2010) and Fizaine and Court (2016) further questioned the possibility of economic growth in a context of declining EROI. This analysis provided an additional point in favor of degrowth, agrowth or post-growth. Indeed, a decreasing societal EROI has direct effects on the development capacity of a society, as depicted by Hall (2013) and King and van den Bergh (2018). Several works were conducted to estimate the minimum EROI for a sustainable society—hereby defined as the current level

³⁷ It is explained by the exponential decrease of the ratio of net energy to used energy.

³⁸ Hall et al. (2014) outlined the difficulty to measure renewable energies EROI, as they are intermittent, and because of the need to account for over-capacities, storage technologies, and grid connection. In the same vein, Carbon Capture and Storage (CCS) or Carbon Capture and Use (CCU) would need to be accounted for in fossil fuels EROI if displayed at a large scale. Some studies proposed to further enlarge the scope of EROI. Moriarty and Honnery (2019) introduced the new notion of green net energy, defined as the primary energy minus the input energy and the "energy costs needed for energy maintenance". The authors showed a potential decrease of green net energy in about a decade, and emphasized the need to assess of the evolution of a green EROI.

³⁹ These results could be significantly impacted by the technological improvements of renewables.

⁴⁰ Except in the case of drastic raise of gross energy, which could provide sufficient net energy even within a low-EROI society while having a tremendous biophysical cost (Trainer, 2018).

⁴¹ This remark does not take into account possible energy savings.

⁴² Murphy and Hall (2010) showed that every historical US recessions occurred after an oil price peak.

of development of western society. [Hall et al. \(2009\)](#) estimated a minimum value of 3:1 for a society to run, without art, medicine or education, while [Brandt \(2017\)](#); [Hall et al. \(2009\)](#) and [Hall \(2017\)](#) concluded on a minimum societal EROI of about 5:1 to 6:1 for a modern Western society—which current EROI was evaluated to 20:1 ([King and van den Bergh, 2018](#)). The estimated levels of EROI in a low-carbon transition could therefore affect our lifestyles, and while [Hall et al. \(2014\)](#) concluded that "[they] see no easy solution [to the current energy and climate challenge] when EROI is considered", [Moriarty and Honnery \(2021\)](#) emphasized the higher potential of primary energy reductions than a massive renewable development.

Besides the biophysical aspects previously described, the shift from fossil energy sources to renewables could have significant technical consequences. Among them, the impact on the power grid of the increasing share of renewable energies in the power mix has been widely studied in the literature, and several main concerns have been raised. Firstly, the intermittent nature of wind and power energies could create supply issues and requires the deployment of large storage capacities or redundant plants ([Trainer, 2013](#)), which are local options. At a larger scale, existing and projected power grid interconnections could provide an additional alternative to tackle intermittency, optimize the penetration of renewables in low potential areas and achieve cost reductions ([Yang, 2020](#); [Li et al., 2020a](#)). Multi-national interconnections have already been successfully implemented (e.g. Continental Europe, Nordic Europe, Central American Electrical Interconnection System, Integrated/Unified Power System...) and numerous are currently discussed at governments level and analyzed in the literature, such as in the Middle-East ([Zhang et al., 2017](#)), in North-East Asia ([Ichimura and Omatsu, 2019](#); [Ogino, 2020](#)), in the Association of Southeast Asian Nations ([Ahmed et al., 2017](#); [Jiang et al., 2019](#)) or in Africa ([Wu et al., 2017](#); [Juma et al., 2020](#)). Secondly, the current power grids rely on synchronous sources to help ensuring the stability of the network⁴³, mainly through their reactive power⁴⁴ absorption and inertia. Given that wind and PV are decentralized generation technologies and display various installations scale, they can be connected in the low to high voltage grid. However, the French law prohibits installations connected to the low voltage network from absorbing reactive power, which creates high-voltage issues ([Commission de Régulation de l'Énergie, 2020](#)). Given the numerous low-scale renewables projects connected in the low-voltage network, the French energy regulator proposed to lift this restriction. The further development of large scale projects could allow for a more systematic inclusion of reactive power absorption devices, as well as other systems enhancing the grid stability. The second main characteristic altered by the development of renewables is inertia. Synchronous inertia is defined as the "instantaneous physical response of conventional generators having directly coupled rotating mass, which acts to overcome the imbalance of supply and demand by changing the rotational speed" ([Hartmann et al., 2019](#)). The current decrease of synchronous inertia-as wind and PV are not synchronous devices-could therefore hamper the frequency stability of the grid ([Yan et al., 2015](#); [Seneviratne and Ozansoy, 2016](#)), and recent publications have analyzed the minimum level of inertia (or critical inertia) for a grid to be stable in case studies ([Ahmadyar et al., 2016](#); [Gu et al., 2018](#); [Garcia-Casals et al., 2019](#); [Johnson et al., 2019](#)). In order to offset the inertia reduction and maintain frequency stability, new systems are required. Their use is locally designed, as the power mix and grid resilience display various regional profiles. Several stability options aims at providing additional inertia or tackling frequency instability, such as synthetic/virtual inertia from electric vehicles ([Magdy et al., 2021](#)) or wind turbines ([Fernández-Guillamón, 2019](#); [Berizzi et al., 2020](#))⁴⁵ and fast frequency response, while other systems enhance the grid flexibility, such as demand response and energy storage ([Denholm and Hand, 2011](#); [Vogler-Finck and Früh, 2015](#); [McPherson and Tahseen, 2018](#); [Saygin et al., 2021](#))⁴⁶. The increasing share of renewables in the power mix could therefore have significant consequences on the grid behaviour. A joint study of the IEA and the French Transmission System Operator assessed a maximum proportion of wind and PV-for the power grid to remain stable-of about 50% by 2035. Increasing this share will require further systems and grid development ([IEA and RTE, 2021](#)) and expensive structural changes of power grids are expected⁴⁷, in addition to grid expansion to connect the new decentralized generation units.

⁴³The power system stability is commonly segmented into three main aspects: rotor angle stability, frequency stability and voltage stability ([Kundur et al., 2004](#)).

⁴⁴Reactive power is an "unused" power generated by power installations.

⁴⁵Virtual or synthetic inertial is now mandatory on a share of the installed wind turbines in several countries ([Tamrakar et al., 2017](#)). Such inertia is referred to as virtual because it remains triggered after a contingency and displays higher response time than instantaneous physical response.

⁴⁶Pilote projects have already been developed to assess the support potential of renewable plants. For instance, a 300 MW solar PV plant equipped with advanced power electronics displayed encouraging results to "contribute to system-wide reliability" ([Loutan et al., 2017](#)).

⁴⁷The four German Transmission System Operators presented in January 2021 their [2035 plan](#) to achieve a share of renewables in the power mix

The temporal and biophysical constraints, as well as the required power systems adaptation illustrate some of the upcoming challenges of the energy transition. They outline the versatile stakes of the next decades, as the transition presents temporal or technical obstacles, questions the development of human societies and the role of cheap and abundant energy in the growth paradigm, but also represents an economic conundrum. The energy systems development and adaptation will require increasing capital needs which could not be met in a business-as-usual scenario (Dupont et al., 2021). The difficult economic context due to the COVID-19 health-and more generally the successive financial, economic or terrorist crisis context-could further hamper the investment pace. Alongside the previously depicted challenges, numerous authors have identified an emerging physical paradigm due to the parallel multi-sector shift towards low-carbon technologies, which is described in the next Section.

1.3.4 The minerals and metals research field

The analysis of minerals and metals in the anthroposphere has been studied for over 20 years in the literature. After an early period of top-down studies⁴⁸ focusing on assessing the global or regional stocks and flows of base materials between the lithosphere and the anthroposphere (e.g. in the Stocks and Flows Project (STAF) (Graedel et al., 2002; Spataro et al., 2002; Kapur et al., 2003; Vexler et al., 2004)), bottom-up studies⁴⁹ have progressively gained interest in order to analyze the sector drivers of demand and provide with a better description of technologies characteristics and evolution. A special emphasis on the energy (e.g. Elshkaki (2019b); Moreau et al. (2019b) and Ren et al. (2021)) and building sectors (e.g. Müller (2006); Wiedenhofer et al. (2015); Deetman et al. (2020) and Marinova et al. (2020a)) has been observed over the years, as they represent major drivers of the materials consumption. The analysis allowed for a progressive better insight of elements and materials cycles in the anthroposphere (Figure 1.15), as our system relies on a majority of them without a thorough understanding of the types of uses, lifetimes, losses or recycling rates (Chen and Graedel, 2012). The Figure 1.15 offers a simplified view of metals stocks and flows cycle in the anthroposphere. Several steps are required to extract and transform a metal for its uses (A, B and C), and for a metal to be recycled (D and F). However, scrap is generated at several stages (G, I and J) and losses occur (E and M), which hampers the recycling rate of metals. Even if the metals are infinitely recyclable, the losses in the processes are irremediable (Gordon et al., 2006).

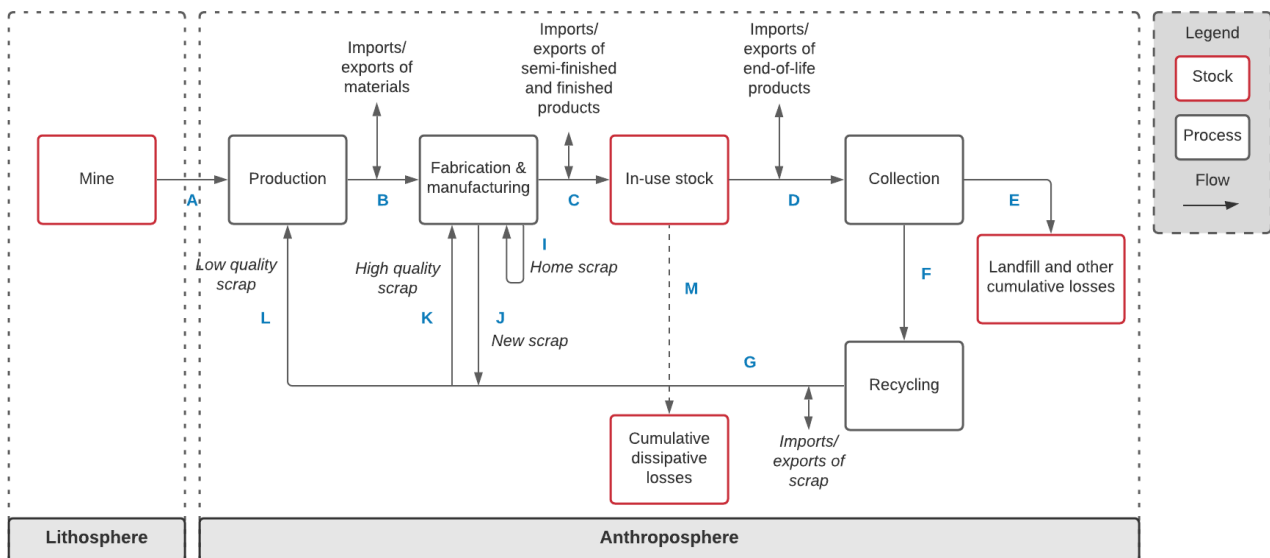


Figure 1.15: Simplified metals stocks and flows cycle (adapted from Graedel et al. (2011); Glöser et al. (2013) and Maung et al. (2017)). A: Primary metals, B: Refined metals, C: Semi-finished and finished products, D: End-of-life products, E: Losses in the collection, F: Collected metals, G: Recycled metals or old scrap, H: New scrap.

From the publications, two categories can be distinguished among the minerals and metals, and a better understanding of the development phases of material demand emerged. While the technological metals are used for specific uses

of about 70%, which could require an investment estimated to more than 70 billions euros.

⁴⁸A top-down study is defined as a modeling relying on input-output tables or which assesses stocks from a flow analysis.

⁴⁹Bottom-up modeling focuses on describing parts of the system in details and then conducting a part-whole modeling.

in technologies applications (e.g. neodymium in permanent magnets, selenium in solar cells or lithium in batteries), the structural materials provide the basis of the infrastructures in our society (e.g. aluminum, concrete, copper, steel, iron, chromium, manganese⁵⁰). Technological metals display lower reserves and are extracted in smaller quantities. The segmentation allows for a more accurate picture of the dynamics of materials consumption. Bleischwitz et al. (2018b) identified three stages in the stocks and flows of steel, cement, aluminum and copper. In the first step of industrialization, the demand and the per capita stock rapidly grow to build the infrastructures (*growth stage*), before observing a stabilization of the demand and a slower growth of the per capita stock in a *maturing stage*, and a final *saturation stage* with a stabilization of the per capita stock and a decrease of the demand. From an historical analysis, the authors estimated saturation thresholds of about \$12,000 GDP/cap for steel and cement, around \$ 20,000 GDP/cap for copper, and a weaker saturation trend for aluminum. The successive industrialization of Western Europe, Northern America, OECD Pacific⁵¹, or China has therefore led to a substantial surge in raw materials demand between 1950 and 2020, estimated to 1.4%/yr for manganese, 4%/yr for nickel, 2.5%/yr for zinc, 5.5%/yr for aluminum, 3%/yr for copper, 3.2%/yr for steel and 5%/yr for cement (USGS, 2021b). The future industrialization of developing countries will create a further increase in materials demand, in parallel of other drivers. Subsequent to the structural development, a society requires increasing technological materials for high-technologies. New materials are used for new technologies, new properties on existing devices or efficiency improvements (Graedel et al., 2015), and the annual growth of numerous metals production reach 10% (Vidal et al., 2017). An overall growth of the demand of raw materials is expected, stimulated by the population increase, the industrialization of developing and poor countries, the urbanization, the materials complexification of technologies and the energy transition (Vidal et al., 2017).

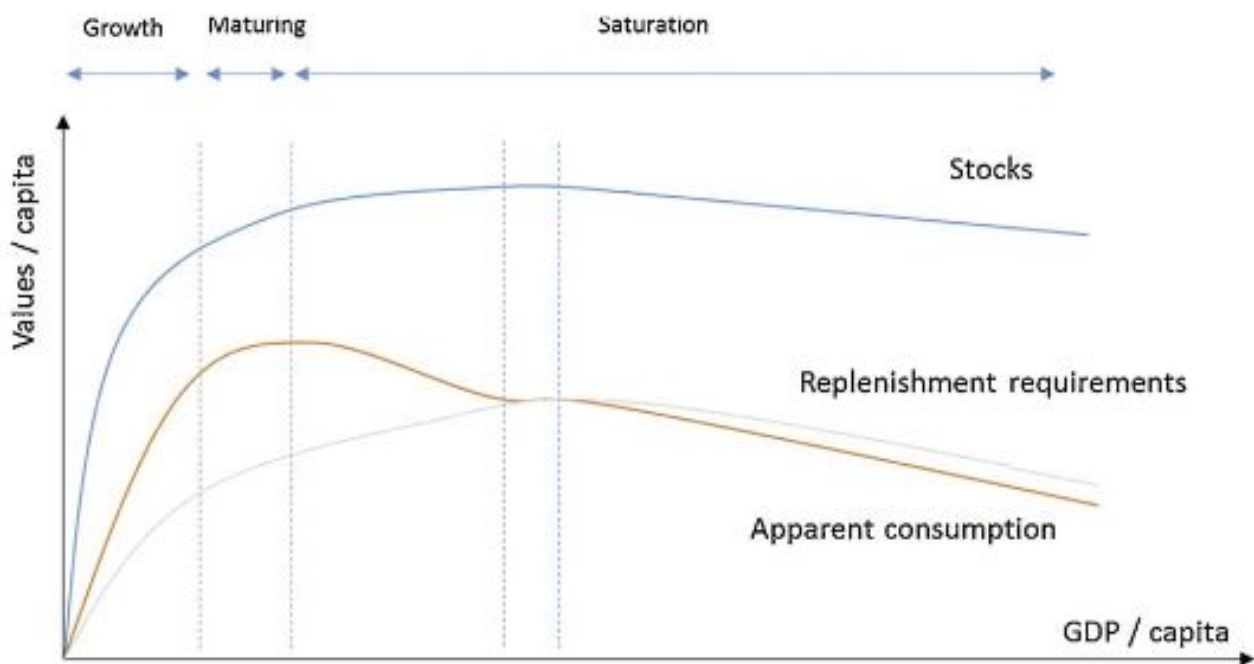


Figure 1.16: Evolution of stock per capita and flow per capita with GDP per capita. Source: Bleischwitz et al. (2018b)

The increasing material constraints emerging from the energy transition have been identified through the estimations of the raw materials intensities of technologies required in the bottom-up approaches. Two main findings were highlighted. Firstly, renewables are decentralized technologies, and therefore display higher materials requirements per installed capacity (t/MW) than thermal units (Kleijn et al., 2011; Elshkaki and Graedel, 2013a; Vidal et al., 2017). The materials intensities of power generation technologies are depicted in Figure 1.17 and the fast evolution (e.g. technological progress or scale effect) of renewables explains the important dispersion of the data. Significant variations are observed between sub-technologies of an energy source (e.g. CSP, PV farm, PV farm tracker and PV roof), which

⁵⁰Chromium, manganese, zinc and nickel are commonly considered as structural raw materials for their use in steel making.

⁵¹OECD Pacific is composed of Australia, New Zealand, Korea and Japan.

could impact the material cost of the regional energy mixes. Moreover, the comparison of materials requirements of supplied energy (t/MWh) magnifies the gap between renewables and thermal units. It is due to the intermittency of solar and PV, as they generate power depending on the weather conditions. For instance, onshore wind consumes two to three times more steel than coal in t/MW, and five times in t/MWh (Vidal, 2018).

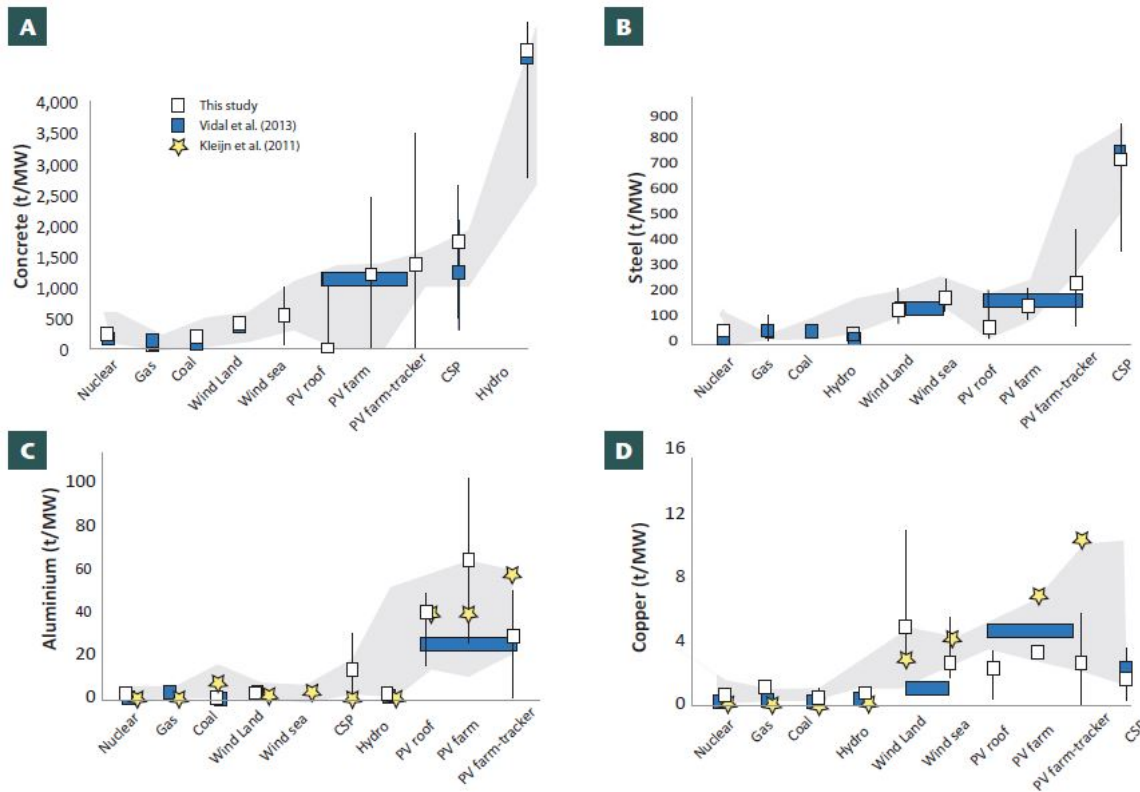


Figure 1.17: Base materials requirement per MW (t/MW) for power generation technologies. Source: Vidal et al. (2017), with data from Kleijn et al. (2011); Vidal et al. (2013).

Secondly, low-carbon technologies and their related modification of the energy system (e.g. storage, power transport, connectivity...) significantly affected raw materials demand from a qualitative perspective, as most of materials of the periodic table of elements are currently used (Figure 1.18). The combination of the two findings with lower lifetimes of low-carbon energies and potential limited substitution for some uses (Graedel et al., 2015) could lead to supply constraints. The mineral industry could experience challenges depending on the scale of the ongoing energy transition, in a context of demand increase in other sectors and of prolonged downturn of mining exploration between 2013 and 2020 (Liu, 2021).

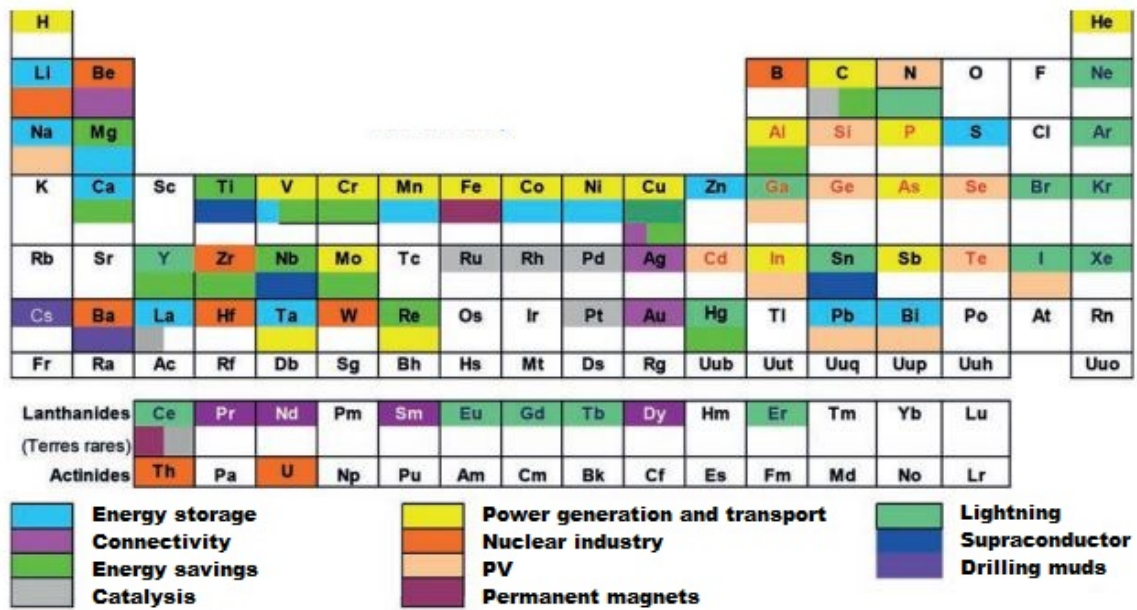


Figure 1.18: Raw materials used in energy technologies. Source: [Christmann \(2016\)](#)

The conjunction of an increase in the amounts and types of raw materials consumed led to a significant growth in the number of publications studying the impact of the energy transition on the mining industry. The current energy system relies on non-renewables energy materials (oil, gas and coal), and the development of wind and solar technologies could operate a shift toward a dependency to minerals and metals ([Vidal et al., 2013](#)). Numerous studies have therefore estimated raw materials need in transition scenarios to better assess the consequences of the upcoming shift in energy ([Elshkaki and Graedel, 2013b](#); [Vidal et al., 2018](#); [Beylot et al., 2019](#); [Deetman et al., 2021b](#)), transport ([Watari et al., 2019](#); [Nguyen et al., 2019a](#); [Dunn et al., 2021](#)) or building and infrastructures ([Marinova et al., 2020a](#); [Deetman et al., 2020](#)). Among the upcoming challenges, the supply constraint and the environmental constraint have been identified. The supply issue could occur for technological materials displaying a potential depletion, sensitivity to geopolitical events, or a surge in demand not met by the mining industry’s capacity. These challenges led to the definition of the criticality concept, which is defined as the levels of importance in use and availability of a material ([National Research Council, 2008](#)). Criticality of metals and its consequences was for instance observed during the rare earth elements (REE) crisis in 2011. China accounts for almost the REE reserves, and its 2011 decision to significantly reduce exports impeded the high-tech production around the world. The second challenge is the environmental and energy impacts of raw materials supply. Unlike the supply constraint, structural materials are the main source of concern of this challenge. The iron/steel and cement/concrete industries represented 12 to 14% of global energy demand and CO₂ emissions in 2018 ([Bataille, 2019](#)), and the primary production energy and environmental impacts could further increase due to the conjunction of the previously depicted situation of expected growth and of declining ore grades. As the most accessible deposits are progressively depleted, the production energy (MJ/kg) rises. Technological progress have so far offset this trend, but future efficiency improvements are limited by a thermodynamic limit of primary production energy ([Vidal, 2021](#)). A higher share of recycled materials could prevent the energy demand rise, as secondary materials display significantly lower energy intensities ([Birat et al., 2013](#); [Chen et al., 2019](#); [Harvey, 2021](#)). The combination of increased demand and higher energy intensity of production leads to a potentially large growth in energy consumption in the mining sector. The current energy mix remains largely dominated by fossil fuels, and the construction of low-carbon infrastructures could therefore take a heavy environmental toll, which could be reduced in case of increasing reliance of materials production on renewable energy ([McLellan, 2012](#)). The deep interaction between the energy system and the mining industry is commonly referred to as the energy-materials nexus, which is a growing research topic in the literature ([Giurco et al., 2014](#); [Tokimatsu et al., 2017](#); [Vidal et al., 2017](#); [Peng et al., 2019](#)). In a broader perspective, the need to adopt system approaches when studying resources has been high-

lighted by [Graedel and van der Voet \(2010\)](#) and thoroughly reviewed in [Bleischwitz et al. \(2018a\)](#). The authors defined the resources nexus as "a set of context-specific interlinkages between two or more natural resources used as inputs into systems providing essential services to humans" and analyzed the links between energy, food, water, materials and land. The resources nexus topic has been recently illustrated by the water crisis in Chile and its impact on copper production⁵², or by the ban on metal mining in El Salvador for water scarcity purposes⁵³. The increasing upcoming dependency to metals and minerals could therefore induce supply, energetic and environmental constraints. It is the role of the academic community to estimate the future impacts of a conjunction of factors leading to a potential significant increase in raw materials extraction, and to assess the potential of alternatives such as substitution and recycling. The numerous scenarios depicted in Section 1.3.3 provide a panel of futures, for which the material dimensions is often lacking and should be more systematically assessed. From the zero-emissions of renewable technologies power generation and the recycling potential of metals and minerals, a more sustainable and circular economy could be envisioned.

1.4 Contribution of this work

The estimation of stocks and flows of materials in a system are generally conducted through material flow analysis. In a first Chapter, the academic literature computing dynamic material flow analyses of materials is reviewed. 129 publications were selected between 2000 and 2021, and the review methodology relies on [Müller et al. \(2014\)](#) and [Wiedenhofer et al. \(2015\)](#). It allows to identify research gaps. The materials sector studies proposed in the remainder of the thesis emerge from these conclusions, and aims at filling four of the identified gaps: (1) a lack of prospective studies in a low-carbon context, (2) a lack of analysis of the energy-material nexus, (3) a lack of modeling of some sectors and (4) a limited number of solution-oriented and political-oriented studies.

My PhD aims at providing further insights on the base material content of the low-carbon transition. It proposes a modeling of the stocks and flows of four of the most structural materials (concrete, steel, aluminum and copper) in two sectors in the context of the low carbon transition. First, a study on the global energy supply system is displayed. It aims at providing an estimation on the material weight of renewable power and fossil fuel technologies in low-carbon scenario, and to assess the recycling potential of decommissioning. Second, the building sector represents most of the solid wastes generation and is a challenge for the circular economy. A material stocks and flows approach of the residential and non-residential buildings was conducted for the period 1950-2100. A multi-regional approach was adopted for energy transitions scenarios of the International Energy Agency and the academic community. It encompasses both construction and thermal renovation.

The sector studies are included in a larger project, aiming at developing the Dynamic Modelling of Energy Matter Demand and Supply (DyMEMDS). It is a stock and flow model computed at a multi-regional and multi-sector scale, relying on System Dynamics and developed in the ISTerre laboratory.

⁵²A Chile court [suspended](#) copper production in a region because of severe drought.

⁵³The Parliament of El Salvador ordered the ban in [early 2017](#).

Chapter 2

Dynamic base materials modeling: a critical review

Summary of the chapter

Objectives and methods

- The present chapter proposes a critical review of 129 dynamic material flow analyses of four base materials (aluminum, concrete, copper and steel) published from 2000 to 2021;
- A review methodology is developed. It relies on previous work by [Müller et al. \(2014\)](#) and [Wiedenhofer et al. \(2020\)](#).

Results of the literature review

- Most studies adopt a *national scope* and focus on the *building, power supply, transportation and infrastructures sectors*;
- They increasingly encompass *several base materials* and consider a *bottom-up* approach;
- However, prospective studies in a *low-carbon perspective* remained limited, a lack of analysis of the *energy-material nexus* was observed, and no analysis proposed *solution-oriented modeling* to decrease the impacts of base materials.

Insights of the literature review

- The data challenge of bottom-up studies is progressively tackled by the development of material intensity databases and sensitivity analyses;
- In-use stocks are linked with regional development levels;
- Material wastes are increasingly analyzed, mostly from a the political perspective;
- Recycling could play a significant role to decrease energy demand and GHG emissions in a context of growing material use;
- Nexus
- The expected pace and magnitude of inflow increase and waste generation in the coming decades raised concerns about the capacity of the political community to display incentives and bidding measures.

Materials represent the "modern basis of human society" (Graedel et al., 2015) and enable an increasing technological complexity and lifestyle improvement. The challenges of quantifying resources stocks and flows in the anthroposphere, their energy and environmental impacts, and their link to development have produced a rich literature in recent decades. Seven analysis reviewed the publications on mineral and metallic materials over the last 10 years¹. They displayed various scopes and objectives. In the first large-scale review, Chen and Graedel (2012) proposed an overview of static and dynamic anthropogenic cycles of materials in 350 papers. The authors showed the limited knowledge of most material cycles and outlined that dynamic cycles were rarely considered. However, dynamic studies have been increasingly developed over the past decade, and the methods displayed in dynamic material flow analyses (MFA)² of metal were reviewed in Müller et al. (2014), based on a standardized review protocol. Moreover, three of the literature reviews focused on the construction sector. Augiseau and Barles (2017) reviewed publications on non-metallic minerals. The authors identified the main methodological approaches, highlighted the role of assumptions and data in the reliability of publication outcomes and outlined the need to develop a study framework for analysing the metabolism of a socioeconomic system. A framework was defined in Göswein et al. (2019) for urban building stock analysis, which allows to choose a method, tool and dynamics of parameters. The literature on construction and demolition waste was reviewed in (Wu et al., 2014b), and the authors proposed a relevance tree of methodology selection for future studies. Finally, two publications proposed a more conceptual approach of materials. While Jin et al. (2016) showed that criticality research is at an early stage, both in terms of scope and methodology, the literature on the decoupling conundrum of GDP, resource use and GHG emissions was reviewed in Haberl et al. (2020) and Wiedenhofer et al. (2020). They showed that relative decoupling of materials and GDP was identified in regions displaying intermediate economic growth or socio-economic and political turmoil, which absolute decoupling was observed only in low economic growth or recession context.

The seven reviews have proposed analyses on MFA methods, the building sector, criticality and decoupling³. They have not yet offered a more general overview of the main insights of publications, which is the focus of the present literature review. The current combination of demographic surge, rapid economic development of emerging countries and low-carbon transition could create a shift from energy materials to minerals and metals. Base materials such as cement, steel, aluminum, chromium, copper, manganese and zinc had large demand among materials in 2020 (USGS, 2021b), showed limited substitution potential, and could account for a substantial share of materials demand for low-carbon technologies. This chapter offers a critical review of 129 dynamic material flow analyses of four base materials: aluminum, concrete, copper and steel published from 2000 to 2021 at national, regional, multi-regional and global scales.

2.1 Methodology

In a first phase, the relevant publications were identified based on research, relevance and analysis methodologies. The research of publication aims at embracing the largest panel of studies in order to have a broad outlook of the previous works. It is crucial to use a multi-database approach to prevent any Matthew effect, as stated by Göswein et al. (2019). The selection methodology intends to narrowing the outputs of the research by setting up a relevance and/or quality review, and sometimes a duplicate removal (Wiedenhofer et al., 2020). Finally, the analysis methodology pursues a in-deep study of the selected literature through a contextual framework. The research phase of the present review was first carried out through a keyword approach on Web of Science, Google Scholar, Semantic Scholar and Connected Papers. 150 articles were finally selected for this literature review, covering a period from 2000 to 2021. Finally, I elaborated a methodology adapted from the ODD protocol (Grimm et al., 2006) and the previous works of Müller et al. (2014) and Wiedenhofer et al. (2020), it relies on 16 main categories and 66 sub-categories allowing a thorough analysis of the dynamics of the bulk materials modeling research field. An overview of the selected papers is

¹The review of Van den Heede and De Belie focus on LCAs of traditional and green concrete without q. The authors showed the significantly lower impact of green concrete, in which cement is partially replaced by industrial by-products.

²MFA is a method which enables to quantify the stocks and flows of resources within a system. It is frequently used in metals and minerals analyses in industrial ecology.

³More information on the reviews is available in Section A.

given in a first section. It covers the general scope of the study (1a and 1b), the materials (2a to 2e), geographic (3a to 3d) and temporal scope (4a to 4c), a scenario segment in case of a prospective study (5a to 5c), as well as the sectors included in the articles (6a to 6i). Then, the characteristics of modeling are identified:

- Modeling characteristics (7) capture the general frame of the model. They focus on either lifetime distribution (7a, e.g. Weibull, D-based, normal etc), bottom-up and/or top-down modeling (7b), and domestic or footprint approach (7c). Domestic approaches measures the materials consumed in an economy, thus considering the total of local extraction plus materials imports minus materials exports. In the opposite, footprint approach evaluates the materials impact of an economy, which consists of the materials consumed in the goods final need (Wiedmann et al., 2015).
- The intensity inputs (8) of the modeling study. Four types of intensities are considered. Material intensities (8a) reports the amount of materials in a given technology, e.g. the concrete consumed to produce a building (in kg/m²). Materials embodied energy (8b), materials embodied CO₂ emissions (8c) and materials embodied environmental impacts (8d, other than CO₂) are, respectively, direct and indirect consumed energy, CO₂ emitted and the other impacts of the extraction and transformation of materials.

Results and analysis are finally specified in the last part of the analysis methodology. It proceeds in five steps:

- The type of materials results is indicated. They can be stocks and/or flows (9a and 9b), and a special focus on waste (9c) and collect and recycling results is provided (9d).
- Three energy results (10) are considered : embodied energy (10a) of the total materials embedded in a system, exergy (10b) and EROI (10c)
- The impacts category corresponds to CO₂ (11a) impacts of material, water (11b), land use (11c) and other impacts (11d).
- The results analysis category encompasses sensitivity (11a) and/or uncertainty (12b) analyses. An uncertainty analysis aims at assessing the errors in the outputs depending on the uncertainties in the inputs, while a sensitivity analysis describes the impacts of an input variations on an output, and shows the impacts of independent variables.

The emphasis was made on the possibility of details in this framework. Thus, 16 of the 46 require specific answers, and 30 allow for a yes/no answer⁴. The detailed framework is presented in Table 2.1.

⁴Only positives answers are apparent for more clarity of the final document.

	Category	Index	Sub-category	Answer	
	General data		Title Author Year Journal/Editor DOI/ISBN		
Overview	1	1a	Stocks and flows modeling	Y/-	
		1b	Energy and environmental impacts modeling	Y/-	
	2	Materials scope	2a	Aluminum	Y/-
			2b	Concrete	Y/-
			2c	Copper	Y/-
			2d	Steel	Y/-
			2e	Aggregated	Y/-
	3	Geographical scope	3a	National	Specify country
			3b	Regional	To be specified region
			3c	Multinational/Multiregional	Y/-
			3d	Global	Y/-
	4	Temporal scope	4a	Retrospective and/or prospective	Retrospective, Prospective or Both
			4b	Start year	To be specified
			4c	End year	To be specified
	5	Scenario	5a	Name/Organization	To be specified
			5b	Other prospective approach	To be specified
			5c	Stock-driven by logistic/Gompertz	Y/-
	6	Sector scope	6a	Power supply	Y/-
			6b	Power grid and energy storage	Y/-
			6c	Fossil fuels supply	Y/-
			6d	Building	Y/-
6e			Domestic appliances	Y/-	
6f			Public infrastructures	Y/-	
6g			Transport	Y/-	
6h			Industry	Y/-	
6i			All sectors aggregated	Y/-	
7	Modeling characteristics	7a	Lifetime distribution	To be specified	
		7b	Bottom-up and/or top-down	Bottom-up, Top-down or Both	
		7c	Domestic or footprint approach	Domestic or footprint	

	Category	Index	Sub-category	Answer	
Model design	8	Intensity inputs	8a	Materials intensities	Static or Dynamic
			8b	Materials embodied energy	Static or Dynamic
			8c	Materials embodied CO2 emissions	Static or Dynamic
			8d	Materials embodied environmental impacts	Static or Dynamic
Results and analysis	9	Materials results	9a	Stocks	In-use, Obsolete, Or Both
			9b	Flows	Y/-
			9c	Waste stocks and/or flows	Stocks, Flows, or Both
			9d	Collect and recycling	Y/-
	10	Energy results	10a	Embodied energy	Y/-
			10b	Exergy	Y/-
			10c	EROI	Y/-
	11	Impact results	11a	CO ₂	Y/-
			11b	Water	Y/-
			11c	Land use	Y/-
			11c	Other	Y/-
	12	Results analysis	12a	Sensitivity analysis	Y/-
12b			Uncertainty analysis	Y/-	

Table 2.1: Analysis methodology of the literature review

2.2 Results

The results of the literature review are displayed in the present Section. The Table 2.2 presents the main results and more details are available in the text and the supplementary information.

Index	Sub-category	Results	Notes
1b	Materials embodied environmental impacts	18/129	
2a	Aluminum	47/129	
2b	Cement/concrete	34/129	
2c	Copper	54/129	
2d	Steel	64/129	
3a	National	86/129	Domination of China and the USA.
3b	Regional	6/129	Only on the European scope.
3c	Multinational/ Multiregional	20/129	
4a	Prospective	66/129	Mostly combined retrospective and prospective approaches.
6a	Power supply	32/129	
6b	Power grid and energy storage	26/129	Mostly combined with energy supply modeling.
6c	Fossil fuels supply	1/129	Only pipelines on the Chinese scope.
6d	Building	65/129	
6e	Domestic appliances	20/129	
6f	Public infrastructures	53/129	
6g	Transport	56/129	
6h	Industry	26/129	
6i	Final demand goods	20/129	
6j	Trade	14/129	In top-down studies.
7b	Bottom-up	49/129	
9d	Collect and recycling	83/129	
10a	Embodied energy	13/129	
11a	CO ₂	19/129	
11b	Water	2/129	
12a	Sensitivity analysis	39/129	
12b	Uncertainty analysis	36/129	Mostly combined with a sensitivity analysis.

Table 2.2: Main results of the literature review

2.2.1 Materials studied

The selected publications study four base materials, namely aluminum, concrete, copper and steel. As previously stated, iron and steel were associated in this study, as well as cement and concrete. Iron/steel and copper were the first dynamically studied materials between 2000 and 2003. The number of publications then remained low but homogeneous between materials until 2010. A domination of iron/steel is then observed until 2017, and of copper in 2018 and 2019 (Figure 2.1a). The number of publications per material finally converged between 2019 and 2021, which is explained by the domination of multi-materials over single-material studies since 2019. The multi-materials approach experienced a quick increase since 2011 (Figure 2.1b).

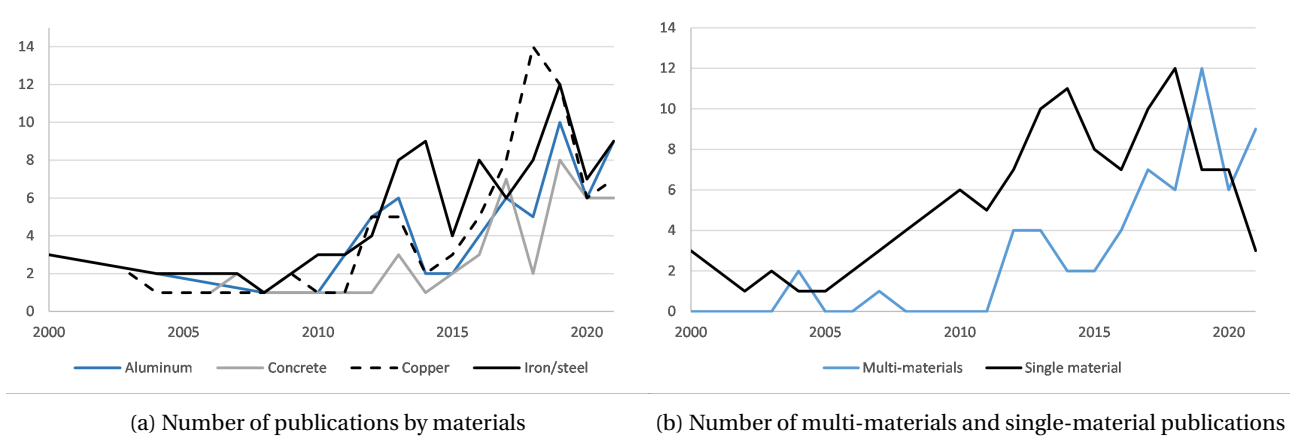


Figure 2.1: Publication by materials and multi-materials or single-material approach between 2000 and 2021.

2.2.2 Temporal and geographic scope

A majority of the 129 publications display a national approach, while the least represented geographic modeling are regional (Table 2.2). All the regional-scale studies focus on Europe, adopting several perimeters (EU15, EU25, EU28). The high number of national studies conceals significant differences in modeling across countries. Input-output modeling and multi-national database development are used for most countries around the globe, mainly from a top-down flow perspective. Great geographical disparities were identified. China accounts for most national, ahead of the USA and Japan. Those three countries gather 54 national scale analyses in the selected literature, while most of the remaining countries are modeled in one or two studies (Figure 2.2).

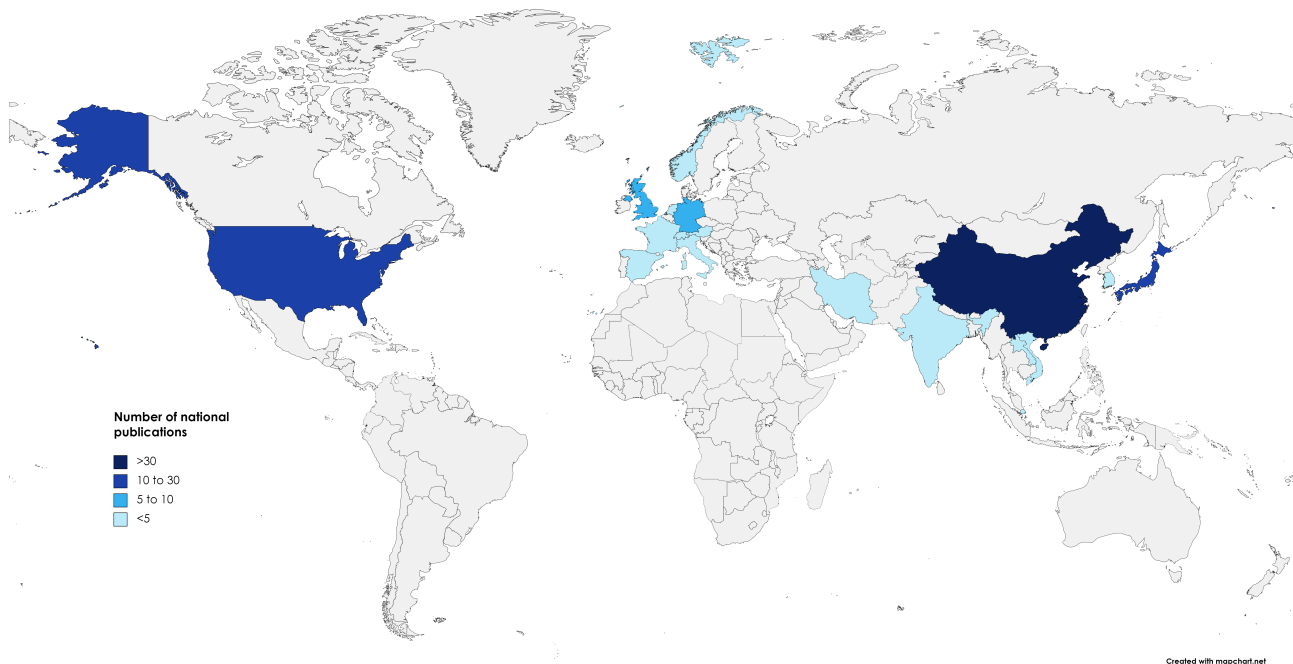


Figure 2.2: Number of national studies by country. The map was generated using [Mapchart](#).

The temporal scope of the selected studies extends from 1700 to 2150. The retrospective approach represents 63 of the 129 material stocks and flows modeling analysis, and 66 publications present a prospective (or combined prospective and retrospective approach). The majority of these prospective modeling considers a time frame up to 2050. In order to model sector and/or overall material stocks and flows, they rely on two types of future assumptions. A first panel of publications consider global or national existing scenarios from different sources :

- Institutions : International Energy Agency ([Elshkaki and Shen, 2019](#); [Elshkaki, 2019a,c](#); [Moreau et al., 2019a](#);

Watari et al., 2019; Kuipers et al., 2018; Vidal et al., 2018, 2017; Valero et al., 2018; Månberger and Stenqvist, 2018), International Renewable Energy Agency (Moreau et al., 2019a), World Energy council (Elshkaki, 2019c), United Nations Environment Programme (Elshkaki et al., 2016), National Research Coordination Alliance for Energy in France (Beylot et al., 2019), National Development and Reform Commission in China (Elshkaki, 2019a);

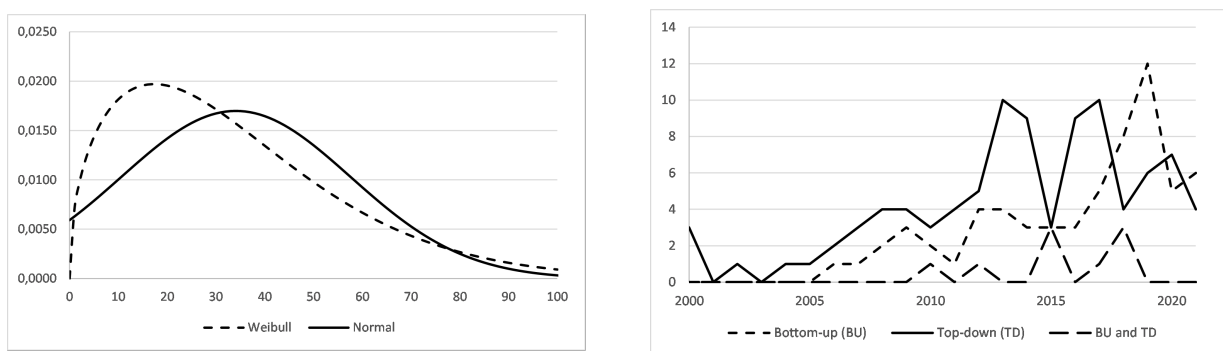
- Non-governmental organizations : World Wild Fund (Vidal et al., 2017, 2018; Moreau et al., 2019a), Greenpeace (Valero et al., 2018; Elshkaki, 2019c);
- Private firms : Statoil (Elshkaki, 2019c);
- The climate change research community : Shared Socioeconomic Pathways (Deetman et al., 2021b; Marinova et al., 2020a; Schipper et al., 2018)

The authors of a second panel of studies develop their own scenarios:

- Assumptions of various evolutions such as high or low growth, extrapolation of current market or growth trends (Yang et al., 2021; Streeck et al., 2021) or demand stagnation in various years in Morfeldt et al. (2015); Wiedenhofer et al. (2019) or sectoral hypothesis (Hong et al., 2016; Pfaff et al., 2018));
- Own scenarios, sometimes compatible with existing institutional scenarios (Seck et al., 2020; Elshkaki et al., 2018; Elshkaki, 2019a; Tokimatsu et al., 2017; Månberger and Stenqvist, 2018).

2.2.3 Modeling characteristics, modeling tools and inputs

A top-down study was adopted in 80 analyses, while 49 bottom-up modeling were identified. The number of bottom-up studies has been increasing over the past few years (Figure 2.3b). Only 38 footprint studies adopted a footprint approach—including imports and exports of materials in final goods. As described in Müller et al. (2014), the MFA/SFA approaches use the same loop-based description with various levels of stocks and flows computation. The overall input/in-use stock/output structure is always observed, while secondary flows, obsolete stocks and trade flows are considered depending on the purpose, scope and details level of the study. An average lifetime is usually considered, and 72 of the 129 selected studies use one or several lifetime distributions. As stated in Cao et al. (2017a), these mathematical tools allow to assess the probability of an amount of materials to survive a certain time. A domination of Weibull distribution is observed, ahead of normal distributions (Figure A.8). A rare use of log-normal, logistic, gamma or beta lifetime distributions was also noticed. A summary of the building-related lifetime distributions, their scopes, mean values and standard deviations is displayed in Table 4.3 in Chapter 4.



(a) Example of Weibull and normal distributions (Zhou et al. (2019)) (b) Number of top-down, bottom-up and joint approaches publications

Figure 2.3: Example of Weibull and normal distributions with a mean value of 34.1 and a standard deviation of 23.5 as observed for Chinese urban residential buildings in Zhou et al. (2019) (left graph) and number of top-down, bottom-up and joint approaches publications between 2000 and 2021 (right graph).

The assumption of in-use stock stagnation is observed in many studies through logistic or Gompertz approaches. They depict a three-phase behavior of infrastructure and raw material stocks using an S-curve profile. These mathematical tools were originally developed to analyze the evolution of the population (Gompertz, 1825; Verhulst, 1845).

Applied to infrastructures, these curves outline a gradual change towards a state of saturation. The difference between these two mathematical tools lies in the rate of growth before reaching saturation.

Materials intensities inputs were identified in bottom-up studies. A majority of the studies consider static intensities (19/53) and no clear trend towards more dynamic material intensities was found. Given their low occurrences, embodied energy and impacts intensities analysis are difficult to formulate.

2.2.4 Sectors

The use of materials and goods database allow to compute all sectors and trade exchanges in top-down approach (The yearbook of nonferrous metals industry of China, [USGS](#), [UN Comtrade database](#), [Worldsteel](#), [Copper Alliance](#)) mainly through a flow-driven approach. The sector most commonly included in bottom-up computing is building, ahead of power supply, transportation and infrastructures. Multi-sector approaches are usually observed in the considered studies, with some overall patterns. Infrastructures and domestic appliances have a strong dependency with the building sector, and the power grid, energy storage sector and the electrical vehicles are usually studied in parallel of power supply. Only five publications carry out a detailed bottom-up approach for a large set of infrastructures. [Valero et al. \(2018\)](#); [Wang et al. \(2015a\)](#); [Dong et al. \(2019\)](#); [Yin and Chen \(2013\)](#) pursued physical approach of material content, and [Chen \(2018\)](#) adopted a monetary approach. Moreover, some sector gaps were exhibit, such as a lack of study of the industry sector ([Dong et al. \(2019\)](#) considered an average copper intent for the industrial infrastructures in China), final demand goods ([Dong et al., 2021](#); [Chen, 2018](#)) and regional or global trade. Some sectors are not well represented, such as fossil fuel supply infrastructures.

2.2.5 Materials, energy and impacts results and analysis

The results are segmented into three categories : materials, energy and impacts. As previously noticed, most of the considered study do not focus on embodied energy and impacts of materials. Few results on energy and impacts are observed. Material flow results are observed in most of the studies, either through a flow-driven or stock-driven analysis. A domination of in-use stock over obsolete stock was identified. Moreover, it was found out that recycling is a growing research field in the literature selected, from an increasing number of aspects such as its quantification, modeling assumptions (e.g. recovery rate, raising recycling rate), the role of scrap quality, its link with stock dynamics and its implications (e.g. policy, scrap trade).

An intermediate number of uncertainty and sensitivity analyses were conducted in the literature (Table 2.2). They offer insights on the most influential input parameters. Two main insights were identified. First, uncertainties in the lifetime represent a major share of the impacts in the outputs ([Pauliuk et al., 2013](#); [Hu et al., 2010](#); [Spatari et al., 2005](#)). It was found that the standard deviation and shape of lifetime distributions had little or moderate impacts on the results ([Müller et al., 2011](#); [Glöser et al., 2013](#); [Wiedenhofer et al., 2019](#); [Cao et al., 2017a](#); [Ciacci et al., 2013](#); [Deetman et al., 2020](#)), and that the mean value of the lifetime distributions could have substantial impacts on the outputs. Secondly, [Miatto et al. \(2017b\)](#) showed the intuitive linear effect of material intensities variations on outputs. Static assumptions about their regional values can therefore carry substantial impacts ([Deetman et al., 2020](#); [Watari et al., 2019](#)).

2.3 Insights

2.3.1 Materials modeling: a data challenge

Initial MFA studies proposed a top-down approaches⁵, and relied on the rapid development of material flows databases⁶. However, modeling the drivers of material stocks and flows requires further bottom-up approaches, allowing for a more accurate computation of each sector. Most of the bottom-up studies consider a technological stock-driven

⁵We can cite the Stock and Flow project (STAF) of the Center for Industrial Ecology with several publications in the early 2000s ([Graedel et al., 2002](#); [Spatari et al., 2002](#); [Bertram et al., 2003](#)).

⁶Such as the data from [World Steel Association](#) or [Copper Alliance](#).

modeling which compels to a more desegregated level of data. They rely on a significant number of material parameters (material intensities, recycling rates...) and technological parameters (technology desegregation, market share, lifetime...). Moreover, the data challenge is further emphasized as several recent studies have proposed bottom-up analysis at regional and multi-regional scales, with time and/or space dynamic parameters (Marinova et al., 2020a; Deetman et al., 2020; Dunn et al., 2021). The identified data challenge can occur in several ways. A lack of data quality can be observed-such as statistical breaks-or a lack of data intensity-such as incomplete perimeters and data gaps (Wiedenhofer et al., 2015)⁷. In particular, given the lack of accurate data on specific materials, waste flows are not well understood and carry most of the modeling uncertainties. Substantial impacts are observed the assessment of materials in-use and obsolete stocks, and on recycling indicators (Glöser et al., 2013).

Several trends can be identified in the literature to cope with the data challenge. First, databases have been developed over the recent years. They provide extensive data on material intensity for seven building types on the Dutch perimeter (Sprecher et al., 2021), 46 residential buildings on the Swedish perimeter (Gontia et al., 2018) and for 22 countries Heeren and Fishman (2019)⁸. Second, Cao et al. (2018) and Heeren and Hellweg (2019) have proposed probabilistic analysis of the building sector, which allowed to obtain results with confidence interval. Lastly, we observed an increasing use of sensitivity analysis in the literature. The identified data challenge leads to gaps in the modeling scope, as the fossil fuels supply chain, power grid and storage, public infrastructures, the industry and final demand goods are rarely modelled in bottom-up approaches.

2.3.2 A growing emphasis of stock importance

Unlike energy materials, food or water, raw materials provide services to humans through their in-use stocks⁹. Material in-use stocks are a pivotal part of MFA, and they encompass various roles in the socio-economic metabolism (Pauliuk and Müller, 2014)¹⁰. The in-use stocks analysis has proven to be pertinent to provide insights about the population and the lifestyle (Müller, 2006), development levels (Gerst, 2009; Bader et al., 2011; Pauliuk et al., 2013), and development patterns. Bleischwitz et al. (2018b) identified a pseudo-logistic profile of the material in-use stocks with three stages describing the development level of a society: growth, maturing and saturation. The authors empirically estimated saturation levels of the in-use stocks per capita. They outlined the larger differences in saturation levels between countries for concrete and steel than for aluminum and copper, which could be explained by the higher technological uses of those latter and the more common standards of materials demand in high-tech products. The described profile further allow to understand the drivers of both the inflow and the outflow. The inflow can be envisioned as the supplier of the maintenance and expansion parts of the in-use stock. It therefore displays various patterns depending on sectors and regions, as a shift from expansion to maintenance is observed as a society develops (Wiedenhofer et al., 2015; Miatto et al., 2017a; Nguyen et al., 2019b). The outflow is strongly impacted by the pace of the stock expansion. A rapid expansion of the in-use stock requires higher material demand and could hamper its recycling content¹¹, which is observed in the low-carbon transition (Vidal et al., 2018) and rapid growth of developing countries (Müller et al., 2011). Finally, both the inflow and the outflow are dependent on the lifetime of the in-use stock¹² and many authors insist on the benefit of increasing lifetime to reduce material inflow and environmental impact (Hu et al., 2010; Huang et al., 2013; Cao et al., 2017b; Krausmann et al., 2017; Zhang et al., 2019).

2.3.3 Waste generation and recycling

Recycling has been widely addressed in the considered literature. It is explained by the usefulness of material flow analysis to assess the circularity potential of materials in human systems and the high annual growth rate of metals

⁷Such difficulties could enhance the use of alternative methods in regions displaying poor data quality and/or intensity. Hattori et al. (2014); Hsu et al. (2011) and Hsu et al. (2013) outlined the lack of data availability and the lower data "cost" of NTL studies.

⁸These three studies are out of the scope of the current review and are presented for the interested readers. In a lesser extent, Ortlepp et al. (2018) and Kleemann et al. (2017) have also provided extensive dataset in their publications.

⁹The stock-flow-service nexus intend to analyse the "interrelations between material and energy flows, socioeconomic material stocks ("in-use stocks of materials") and the services provided by specific stock/flow combinations" (Haberl et al., 2017).

¹⁰The authors proposed a review of the roles of in-use stocks in the socio-economic metabolism

¹¹The recycling content is defined as the share of recycled materials in the inflow.

¹²Which can be estimated from the technological lifetime and the material content of products.

demand. In this section, the main aspects of recycling discussed in the literature are described: the environmental interest, the link with product lifetimes, the impact on material trade, its challenges and the rapid development of recycling indicators. It allows a lower use of primary materials, and a slower depletion of reserves and a reduction of environmental impacts. The depletion of reserves remains a marginal issue for the selected base materials, and only copper could eventually face a risk (Pfaff et al., 2018). Conversely, base materials represent a substantial part of total material demand, energy demand and environmental impacts. Increasing the share of secondary materials could provide a valuable solution to decrease these impacts¹³. This aspect is increasingly mentioned in the literature, but rarely addressed properly. Most MFA studies do not compute the environmental impacts of material production, but focus on the technical and political constraints of recycling.

The recycled materials are recovered and recycled after the end-of-life of the infrastructures. Their availability depends on the lifetime of products and the demand level, which both vary by country and sector. The recent and rapid development of some countries leads to a need of understanding of scrap generation dynamics, and its relationship with the in-use stock. As a country develops, the scrap generation and the share of recycled materials in the total inflow increase, which is explained by the progressive saturation of the in-use stock (Vidal et al., 2017). The rapid accumulation of materials in the in-use stocks could create a massive scrap generation, and developing countries need to develop recycling infrastructures (Dong et al., 2019). For example, a low secondary aluminum production is currently observed in China, and scrap generation is expected to grow in the years to come since most of Chinese consumed aluminum is the stocks (Liu, 2019; Li et al., 2020b)¹⁴. At a sector level, the different lifetimes of products influence the availability of scrap for each materials. For example, while copper is mostly embedded in buildings-with long lifetimes, the distribution of aluminum and steel stocks are more homogeneous between sectors. A low copper scrap availability can therefore be observed, but the increasing use of copper in electronics could reduce the delay of scrap availability Ciacci et al. (2017).

Despite its link with environmental impacts reduction, recycling is mostly analyzed through its policy implications in the literature. An increase of the recycled content of the inflow could have significant effects on imports and exports of raw materials (Bader et al., 2011). A growing emphasis on the role of urban mines for a decreasing dependency on imports was observed in the publications. Liu (2019) emphasized the highly disruptive dimension of trade wars in primary materials imports and regional availability, and the role of secondary materials to hamper trade dependency. However, the higher reliance on domestic recycled resources could be hindered by the local recycling cost, grade quality demand and environmental policies, e.g. for copper in the USA (Chen et al., 2016). The combination of these constraints with the manufacturing role of China explains the distribution of material flows. While China imported mostly primary, refined and scrap copper between 1990 and 2015, the country displayed almost no export of copper scrap, and mostly exported finished goods (Soulier et al., 2018b). Conversely, three trends have been observed in copper demand in the USA: an increase of overall material demand, a decline in secondary production and a rise of old scrap export. It is explained by the high cost of cleaning copper old scrap before recycling, and the environmental concerns of processes in local US companies (Chen et al., 2016; Gorman and Dzombak, 2020). The direct effect of local policies on global scrap flows was also identified for aluminum flows. Aluminum scrap exports to China were significantly reduced by tariffs evolution in Europe and the USA for political matters¹⁵. It had significant consequences on the Chinese aluminum recycling policy, and led to recent improvements (Li et al., 2020b)¹⁶.

Four main future challenges of an increase of the recycling content of the inflow were identified in the literature. The first two are related to the secondary material prices, as the economic viability of recycling relies on its competitiveness compared to primary materials. First, the recycling prices could be increased by quality requirements and processing needs (Chen et al., 2016). It would constitute a limit to recycling, especially for low-quality copper scrap which requires

¹³Secondary materials have lower production energy and impacts than environmental materials (Birat et al., 2013; Gutowski et al., 2013; Vidal, 2021)

¹⁴Informal recycling can however hamper the estimates of the recycled content of the inflow, for instance in copper studies (Dong et al., 2019).

¹⁵The European Commission aims at further tightening the control of copper in Waste from Electrical and Electronic Equipment (WEEE) as significant amounts are illegally exported to developing countries (Ciacci et al., 2017).

¹⁶The Chinese efficiency recycling rate remains low, but recent measures such as the “Green Fence Policy” should allow its progressive increase (Soulier et al., 2018b).

energy-intensive processes (Ciacci et al., 2017; Wang et al., 2021)¹⁷. Second, the collection costs of end-of-life materials could be prohibitive at current primary material prices¹⁸. Future metal prices will significantly impact the potential of recycling (Ciacci et al., 2017), and the progressive depletion of primary reserves could result in prices rise, which could finally have a beneficial impact on recycling (Vidal et al., 2017). Third, down-cycling is frequently observed in steel alloys (Hatayama et al., 2010) and construction and demolition waste recycling (Miatto et al., 2017b)¹⁹, which could reduce the recycled content in products requiring high-grade materials. Ciacci et al. (2017) highlighted the existing solutions to increase the share of functional recycling for steel and aluminum, such as the differentiation of sorting techniques by alloy and a reduction of the number of elements in alloys. The authors further emphasized their potential implementation for copper. The needed improvement in alloys scrap is also outlined for stainless steel, and could result in a reduction of environmental impacts (Igarashi et al., 2007). The last challenge lies in the lack of mature recycling system in some countries, such as in China, leading to an increase of landfill deposits (Li et al., 2020b). Scrap aluminum is therefore imported in China, despite metals availability in end-of-life products²⁰.

Overcoming the challenges and developing an efficient recycling industry requires enhancing the knowledge of recycling flows. A broad range of ratios and more detailed flows has been developed in the literature to provide better insights in the recycling chain difficulties. A simplified cycle is presented in Figure A.9 to define ratios and for ease of reading²¹.

Among the listed ratios and flows, the end-of-life collection rate (EOL-CR)²² and the dissipative losses have gained attention. Top-down studies have allowed better estimations of global and regional EOL-CR for copper (Spatari et al., 2005; Soulier et al., 2018a; Pfaff et al., 2018) or aluminum (Ciacci et al., 2013; Seigné-Itoiz et al., 2014). However, the EOL-CR remains product-related, region-related and material-related, and few data is available at a regional and product level²³. A better knowledge of the material composition and quality of products is crucial to enhance the EOL-CR²⁴, which could ultimately lead to higher EOL-RR and lower environmental impacts (Seigné-Itoiz et al., 2014). However, Gorman and Dzombak (2020) emphasized that the US EOL-CR remains insufficient to achieve high EOL-RR, as about half of the copper wastes collected were ultimately landfilled in 2015. Several recent publications have estimated and discussed regional and sectoral EOL-CR. Low EOL-CR were observed in electronic products in the USA (Wang et al., 2021), or in Europe, where Ciacci et al. (2017) outlined inefficiency in copper collection in end-of-life vehicles (ELV) and waste of electrical and electronic equipment (WEEE). The EOL-CR is impacted by the yearly end-of-life products flows, and significant variations of the copper EOL-CR over time were estimated in China (Gorman and Dzombak, 2020), in the USA (Soulier et al., 2018b), and in Spain for aluminum (Seigné-Itoiz et al., 2014). Few data are also available on the dissipative losses (Lifset et al., 2012). They are defined as lost materials accounted for in the in-use stocks (Hashimoto et al., 2007)²⁵. These materials cannot be collected and are rarely estimated in the selected literature, because of assessment difficulties. However, their inclusion in MFA studies is essential to identify the material losses in the use stage and to enhance the estimation of environmental impacts of materials. The dissipa-

¹⁷ Energy-intensive processes can also be observed for technological metals, which are outside the scope of this study. Their recycling displays an opposite relationship with the dilution rate of metals, which explains the low recycling rate of technological metals in high-tech products (Vidal et al., 2017).

¹⁸ Falconer (2009) showed that buried cables represent a substantial part of the copper consumed in wind farms, and that no or little recovery of the cables was planned during the decommissioning of wind farms. He further estimated that 70% to 80% of the copper in-use stock in wind farms could remain buried in the UK.

¹⁹ Down-cycling is defined as the recycling resulting in a lower quality of materials, and therefore a loss of functionalities. The down-cycled materials are used for applications requiring lower performance materials. An example is the reuse of high performance concrete in non-structural applications (e.g. roads, noise barriers...).

²⁰ Further limitations on the Chinese recycling system are detailed in Wübbecke and Heroth (2014).

²¹ The issue of harmonizing recycling and end-of-life indicators was identified by Graedel et al. (2011) and Glöser et al. (2013). The authors proposed a set of rates along the collection and recycling chain, which are described in the Section of SI

²² EOL-CR is the share of metals embedded in end-of-life products actually collected

²³ The EOL-CR can be alloy-related for a same material. For instance, Yoshimura and Matsuno (2018) outlined differences in the collection and recycling between copper and copper alloys, and the authors emphasized the need to consider different EOL-RR. It can result in significant and growing variations in the final share of secondary materials in the inflow.

²⁴ In parallel, the appropriate form of the collection sector should be discussed. Markus et al. (2013) emphasized the different outcomes in collection rates between a "formal sector" in which consumers pay for end-of-life products to be collected, and an "informal sector" in which the consumers are paid for obsolete products, with higher collection rates.

²⁵ Lifset et al. (2012) further proposed the distinction between intentional and unintentional dissipative losses, and conducted a short review on previous studies on dissipation of materials. The authors proposed an estimation of the dissipative losses of copper in the USA between 1975 and 2000, but this study is outside the scope of this review.

tive losses occur in specific product use-e.g. brake pads, pesticides²⁶, paint, treated wood. Differences were identified between sectors (e.g. in France (Bonnin et al., 2013)), and an increasing use of these products has been observed (e.g. in China (Chen and Shi, 2012) and in Japan (Hashimoto et al., 2009)).

2.3.4 Increasing policy considerations

The material basis of our modern society confers on metals and minerals a political dimension. However, a limited number of studies proposed a political contextualization of the results, and the formulation of recommendations. They emerged from concerns about material supply security in both Europe and China. The current and expected surge in Chinese material demand accentuates its dependency to foreign imports. Several authors formulated policy recommendations to mitigate this trend. For copper, they identified the need to: (1) enhance geological exploration, (2) guarantee copper imports, (3) increase the collection rate, (4) rapidly develop the Chinese recycling infrastructures and (5) achieve sustainable recycling by involving laws and institutions to monitor the firms (Zhang et al., 2015a; Wang et al., 2017). For steel, Guo and Zhang (2016) provided a thorough analysis of the existing policy and proposed several policy measures. The authors emphasized the need (1) to develop new governmental guidance to the steel industry, (2) to adapt the industrial products to market changes (e.g. cost or demand), (3) to implement optimized loss and export policies.

In Europe, a modelling of the European Waste Framework Directive showed its significant potential to achieve high recycled share in the nonmetallic minerals inflow (Wiedenhofer et al., 2015). Moreover, a higher reliance on exports is observed for aluminum (Ciacci et al., 2013) and copper. Ciacci et al. (2017) estimated that industrial companies and consumers could experience copper shortages in case of a disruption of the primary copper supply chain, despite increasing scrap generation. The authors reported that environmental legislation, technological improvements and Asian copper recycling industry development have hampered the EU copper recycling industry, resulting in growing exports of scrap to other countries. They further emphasized the opposition of these observations with the European Circular Economy Strategy. The concomitant lack of European recycling industry, implementation of legislation to improve the collection of copper scrap and potential constraints of higher recycling content in products-such as in batteries (Commission, 2020)-could therefore further enhance the dependency to foreign recycling industries and result in a shortage risk. At a global scale, Seck et al. (2020) modelled the implications of two policies implementation in copper demand scenarios. First, the authors considered the development of regional recycling industries and showed the need to enhance recycling capacities in developing countries, as demand growth in long-lifetime technologies leads to a higher reliance on imports and lower scrap availability. Secondly, they implemented accelerating sustainable mobility policies and estimated that "soft transportation" could induce medium copper demand reduction.

An increase of the recycled content of the material inflow could be achieved by policies implementations, e.g. through a minimum share of secondary materials content in products (Wang et al., 2021; Ciacci et al., 2017). In Europe, the amending Regulation (EU) N° 2019/1020 of directive 2006/66/EC aims at implementing a minimum recycled content for technological materials in industrial and transport batteries (Commission, 2020), and could allow recycling investment to tackle low competitiveness of secondary materials.

2.4 Conclusion

This critical literature review covered dynamic material flow analysis of four base materials: aluminum, concrete, copper and steel. The review included 129 articles quantifying prospective and retrospective stocks and flows, as well as embodied energy and climate impacts of the use of these materials. It was conducted from 2000 to 2021 at national, regional, multi-regional and global scales. A review methodology was developed, relying on previous works by Müller et al. (2014) and Wiedenhofer et al. (2020).

It enabled to efficiently grasp the scopes, the model designs, as well as the result and analysis categories displayed in the publications. It was found that (1) most studies adopted a national scope and (2) focused on the building, power

²⁶Lifset et al. (2012) reported pesticides use to represent the main source of copper dissipation in 1975.

supply, transportation and infrastructures sectors. They increasingly (3) encompassed several base materials and (4) considered a bottom-up approach. However, (5) prospective studies in a low-carbon perspective remained limited, (6) a lack of analysis of the energy-material nexus was observed, and (7) no analysis proposed solution-oriented modeling to decrease the impacts of base materials. The main insights of the publications were identified:

- Bottom-up studies represent a data and assumptions challenge progressively tackled by material intensities databases and sensitivity analysis;
- In-use stocks has a link with development level, and the regional patterns of maintenance and expansion of materials in-use stocks carry a significant impact in the inflow and waste dynamics;
- Material wastes are increasingly analyzed, mostly from a the political perspective;
- Recycling could play a significant role to decrease energy demand and GHG emissions in a context of growing material use;
- Policy-makers have a crucial role to successfully decrease regional supply security and environmental concerns;
- The expected pace and magnitude of inflow increase and waste generation in the coming decades raised concerns about the capacity of the political community to display incentives and bidding measures.

The results and the insights enabled to identified research gaps:

- A lack of modeling of some sectors;
- A lack of prospective studies in a low-carbon context;
- A limited number of solution-oriented and political-oriented studies;
- A lack of analysis of the energy-material nexus.

Chapter 3

The DyMEMDS model

Summary of the chapter

- The Dynamic Modelling of Energy and Matter Demand and Supply (DyMEMDS) is a stock and flow model.
- The DyMEMDS model computes the raw material stocks and flows and the associated energy demand and environmental impacts.
- The model covers the entire energy chain and the three end-use sectors (industry, building and transport).
- The general model structure is presented in the chapter.

The *DyMEMDS* (Dynamic Modelling of Energy and Matter Demand and Supply) model is presented in this section. The description is not exhaustive and up to date, as the model is constantly evolving, and only the methodology behind the main features is depicted. The *DyMEMDS* model is currently developed in the Institute of Earth Sciences (ISTerre) in Grenoble¹. It aims at computing the raw materials stocks and flows, with an initial focus on the base materials², as well as the final energy demand and an increasing number of environmental impacts³ resulting from materials production. The model covers the entire energy chain and the three end-use sectors (industry, building and transport) and encompasses four types of physical variables:

- The technological unit (TU), which are defined as the infrastructures in the energy chain and end-use sectors;
- The raw materials (RM);
- The energy;
- The environmental impacts.

The overall structure of the *DyMEMDS* model is presented on Figure 3.1. In a first step, the stock of TU is assessed for each sector. The number of TU depends on the sector, as only two TU are considered for the building sector (residential and non-residential) while the transport sector is desegregated into 47 TU. The TU stocks can be estimated through four methodologies (Figure 3.1), which enable to compute a wide range of scenarios:

- The energy approach. The sector energy demand (J/yr) and the energy demand by TU (in J/TU/yr) allows to endogenously estimate the stocks. This approach is used in the transport and energy sectors.
- The stock approach, in which the TU stocks are an exogenous variable;
- The Gompertz/logistic stock approach. The Gompertz/logistic curves depends on the GDP per capita, and provide 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 enables to compute a trend-based approach without the usual reliance on scenarios. This approach is used in the building sector.
- The combined energy and stock approach. It is used for the fossil fuels supply chain, for which the historical data where extrapolated using the historical and prospective energy supply.

In parallel, two calculation methods are implemented in the *DyMEMDS* model. They aim at criticizing the scenarios assumptions. In the **share** methodology, the full set of exogenous scenario data are considered (i.e. final energy demand of the building, transport and industry sectors, and the energy supply). The results are therefore in line with the scenario. Conversely, in the **feedback** methodology, only the final energy demand of the building and transport sectors are considered as exogenous data feeding the model. The final energy demand of the industrial sector and the energy supply are endogenously calculated, based on the model assumptions. The differences between the results and the scenario outcomes enable a discussion on the assumptions.

¹The model was initially developed on the [Vensim software](#), and is currently being coded in Python. The initial results are displayed in the published article "Modelling the demand and access of mineral resources in a changing world" in Section B.

²The 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).

³Such as CO₂ emissions, land use or water consumption.

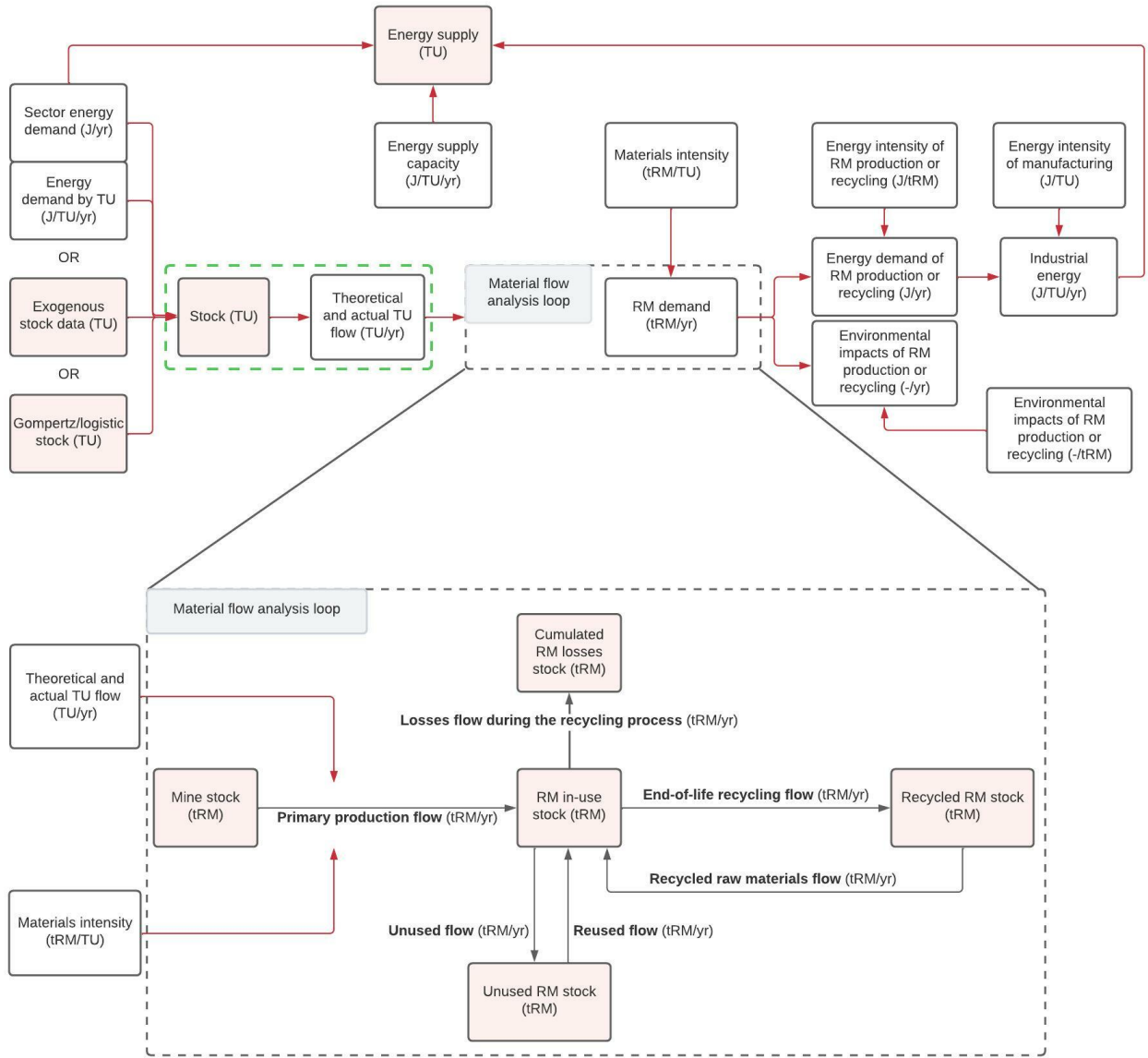


Figure 3.1: Overall DyMEMDS model structure.

In a second step, the theoretical flow of TU (in TU/yr) is derived from the stock, following the equation:

$$S_{tTU} = S_{t-1TU} + F_{t,th.TU} \cdot dt \quad (3.0.1)$$

with S_{tTU} the stock of TU at time t , S_{t-1TU} the stock of TU at time $t - 1$ and $F_{t,th.TU}$ the theoretical flow of TU at time t . However, the end-of-life TU are not accounted for in the *theoretical TU flow*, and the *actual TU flow* is defined as the sum of the *theoretical TU flow* and the *end-of-life TU flow* (Figure 3.2). Moreover, a renewal sub-loop is considered in case of a substantial drop of the *TU stock*. It induces a negative *theoretical TU flow*, and could create a negative *actual TU flow*, which has no physical reality⁴. We assumed that some assets could be removed from the *TU in-use stock* before their end-of-life without being dismantled. A drop of the *TU stock* creates an *unused flow*, which supplies an *unused stock*. It acts as a buffer stock, and prioritized over the *actual flow*, which allows to empty the *unused stock* before any new manufacturing. The TU lifetimes is thus respected, and the total *TU stock* is the sum of the *in-used TU stock* and the *unused TU stock*.

⁴We can consider the COVID19 crisis in which many infrastructures were unused but not dismantled.

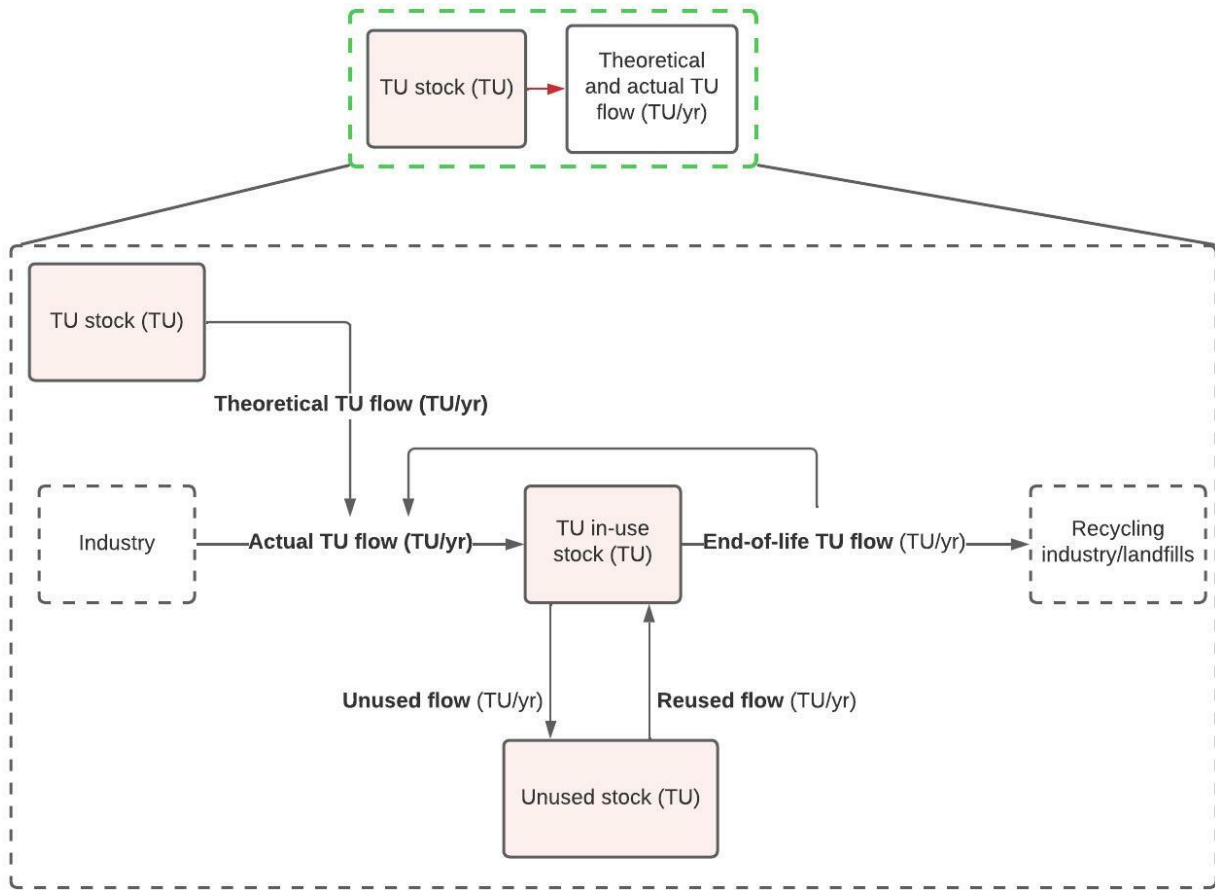


Figure 3.2: TU renewal structure.

The *actual TU flow* and the *material intensities* enable to estimate the *primary RM production flow*, which supplies the *RM in-use stock* (Figure 3.1). At the end of the lifetime of each TU, the *RM in-use stock* is reduced by both the *end-of-life RM recycling flow* and the *losses RM flow during the recycling process*, which respectively feed the *recycled stock* and the *cumulated losses stock*. The *recycled stock* then allows for a *recycled RM flow* which is ultimately reused in the *RM in-use stock*. The new TU thus consume both primary and secondary RM. The *RM demand*, which encompasses both the primary and secondary RM flows, is then used to estimate the *energy demand of RM production or recycling*, and finally the *industrial energy* and the *energy supply* in a **feedback** calculation method.

The sectors are separately computed, and ultimately aggregated in the model to estimate the RM stocks and flows, the energy demand and environmental impacts of RM production and recycling, and finally the industrial energy and energy supply. In order to initially simplify the recycling process in the model, the materials recycled were used in their initial sector (Figure 3.3). This methodology has no or little physical reality, and a proper recycling module requires all the sectors to be modelled, and the industry and transport modules remain under construction. The studies presented in sections 4 and 5 are based on the initial separated recycling loops.

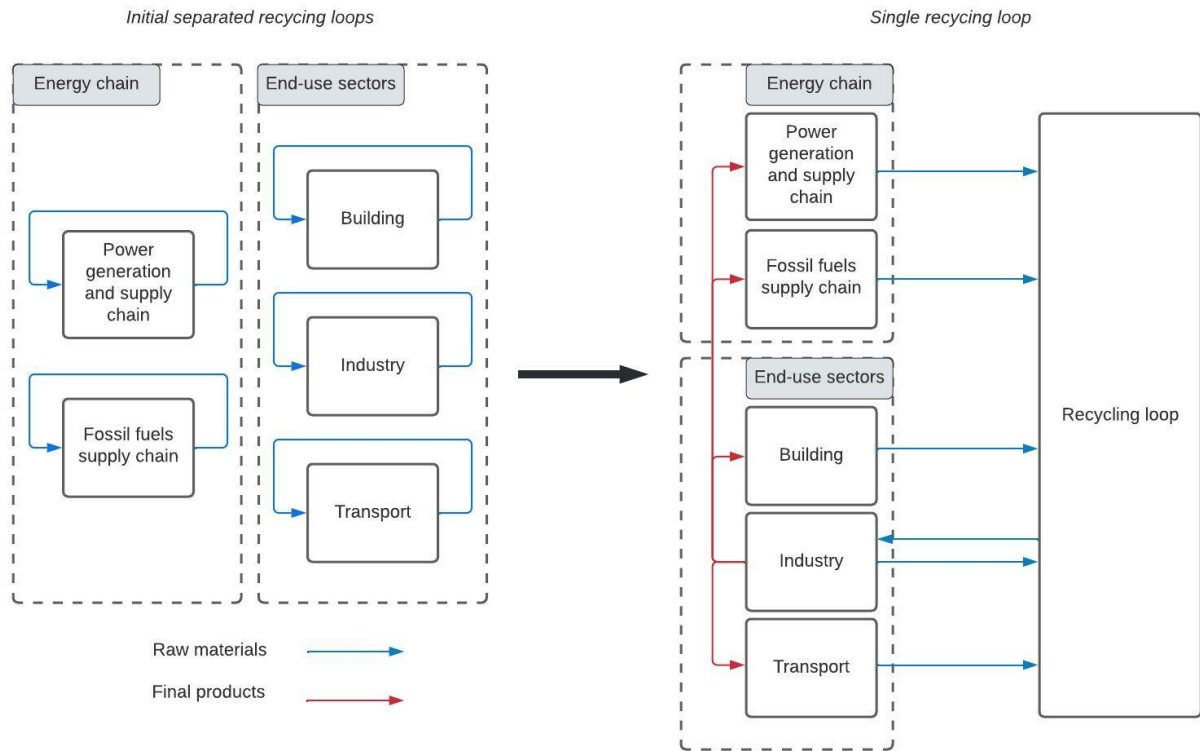


Figure 3.3: Evolution of the DyMEMDS recycling structure.

Chapter 4

Base materials impact of the building sector in the low-carbon transition

Summary of the chapter

Objectives

- Estimating the base material weight of baseline and transition scenarios at a regional scale.
- Estimating the associated energy demand and CO₂ emissions.
- Estimating the base material weight of thermal renovation. CO₂
- Assessing the potential of material engineering to reduce energy demand and environmental impacts of concrete.

Methods

- The prospective regional building stocks of seven scenarios are compared.
- A dynamic material flow analysis (MFA) of base materials is developed and applied between 1950 and 2100 (Section 4.1).

Results

- A significant growth of base material demand is expected in the building sector, with regional disparities (Section 4.2).
- Thermal renovation would represent a small share of the increase, and the energy to produce renovation materials would amount to about 1% of the energy savings.
- 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 and environmental impacts of concrete.

4.1 Base materials impact of the building sector in the low-carbon transition

Base materials impact of the building sector in the low-carbon transition

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ABSTRACT

The significant weight of the building sector in global material demand has been addressed in several publications, but a lack of consideration of renovation and energy-materials nexus dimension was identified. To fill these gaps, 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 combined increasing stocks in the less developed countries and the development of renovation strategies in the most developed countries results in a rise of the inflows; (ii) it induces a large energy demand and environmental impacts, which could question the feasibility of some low-energy demand scenarios; (iii) the large-scale use of recycled concrete aggregates and green concrete¹ displays a significant potential to enhance the reduction of energy and GHG impacts of concrete. 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 20th 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 literature¹.

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 metabolism² 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 societies³ and a

²The 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)

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

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¹The 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.

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 demand⁴. 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 scale⁵. 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 materials weight of the building sector in a low-carbon transition context through thermal renovation, and 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 topic⁶. Indeed, 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 and of CO₂ emissions 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

⁴The 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).

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

⁶The reader can refer to recent publications such as Giurco et al. (2014); McLellan (2017); Vidal et al. (2017) or Elshkaki (2019). The inclusion of resource studies within a broader nexus has been studied by Bleischwitz et al. (2018a)

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 production⁷. 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 RAC using 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 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)⁸. The most common SCM are coal fly ash (CFA)⁹, blast furnace slags (BFS)¹⁰, silica fume, or metakaolin (Habert, 2014; Holland et al., 2016)¹¹. 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.

⁷Shares 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)

⁸The 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".

⁹CFA is a by-product of the combustion of coal to generate electricity.

¹⁰BFS is produced during the iron-making process.

¹¹Many 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).

1.4. Scope and objectives of this study

The present study aims at filling the identified gaps by (1) estimating the base materials (concrete, aluminum, copper and steel) weight of both construction and thermal renovation¹² in low-carbon transition scenarios, (2) estimating the historical and prospective energy demand and CO₂ emissions of the materials production in the building sector and (3) assessing the potential of energy demand and environmental impact 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 three-step methodology was developed. First, historical and prospective floor areas were obtained. Second, the base material stocks and flows in the building sector were estimated using dynamic regional material intensities and lifetimes in the DyMEMDS model. Lastly, their energy and environmental impact was assessed and two solutions were considered for a reduction of concrete demand and impacts: concrete recovery and recycling, and green concrete. Their potential 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 (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/m²)¹³ (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 markers¹⁴ for a specific SSP¹⁵.

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. The renovated surfaces were estimated in Mastrucci et al. (2021). Given the small final energy demand between the SSP2 2p6 and 4p5-and the SSP3 2p6 and 4p5-no difference was considered in the renovation hypothesis. The results were extrapolated as shares of the regional building stocks and used on the surfaces of the selected pathways. The results of the SSP1 were used for the SSP4, as both are low-carbon pathways. The SSP5 is a high carbon scenario, for which no renovation was considered. We observe the highest renovation rates in China, North America and Europe, reaching between 2021 and 2025 3% to 4% in the SSP1 and SSP4 and 1.6% to 2% in the SSP2 and SSP3 period. Moreover, the renovation rates decrease from the 2031-2035 period for most of the regions in the SSP1-4 scenarios¹⁶. On a global average, the SSP2 displays the highest annual renovation rates-reaching 1.73% in the 2026-2030 period, ahead of the SSP1.

2.1.2. The International Energy Agency scenarios

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

¹³The 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).

¹⁴A 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.

¹⁵AIM/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)

¹⁶The detailed regional renovation shares are displayed in the Supplementary Information.

¹²Thermal renovation is related to energy management, and is referred to as renovation in the rest of the study.

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)

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. The IEA (2018) provided renovated surfaces as shares of the global building stocks. The IEA further stated that the renovation would mainly occur in the Western and OECD countries. The total shares were therefore distributed between Europe, North America and the OECD countries. Unlike the SSPs, the renovation rate increases until 2050 in the RTS and B2DS. The estimated rates are provided in the Supplementary Information.

2.2. The DyMEMDS model

The modeling methodology of this study relies on the *DyMEMDS* (Dynamic Modelling of Energy and Matter Demand and Supply) stocks and flows model (Figure 2) which covers the entire energy chain and three end-use energy sector. A stock-driven flow approach is considered to estimate the primary and secondary materials requirements, and their associated production energy and CO₂ emissions (Vidal, 2021; Le Boulzec et al., 2022).

2.2.1. DyMEMDS 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 2100¹⁷. 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 CO₂ emissions associated with the materials production are estimated. The simplified methodology behind the building module of the *DyMEMDS* 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).

2.2.2. Historical and prospective regional building stocks

The stock-driven approach in the *DyMEMDS* 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 5.4 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), the Low Energy Demand (LED) scenario computed in the MESSAGEix-GLOBIOM (Grubler et al., 2018) and the RTS/B2DS scenarios modeled in the Energy Technology Perspectives 2017 (ETP-2017) model (IEA, 2017). The scenarios are briefly described in Section 2.1.

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

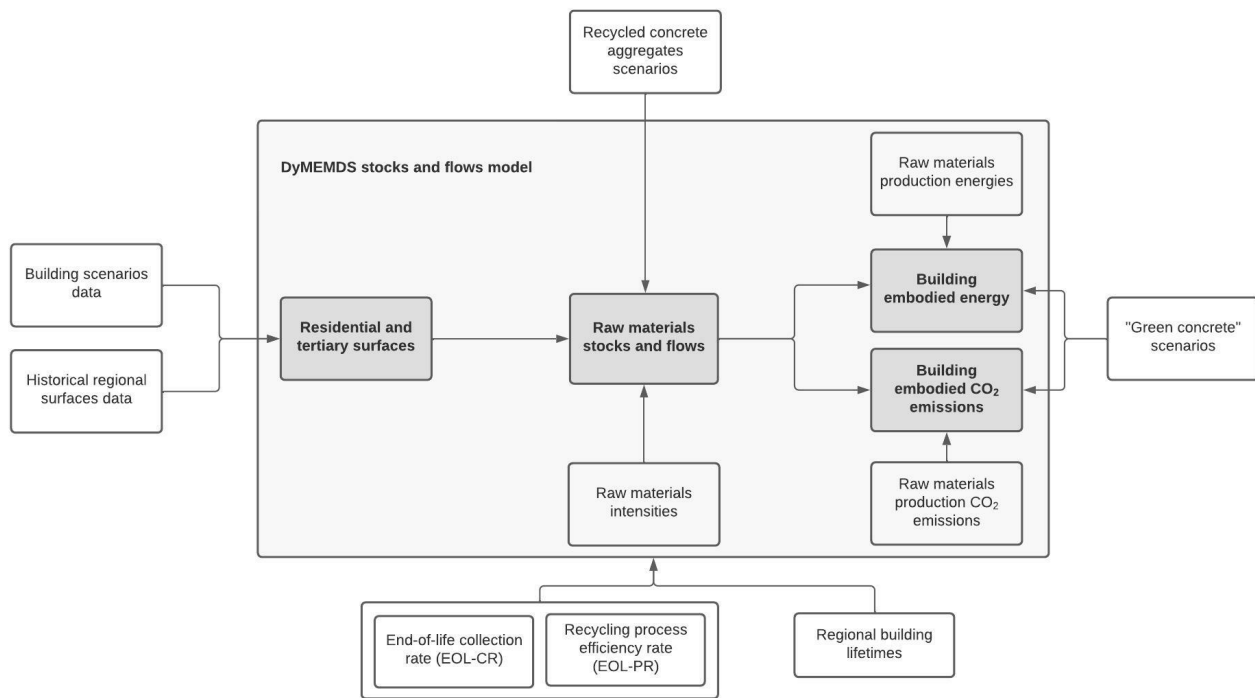


Figure 1: Simplified methodology lying behind the *DyMEMDS* model. Adapted from Le Boulzec et al. (2022).

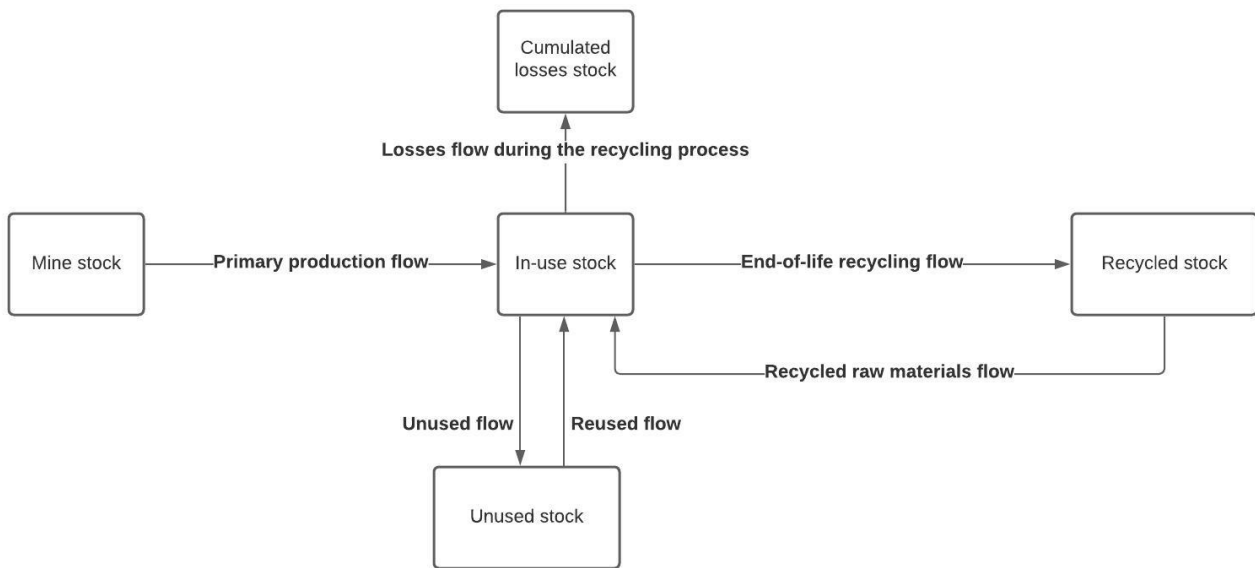


Figure 2: Key loop used in the *DyMEMDS* model to estimate the stocks and flows of materials during the construction and maintenance of the infrastructure. Source: Le Boulzec et al. (2022)

The historical regional residential building floor areas were then extrapolated back to 1900 with a logistic approach based on GDP per capita¹⁸. The non-residential stock was

¹⁸The logistic curve provides a useful tool to describe the behavior of the infrastructures and materials stock through a three-phase profile: growth,

assumed to represent a constant share of the total stock from 1900 to 1990, and the shares observed in the SSPs from 1991 maturation and saturation (Bleischwitz et al., 2018b). It allows to compute the limited "carrying capacity" of a system (Chen and Graedel, 2015). The GDP/capita values were obtained from the Maddison historical statistics and the population from the United nations population

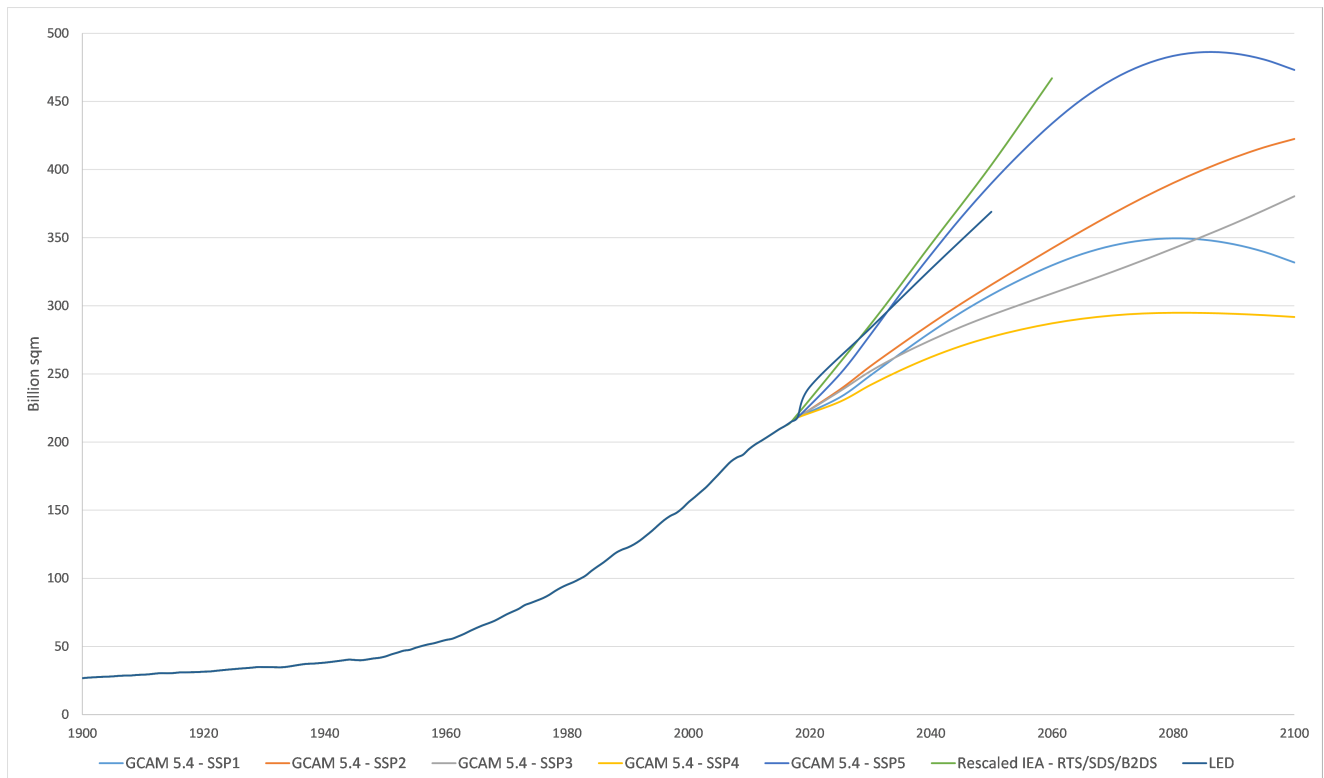


Figure 3: Global building floor areas in the selected scenarios.

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.

In parallel, renovation is considered from 2015 to 2050. The renovation process requires both inflows and waste outflows. Materials intensities of renovation were used to estimate the annual inflows and outflows for the residential segment only. The prospective renovation surfaces were obtained for the SSP 1-5, the RTS and the B2DS (Section 2.1). The global building floor areas are displayed in the Figure 3, and the historical and modeled regional surfaces are detailed in Section S1.2 of the Supplementary Information.

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 materials mix¹⁹ over time and the amounts required. A logistic 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

¹⁹For instance, a rising share of concrete observed in Japan and the Western countries was observed after the Second World War, see Section S1.4 of the Supplementary Information. However, no further evolution of the mix was considered, such as the increasing use of wood.

saturation levels were considered for steel and concrete²⁰, while the same saturation levels were selected for copper and aluminum.

Inflow and waste renovation materials intensities were also considered to estimate the amounts required for the prospective renovation in scenarios. For both intensities, constant French data from ADEME et al. (2018) are considered for aluminum, concrete and steel at a global scale due to a lack of data²¹. Given that no other regional renovation intensities were available to the authors' knowledge, the impacts on results of this choice is unknown. The materials intensities of renovation are low compared to construction for aluminum, concrete and steel, as insulation materials, i.e. glass, coating and plaster represent most of the inflow. Finally, primary production energies estimated in Vidal (2021) and Le Boulzec et al. (2022) were selected, as well as the secondary production energies and the CO₂ emissions from Le Boulzec et al. (2022). The historical data and the modelled intensities are available in Section S1.4 of 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). Dynamic 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. The methodology relies in three successive step. Firstly, current regional lifetimes considered in the literature were studied. Secondly, a four-parameter logistic function was used to estimate dynamic lifetimes between 1900 and 2100. An initial value of 10 years and saturation levels 20 years higher than the current values were assumed for all the regions (Figure S1). Finally, normal distribution were applied on the logistic-based mean lifetimes (μ) and standard deviation values of $0.3 \cdot \mu$ were considered. A full documentation of the data and the lifetime distributions are available in Section S1.3 of the Supplementary Information.

²⁰It 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).

²¹Copper is not considered in ADEME et al. (2018).

2.4. Reducing the energy and environmental burden 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 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 and CO₂ emissions reductions. Further solutions such as substitution or reducing the amount of cement in concrete (Shanks et al., 2019) are not considered and could provide additional tools in a further analysis. This section describes the methodology to compute the two considered solutions.

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 management²². 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

²²The European Union implemented a Waste Framework Directive, which set quantitative objective by 2020.

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.

environmental impact reductions were considered²³. More information about the literature and the methodology is available in Section S1.5 of 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 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 aggregated²⁴, or steel slag²⁵;
- Replacement of Ordinary Portland cement, by coal fly ash (CFA)²⁶ or blast furnace slag (BFS)²⁷.

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.

3. Results

The stock-driven flow modeling approach conducted offers a regional and dynamic analysis of materials, and their production energy and CO₂ between 1950 and 2100 for the SSPs, and 2060 for the RTS and B2DS. The results are depicted in this section. The global level results are presented, with both regional and segments distinction, and

²³The 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).

²⁴It 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.

²⁵Steel 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.

²⁶Coal fly ash (CFA) is a by-products of coal combustion for power generation.

²⁷Blast furnace slag is a by-products of iron or steel during the blast furnace manufacturing process.

a quantification of the material impacts of renovation is also provided. Since the renovation assumptions are similar for every RCPs within each SSPs, the results are identical for the SSP2 2p6 and 4p5, and for the SSP3 2p6 and 4p5. Therefore, the SSP2 2p6 and 4p5 are referred to as SSP2, and the SSP3 2p6 and 4p5 are referred to as SSP3 in this section.

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 8.8 Gt, the aluminum in-use stock from 5.2 Mt to 386 Mt and the copper in-use stock from 5.1 Mt to 273 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 580 Gt (SSP5) in 2100, while the steel stock grows between 17 Gt (SSP4) and 27 Gt (SSP5), the copper stock between 672 Gt (SSP4) and 1,264 Gt (B2DS in 2060) and the aluminum stock between 827 Gt (SSP4) and 1,340 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. 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 inflows²⁸ (Figure 5). The variations between 2018 and 2030 result

²⁸We refer to the inflow as the sum of both the primary flow and the recycled flow.

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)

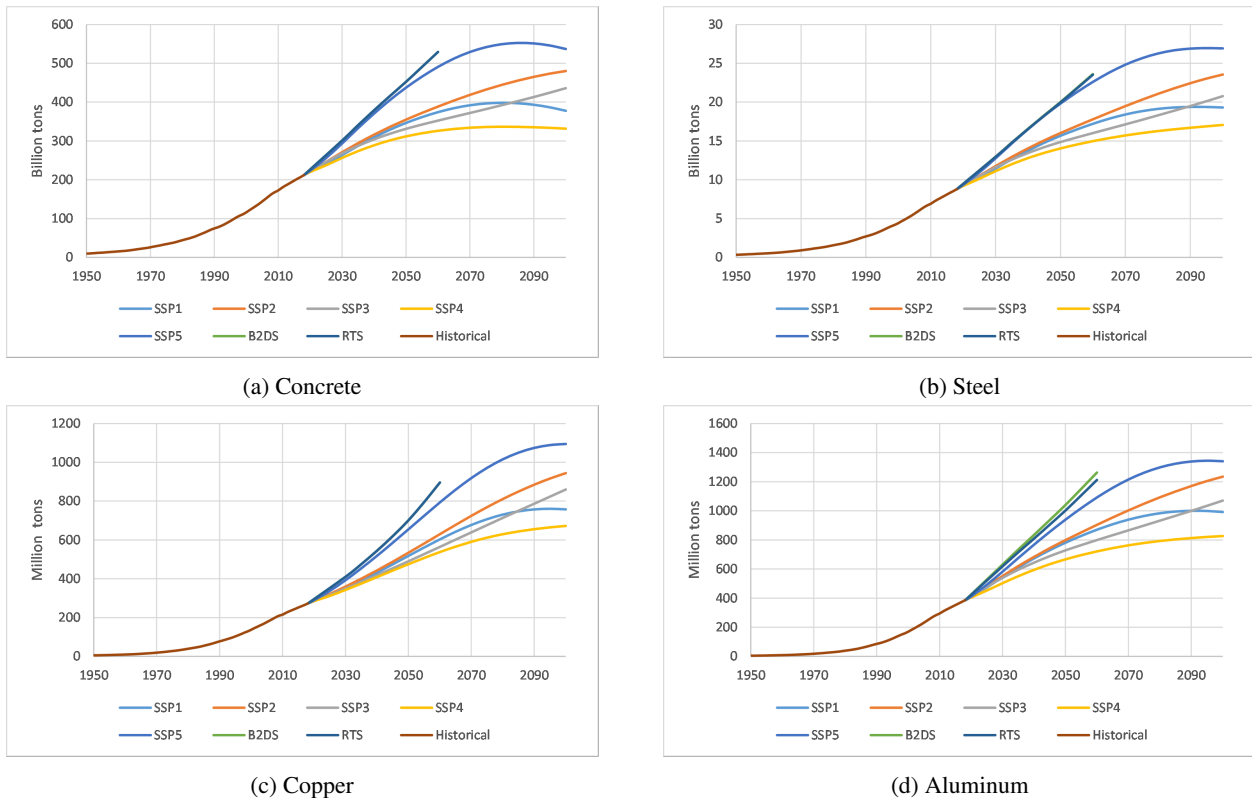


Figure 4: In-use stocks of concrete, steel, copper and aluminum in the global building sector. The RTS and B2DS results are almost similar because of their similar building stock.

of both the transition from the historical modeled surfaces to the prospective scenarios hypothesis and the beginning of the renovation policies in 2015. 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 halving for concrete, steel and aluminum. The SSP5 flows peak to more than 11 Gt/yr for concrete, 0.49 Gt/yr for steel, 24 Mt/yr for aluminum and 19 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 a reduction of the degrowth rate from 2055 to 2100, the SSP4 flows exhibit an increase 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 12.7 Gt/yr of concrete, 0.52 Gt/yr of steel, 30 to 31.4 Mt/yr of aluminum and 13.7 Mt/yr of copper in 2060. Regional materials stocks and flows were obtained for the nine regions (Figures S8 to S29).

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 31% of the concrete stock, 40% of the steel stock, 44% 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 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,

Base materials impact of the building sector in the low-carbon transition

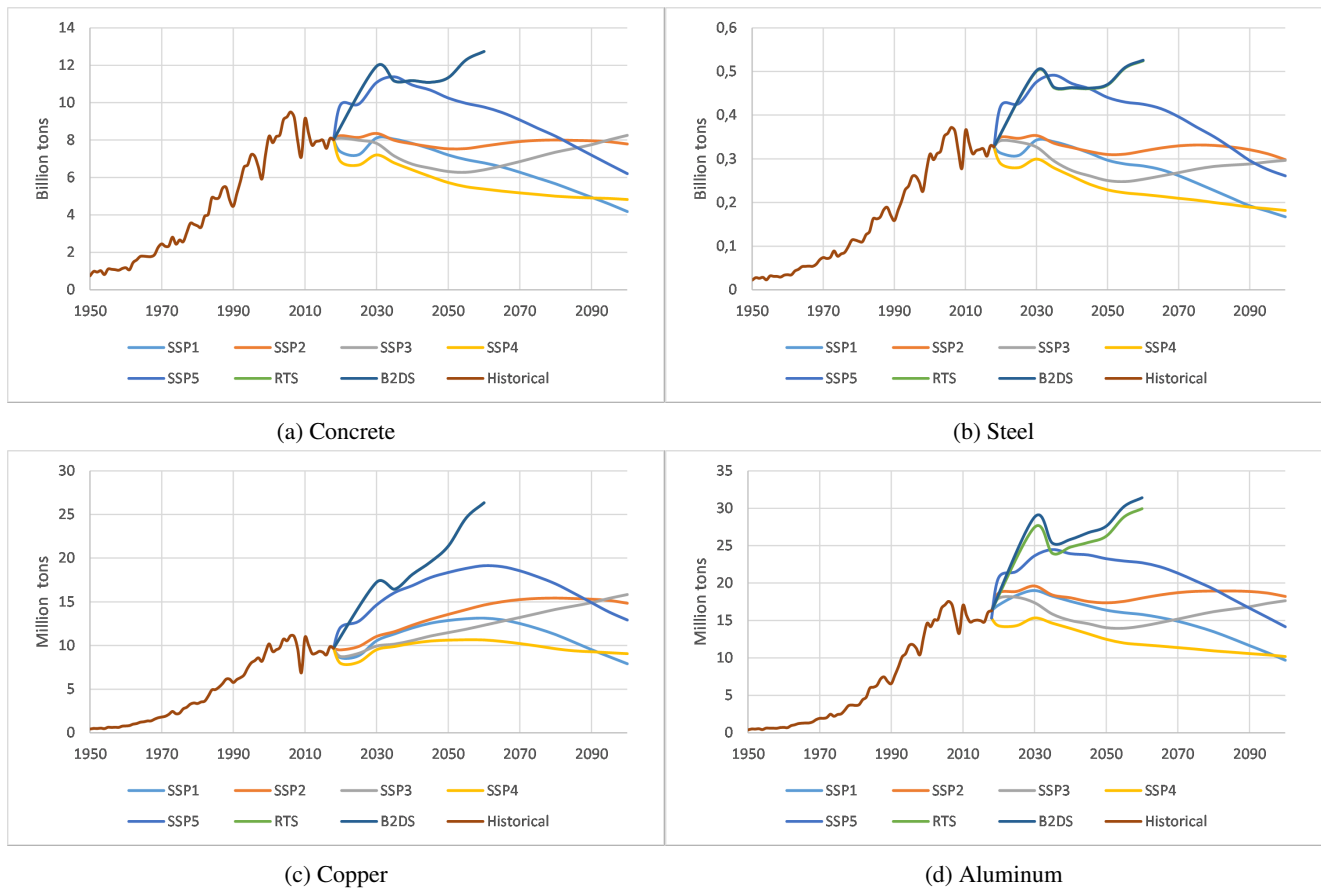


Figure 5: Annual inflows of concrete, steel, copper and aluminum in the global building sector.

and no secondary concrete was assumed in the study. The recycled steel reaches 20% of the annual flow in 2018, while secondary aluminum and copper respectively represent 12% and 10% 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 83% of recycled steel, 58% of recycled aluminum and 49% of recycled copper.

3.1.3. The material weight of thermal building renovation

Projected renovation was considered in the seven scenarios. The assumptions related to material intensities of renovated surfaces ADEME et al. (2018) lead to low amounts of concrete and steel for renovation in comparison with new surfaces. Conversely, the aluminum intensities of renovation is of the same scale as that of new construction. Different renovation strategies were selected in the design of the SSPs and IEA scenarios. While renovated surfaces-and material demand-peak in all SSPs between 2020 and 2030, the need for materials increases up to 2050 in the RTS and B2DS. The SSP3 displays the lowest flow, while the B2DS has the highest renovation flow. The required concrete reaches

between 1.4 Mt/yr and 3 Mt/yr, the steel flow between 1.8 Mt/yr and 3.9 Mt/yr and the aluminum flow between 1.6 Mt/yr and 3.3 Mt/yr. It represents a maximum of more than 1% of the annual new construction steel flow in the SSP1 and SSP4, while reaching more than 18% of the aluminum flow in the same scenarios. However, strong disparities are observed between regions within the scenarios. SSP4 is the one that consumes the most materials for renovation. While the aluminum demand for renovated surfaces represents less than 6% of the new construction inflow in Africa, India, Latin America, Middle East, OECD Pacific and Other Asia, it reaches between 28% and 45% in China, Europe and North America. The same trend is displayed in the other SSPs, the RTS and the B2DS.

3.2. Materials production energy and CO₂

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 4,300 PJ/yr to nearly 34,000 PJ/yr in 2006, before dropping to 23,500 PJ/yr in 2018, as a direct effect of the 2007-2008 financial crisis. It represents about 4% of the global final energy demand. The CO₂ emissions display a similar profile, finally reaching 1,300 MtCO₂/yr in 2018-which represents 4% of the global CO₂ emissions-after a peak at more than 1,700 MtCO₂/yr. The

Scenario	Production energy of materials (EJ)		Building final energy (EJ)	Energy savings from renovation (EJ)
	New buildings	Renovation		
SSP1 2p6	729	3.7	5,410	220
SSP2 2p6	758	3.5	5,510	196
SSP3 4p5	687	2.6	5,530	148
SSP4 4p5	628	3.6	5,620	231
SSP5 baseline	986	0	6,780	0
B2DS	1,025	5.9	5,100	461
RTS	1,018	9.8	4,300	299

Table 4

Estimations of production energy of materials in new building and renovation and comparison with the final energy demand and the energy savings from renovation between 2015 and 2050.

energy consumed for materials production finally reaches between 4,200 PJ/yr and 8,900 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. The same trend is observed in the CO₂ emissions evolution up to 2100. CO₂ emissions could reach between 360 MtCO₂/yr and 735 MtCO₂/yr in 2100 in the SSPs (Figure S49). The energy consumption of the production of materials for renovation reaches between 2.6 EJ and 3.7 EJ in the SSPs, 5.9 EJ in the RTS and 9.8 EJ in the B2DS (Table 4).

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 6). 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 6 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.

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 (Figures S37 to S48).

3.3.3. Green concrete

The computation of the four green concrete mixes shows that their use could reduce the energy demand and the CO₂ emissions of concrete production between 4% and 12% by 2060 for a 20% penetration scenario (Table 5). 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% while the CO₂ emissions decrease by 22% to 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 m²/capita in Europe, 117 m²/capita in North America and 127 m²/capita in the OECD Pacific area in

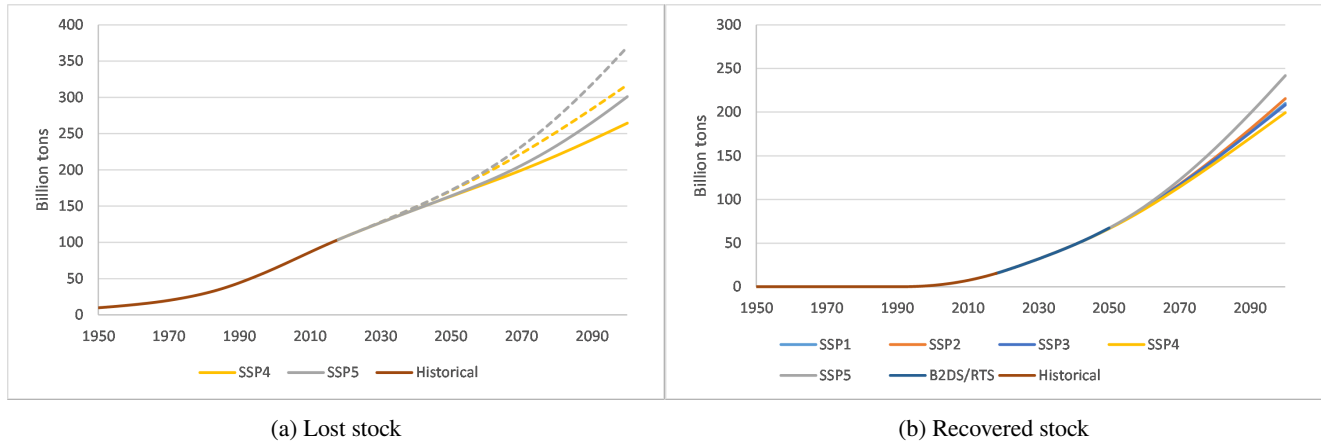


Figure 6: Global concrete lost and recovered stocks in the building sector for the selected scenarios. Only the two scenarios with the lowest and the highest lost stocks are displayed. The filled lines show the lost stocks for increasing share of recovered concrete, and constant 2020 shares are presented by the dashed lines. The residential and non-residential segments are aggregated.

Green concrete	Production energy reduction	CO ₂ emissions reduction
GC1	4%	5%
GC2	8%	10%
GC3	12%	12%
GC4		4%

Table 5
Energy demand and CO₂ emissions reductions in the scenarios in 2100 for a use of green concretes on 20% of the concrete inflow.

2060²⁹. The global average per-capita floor area finally raises from 32 m²/cap in 2017 to 48 m²/cap in 2050 and 53 m²/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 unrealistic³⁰, 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 m²/cap in Europe, 66 and 83 m²/cap in North America and 53 to 66 m²/cap in the OECD Pacific. Deetman et al. (2020) and Marinova et al. (2020) estimated a global value of about 38 m²/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 m²/cap. In China, Hong et al. (2016, 2014) and Cao et al. (2018) depicted potential saturation levels of 46 m²/capita to 50 m²/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

²⁹In 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.

³⁰A saturation level is already observed in France. Insee (2017) reported an almost steady residential floor area per capita of 40 m²/capita since 2006.

global stock could amount to 53 to 58 m²/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)³¹. 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 below 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 not in line with the estimates³². Finally, the results were compared with previous studies. Given the different scenarios considered in the literature, only the SSP2 also selected in Deetman et al. (2020) and the historical results were confronted. The Table S11 shows large disparities in the results of the different studies, and especially for steel and aluminum. The present study displays intermediate historical levels, and lower prospective stocks and flows levels in the SSP2 than in Deetman et al. (2020). It is

³¹We considered a 20% share of cement in concrete.

³²A 25% to 37% share of building and construction in aluminum demand is observed.

explained by slightly lower global building stock estimation in the GCAM 5.4, and lower steel and aluminum intensities in the present study.

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 global CO₂ emissions and final energy consumption in 2018. It was estimated that concrete had the most impact, with 1.9% of the CO₂ emissions and 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 global CO₂ emissions and 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 RCP³³ 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,

³³The Representative Concentration Pathways are scenarios of radiative forcing, as previously presented in Section 2.1. It acts as a climate policy in the SSP.

except for the B2DS. It is explained by the significant reduction in final energy demand, and similar socioeconomic assumptions to the RTS. We further observe higher shares in the RCP 2p6 scenarios than in the RCP 4p5, which is in line with the stronger energy constraints to reach a lower radiative forcing. The high share showed in 2100 in the SSP2 4p5 is explained by a substantial decrease of energy demand at the end of the century. 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 14% of the final energy demand of the building sector in the SSP2 2p6 and 4p5, and 24% in the B2DS (Table 4). The renovation represents a small share of the production energy of materials, but it is worth noticing that it could amount between 34% and 39% of the global energy savings induced by the renovation (Table 4).

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. The share of the base materials production for the building sector increases in 2100 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 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 or 4p5, 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 comparison with a BAU case (Table 6). 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, but our model shows that a penetration of CFA on 100% of the concrete inflow would not 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 of green concretes and their composition would allow to

Scenario	CO ₂ emissions (MtCO ₂)				Final energy (EJ)			
	2018	2040	2060	2100	2018	2040	2060	2100
SSP1 2p6		1,120	834	383		20	13	5
SSP2 2p6 & 4p5		1,120	948	746		20	15	10
SSP3 2p6 & 4p5	1,300	939	764	782	24	17	12	10
SSP4 4p5		897	645	451		16	10	6
SSP5 baseline		1,609	1,237	582		28	19	7
B2DS		1,501	1,608			28	25	
RTS		1,510	1,617			28	25	
SSP2 2p6 & 4p5 with GC2-20%		1,064	903	708		19	14	9
SSP2 2p6 & 4p5 with GC3-20%		1,053	894	700		18	14	9
SSP2 2p6 & 4p5 with GC2-100%	1,300	845	727	559	24	14	11	8
SSP2 2p6 & 4p5 with GC3-100%		896	768	594		11	10	7
B2DS with GC2-20%		1,430	1,530			26	21	
B2DS with GC3-20%		1,413	1,513			26	23	
B2DS with GC2-100%		1,116	1,193			21	19	
B2DS with GC3-100%		1,188	1,270			16	15	

Table 6

Final energy demand and CO₂ emissions 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.

identify the opportunities and the constraints of a large use of green concrete to decrease the environmental impacts of the building sector.

4.5. Limitations

This study proposes a regional approach of the building sector, modeling raw materials as well as their embodied energy and CO₂ emissions. 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), and their evolution over time. 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.

Conversely to the dynamic and regional construction materials intensities, renovation intensities are dynamic and

global. Only French static data about the ongoing national building stock renovation were found by the authors, with no hypothesis about further evolution of the embodied materials. Given the differences in the regional construction mix, it can be assumed that regional renovation intensities also vary. 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, through a MFA, the base materials stocks and flows of the building sector was estimated, as well as the production energy and CO₂ emissions. Secondly, the results were confronted to the prospective energy and CO₂ emissions 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, and the development of renovation strategies in the most developed areas. We further show that (ii) a growing materials demand translates into larger energy demand and environmental impacts, which could question the feasibility of some low-energy demand scenarios, and that (iii) the recycled concrete aggregated display a significant potential to enhance the reduction of accumulated concrete stocks in landfills and green concrete could decrease the environmental burden of concrete.

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. Multi-sector policies would be fundamental to apprehend the dependency between the energy, industry or agriculture sectors, and successfully provide high quality materials for structural uses.

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. **Olivier Vidal:** Software, Writing - Review & Editing, Supervision, Funding acquisition. **Baptiste Andrieu:** Visualization, Software, Writing - Review & Editing. **François Verzier:** Software, Writing - Review & Editing. **Daniel Monfort-Climent:** Writing - Review & Editing.

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

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4.2 Supplementary information to: *Base materials impact of the building sector in the low-carbon transition*

4.2.1 Literature review

Dynamic materials modeling of the building sector

In the identified literature, several authors have identified a lack of knowledge of the anthropogenic stock (Schiller et al., 2017). While initial publications have focused on primary materials inflows, the in-use stock has progressively gained attention, for its role a driver of the construction and demolition flows, and the secondary materials providers (B. Müller, 2006). It enables a better understanding of the dynamics of construction and demolition cycle, and the maintenance and expansion shares of the construction inflow in the building sector. The publications show an increasing share of maintenance in the most developed areas (Wiedenhofer et al., 2015), as well as a grow of the demolition flow (B. Müller, 2006; Bergsdal et al., 2007). Conversely, the developing regions will experience a slowdown of the annual building expansion in the coming decades, which could have profound industrial consequences for the management of waste and secondary materials.

We further observe an increasing focus on the construction and demolition wastes. It provides estimations of the prospective wastes (Bergsdal et al., 2008), potential secondary resources through a better classification of input materials (Hashimoto et al., 2009), circularity achievements (Arora et al., 2019) or analysis of the impacts of policies, for example in the European Waste Framework Directive (Wiedenhofer et al., 2015). Despite a substantial increase of the building in-use stock in China over the past years, per-capita level could further grow (Wang et al., 2015a; Zhang et al., 2015b), before an expected reduction of the building stock expansion in the coming decades in developed areas and China. It could allow a higher reliance on secondary resources to lower primary inputs and environmental impacts, which require the development of an efficient waste management and recycling system (Shi et al., 2012; Wang et al., 2015b).

Finally, the parameters assumptions are discussed in the literature, as they represent a major source of uncertainties (Cao et al., 2018)¹, but could provide tools to better manage materials stocks and flows. Several publications emphasize the significant role of material efficiency to reduce materials demand and their environmental impacts. Material efficiency is a multifaceted concept (Pauliuk and Heeren, 2021), which includes lifetime extension (Hu et al., 2010; Shi et al., 2012; Huang et al., 2018)², a better product design (Shanks et al., 2019)³, or higher recycling and reuse (Shi et al., 2012; Wang et al., 2015b). Pauliuk and Heeren (2021) proposed the implementation of material efficiency strategies in the building and transport sectors in Germany.

The role of materials engineering to reduce impacts

Contrary to the common belief that concrete is not recyclable, Japan or the Netherlands manage to 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 CDW by lowering their amount in landfills. The potential of recycling construction and demolition waste (CDW) is substantial, as they represent a significant part of the society wastes. They reached 25 to 30% of the overall generated European Union wastes in 2017 (European Union (2017)), of which mineral and solidified wastes represented 76% (Reis et al. (2021)). The European Union targeted the CDW in the its Waste Framework Directive⁴, and managed to fulfill the objective to recover or recycle 70% of CDW by 2020 (Villoria Sáez and Osmani (2019)). More than 82% of generated CDW were recycled in 2021, and only 11% were disposed in landfills (European Environment Agency (2021)). However, the European results are not representative of the current global CDW management, and lower recovery rates are

¹Liu et al. (2020) provided a household level desegregation study for a more accurate description of appliances life cycle in the building sector.

²Hu et al. (2010) raised questions about the optimal lifetime to reduce resources use and environmental impact through an increase of the share of secondary materials in the input.

³Conversely to light-weighting products, dynamic and increasing materials intensities are sometimes used in MFA studies to model technological change (Shi et al., 2012; Hatayama and Tahara, 2016).

⁴This directive from 2008 aimed at enhancing the recovery and management of CDW in a circular economy perspective.

observed in other regions (Reis et al. (2021); Tam et al. (2018)).

Concrete is recycled in the form of aggregate by a crushing process, partly replacing natural aggregate content in the concrete production⁵. Two types of recycled aggregates from construction and demolition waste (CDW) are generally considered (Marinković and Carević, 2019). Recycled aggregates (RA) are defined as mixed aggregates. Recycled concrete aggregates (RCA) are mainly made of concrete, and their higher quality would allow a use recycled aggregates concrete (RAC) for structural applications with different standard compositions depending on the countries (Nováková and Mikulica, 2016). Despite potential environmental benefits (Tam et al., 2018), the use of recycled aggregates is often limited to non-structural projects, e.g. in India (Behera et al., 2014), in the USA and in France⁶ because of a lack of confidence of construction actors in RA (Silva et al., 2019; European Environment Agency, 2021). The different applications of RA are described in Reis et al. (2021), and the authors outlined the growing number of encouraging pilot projects using recycled aggregate concrete (RAC). Silva et al. (2019) further provided a review of 31 constructions projects to demonstrate the technical and economic viability of recycled aggregates use. Among these projects, 11 are related to structural use of concrete in buildings. They carry substantial benefits through four reductions : financial, primary resources need, accumulation in landfills and environmental impacts.

The RAC research field has been growing over the past years, and the specific impact of replacing natural aggregates by recycled concrete aggregates (RCA) on the properties of RAC was under focus. RCA is defined as aggregates recovered from concrete in which other materials represent less than few percents (Marinković and Carević, 2019), and it can be used for higher strength concrete than RA (Purnell and Dunster, 2010). However, Behera et al. (2014) showed lower mechanical and durability performance of RAC, and emphasized the need of further assessment of RA quality and its impact on concrete. In reviews on the RCA impacts on RAC production, Silva et al. (2014) and Verian et al. (2018) provided recommendations for an optimal use of recycled concrete aggregates (RCA) in concrete production. The authors showed different challenges depending on the use of fine and coarse aggregates⁷, but a potential was identified for both types. The authors further reported that some researches estimate a 30% limit in the use of coarse RCA in concrete, but state that there could be no limit in its potential share if specific process conditions are respected⁸. Thomas et al. (2013) further outlined the need for more assessment of RAC in different exposure conditions. For moderate conditions, Thomas et al. (2018) estimated that a 25% replacement of NA by RCA displays viable strength results. Guo et al. (2018) and Verian et al. (2018) further identified the potential to enhance recycled aggregate concrete performances, using for example CO₂ treatment and pozzolanic materials (e.g. fly ash). Several studies have conducted further environmental assessment of RCA and natural aggregated for different mixes and geographic perimeters, showing transport distances influence (Marinković et al., 2010) and avoided emissions in steel production and waste disposal (Knoeri et al., 2013). However, no concordance in the potential reduction was observed in the literature, and Wijayasundara et al. (2017) further showed similar embodied energy and impacts of RCA and natural aggregates in a cradle-to-gate analysis of RCA in Australia. Given the lack of consensus, no energy demand and environmental impact reductions were considered.

In parallel of improving concrete recovery and recycling, "green concrete" aims at cutting the environmental impact. It is defined as a low-carbon concrete, which production mainly relies on the use of industries or agriculture 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 could achieve lower impacts of concrete production (Reiners and Palm, 2015). The use of wastes in concrete production has already been implemented for decades in the concrete industry through supplementary cementitious materials (SCM)⁹. The most com-

⁵Shares 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)

⁶Most of the recycled CDW in France are used in non-structural applications. The RECYBETON project aims at increasing the share of RA in concrete.

⁷Bravo et al. (2015) found that fine aggregates use hampers concrete performance, but that a limited share of coarse aggregates is viable. This higher impact of fine RCA was also highlighted in Guo et al. (2018).

⁸Coarse and fine aggregates are defined by the size of their particles.

⁹The 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".

mon SCM are coal fly ash (CFA)¹⁰, blast furnace slags (BFS)¹¹, silica fume, or metakaolin (Habert, 2014; Holland et al., 2016)¹². The study of "green concrete" performances and environmental impacts has showed a growing interest in the literature and several publications recently reviewed the by-products studies (Siddique, 2014; Gu and Ozbakkaloglu, 2016; Paris et al., 2016; Jiang et al., 2018; Sandanayake et al., 2020).

4.2.2 Methodology

This section provides further documentation on the methodology in this study. The following items are detailed :

- The perimeter of the multinational areas considered in the scenarios are described in Section 4.2.2;
- The historical regional floor areas are displayed in Section 4.2.2;
- The regional lifetimes methodology and data are detailed in Section 4.2.2;
- The regional historical materials intensities and the methodology to set their logistic profiles up to 2100 are explicated in Section 4.2.2.

Regional segmentation in the scenarios

Nine multinational areas are considered in this study. They are detailed in the Table 4.1.

Regions	Countries
Africa	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome & Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, South Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe
China	
Europe	Albania, Austria, Belarus, Belgium, Bulgaria, Bosnia and Herzegovina, Cyprus, Czech Republic, Croatia, Denmark, Estonia, Germany, Gibraltar, Greece, Finland, France, Hungary, Ireland, Iceland, Israel, Italy, Kosovo, Latvia, Lithuania, Luxembourg, Malta, Moldova, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine United Kingdom
India	
Latin America	Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Curacao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Venezuela
Middle East	Bahrain, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen
North America	Canada, Mexico, United States of America
OECD Pacific	Australia, Japan, Korea, New Zealand
Other Asia	Afghanistan, Armenia, Azerbaijan, Bangladesh, Bhutan, Brunei, Brunei Darussalam, Cambodia, Hong Kong, Indonesia, Kazakhstan, Dem. People's Republic of Korea, Kyrgyzstan, Laos, Macao, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Oceania (excluding Australia and New Zealand), Pakistan, Philippines, Singapore, Sri Lanka, Taiwan, Tajikistan, Thailand, Turkmenistan, Uzbekistan, Vietnam

Table 4.1: Summary of the considered regions.

¹⁰CFA is a by-product of the combustion of coal to generate electricity.

¹¹BFS is produced during the iron-making process.

¹²Many 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)

Historical regional building stocks

The surfaces obtained from the logistic approach adopted in this article are displayed in the Figure 4.1 for the residential segment and in the Figure 4.2 for the non-residential segment.

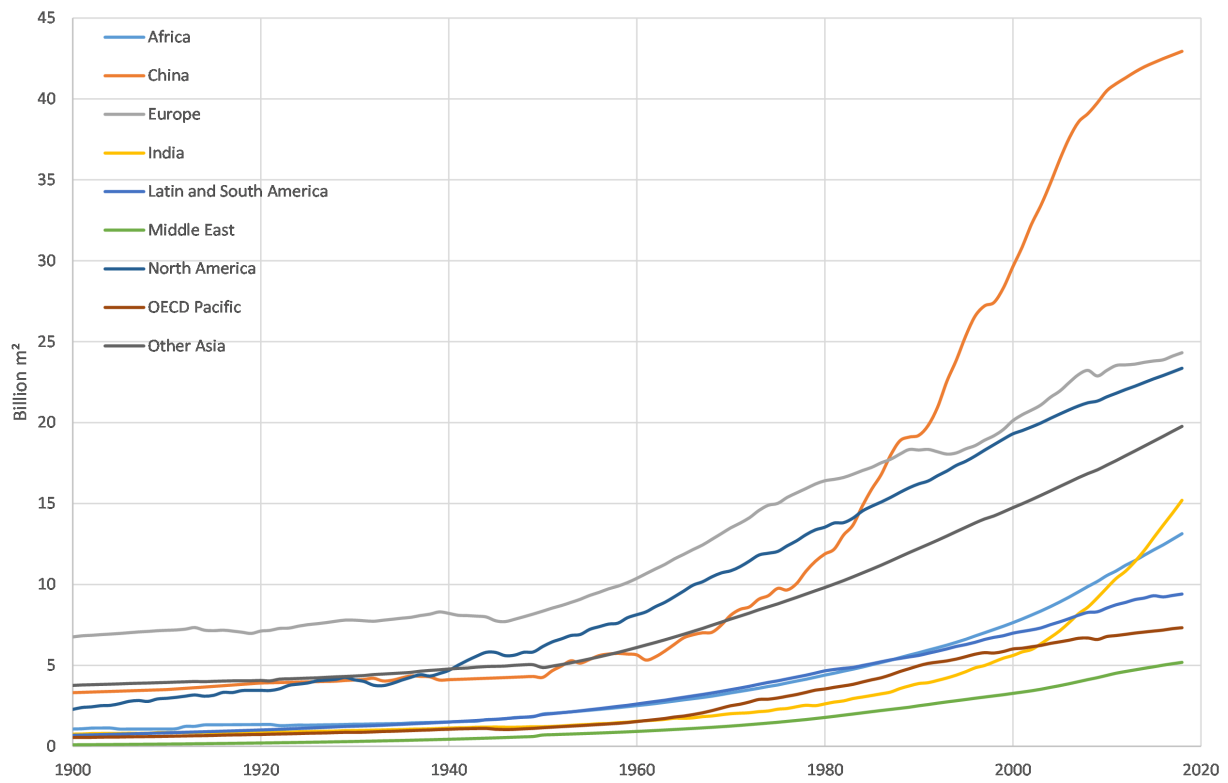


Figure 4.1: Historical residential regional floor areas.

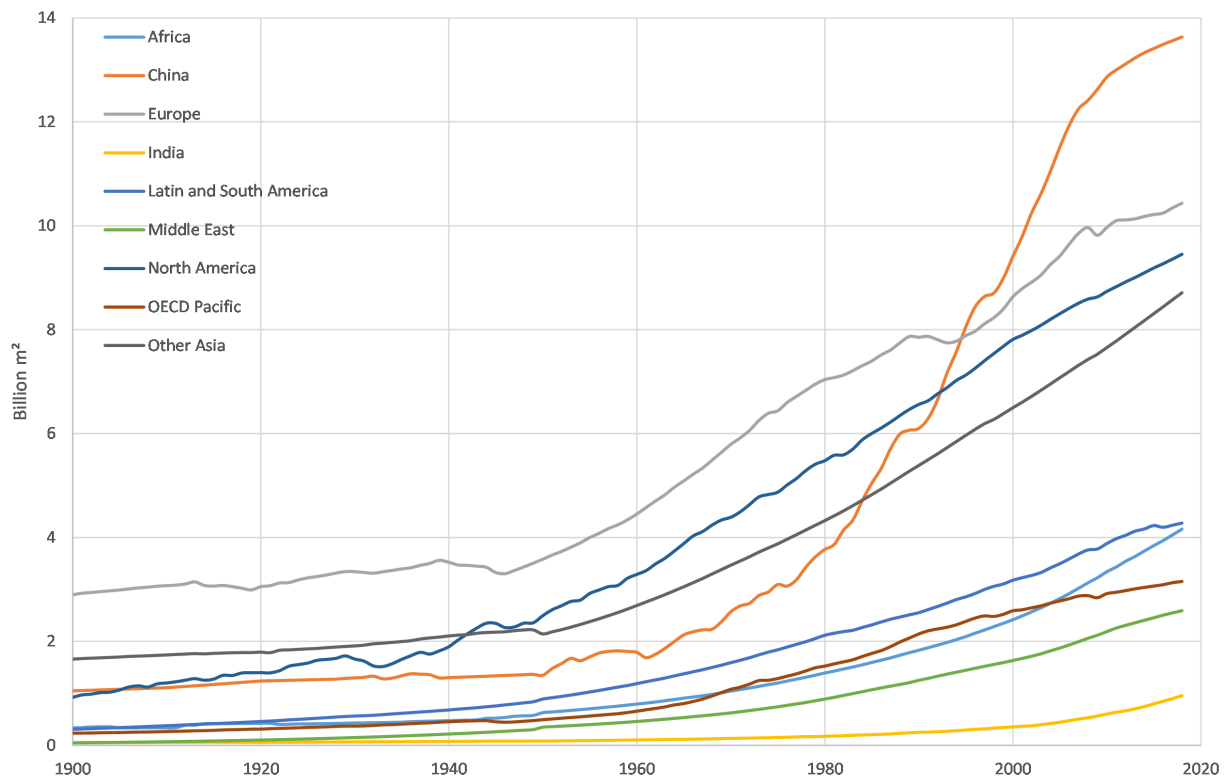


Figure 4.2: Historical non-residential regional floor areas.

Regional lifetimes

Recent publications analyzed the impact of lifetime in infrastructures modeling (Aktas and Bilec, 2012; Marsh, 2017; Zhou et al., 2019; Cao et al., 2019). The authors outlined two major aspects of lifetime assessment. Firstly, the need for a more systematic use of lifetime distribution. Numerous statistical distributions exist, such as Weibull, normal, log-normal, Gamma or Gompertz-based. They are widely used in the literature (Table 4.3), but no insights were available about the best suited approach to model building lifetime. Miatto et al. (2017a) recently provided such an analysis. The authors tested the sensitivity of the distribution on materials modeling at national and city scales, and concluded on the low effects on stocks results and higher impacts on output flows. They further outlined the need to use several distribution lifetimes when various buildings categories are considered, and the low impact of the distribution choice in an aggregated building stock. Secondly, the inverse relation between lifetime and environmental impacts was depicted in Marsh (2017). They showed that a lifetime value of 100 years reduces the environmental impacts by 38% in comparison with a 50-year level at the Danish scale. An optimal modeling of building lifetime therefore lies in a combination of a dynamic mean value with a statistical distribution. This approach was conducted by Hu et al. (2010) for the Chinese residential building stock, assuming a gradual increase of the mean value of a normal lifetime distribution. A similar approach was selected in this study, using a Gompertz-modeled mean value over time and a regional normal distribution.

The selected methodology thus intends to provide regional dynamic lifetimes in accordance with the previously depicted conclusions. However it does not consider local exceptions, such as a diminishing average lifetime in Norway described in Brattebø et al. (2009). As previously stated, the building stock was segmented into two categories : residential and non-residential. Due to a lack of data about the non-residential building stocks lifetime characteristics, similar values are considered for both categories. The methodology relies in three successive steps :

1. Estimating current average regional lifetimes;
2. Evaluating logistic-based profiles for those lifetime between 1900 and 2100;

3. Calibrating regional normal distributions with dynamic mean values.

The life span of buildings and their typology vary according to geography (AIMCC, 2015). In a first step, current regional lifetimes considered in the literature were studied. They were obtained from a regional analysis and a census of the observed mean values in lifetime distributions. A summary of those latter is presented in Table 4.3). At the European level, JRC (2011) reported a life span of about 50 years for more than half of the French housing stock, 20% of the buildings reaching 100 years. Wang et al. (2018) identified data from several studies, showing longer building lifetimes for European buildings than Chinese or North American buildings. The values range from 64 to 132.6 years for Germany, Spain, Belgium, the Netherlands, Switzerland, Austria, France, and the United Kingdom. Similarly, AIMCC (2015) presented the results of several European studies predicting lifetimes between 50 and 75 years. Except for Ciacci et al. (2013) and Hatayama et al. (2009), those values are commonly observed in the lifetime distribution summarized in Table 4.3. Based on these results, an average service life of 70 years was considered for European commercial and residential buildings.

In North America, Aktas and Bilec (2012) reported a slightly increasing life span since the late 1990s. The life span of U.S. residential buildings has evolved from 50 years in 1997 to 61 years in 2009. Wang et al. (2018) estimated close life spans for the United States and Canada buildings, respectively, with 60 and 70 years. There are large differences in service life by construction type. In a study conducted in the United States and Canada, O'Connor (2004) revealed that only one third of North American non-residential concrete buildings are more than 50 years old, compared to 63% of wood buildings and 20% of steel buildings. Wood has a longer life span than concrete, with a majority of buildings destroyed after 75 years of life. Lifetimes ranging from 26 to 50 years are observed for concrete buildings. The practical observations are therefore lower than the theoretical values of 51.6 years for wood buildings and 87.2 for concrete buildings (O'Connor, 2004). It covers a variety of reasons for demolition. In North America, nearly 80% of concrete buildings are demolished for lack of use or for a new building project. Lower levels are observed for wood (50%) and steel (60%). Only 31% of the buildings are demolished at the end of their life in O'Connor (2004), which emphasizes the unreliability of the theoretical life span. An average life of 50 years was therefore considered for the entire North American building stock¹³.

In China, a different trend is observed by Cao et al. (2019). The authors estimated a life span of 39.4 years for the building flows between 1950 and 1969, and 37 years between 1970 and 1979. Lifetime then dropped to 25.3 years for buildings finished between 1980 and 1989, and increases to 26.6 years in the 1990-1999 period and 33.8 years between 2000 and 2015. The life span of Chinese housing thus remains low, explaining the high annual demolition rate. On average, Cai et al. (2015) estimated a current life span of Chinese residential buildings of 23.2 years, while Hu et al. (2010) suggested average life spans of 30/40 years in the urban sector in the 1970s and 1980s, and 15 years in the rural sector. These would increase over time for both rural and urban buildings due to China's economic reform in 1978, allowing for improved construction techniques (Hu et al. (2010)). These values and trend are confirmed by Wang et al. (2018), surveying several studies and announcing a final value of 35 years for the Chinese building stock. Moreover, Hu et al. (2010) depicted a significant increase of life span in the future, finally reaching 75 years. An average value of 35 years was considered in this study.

In Japan, the life span has been decreasing since the end of World War II, reaching 25 to 30 years in recent years (Wuyts et al., 2019; Kobayashi, 2016), although with disparities depending on the construction method¹⁴. This low average life span is explained by the depreciation of buildings observed in Japan, and remains slightly below the observed values in Table 4.3. An average value of 30 years was finally considered for the Japanese building stock. A low value is also observed in South Korea, with an average of 22.4 years (Seo and Hwang (1999)). A minimum value of 50 years seems to be common in the New Zealand market, and Deetman et al. (2020) modeled the Oceania building stock with a mean value of 83 years. Japan and Korea accounting for 85% of the total ASEAN population in 2020, a 35 year-value is considered for this region.

¹³The concrete-made and steel-made building market shares were used to evaluate building lifetime. Concrete market share reached 34% in non-residential and multi-story buildings, while steel market share was 46%.

¹⁴This is in accordance with the reported values of the Chinese Vice-Minister of Housing and Urban-Rural Development.

In the Middle East, a lack of data is observed. The combination of poor quality materials and harsh climatic conditions explains why buildings are renewed faster than in Western countries. Thus, we observe an average building life of about 20 years in the United Arab Emirates¹⁵, 25 to 50 years in Saudi Arabia¹⁶ and 25 to 35 years in Iran¹⁷ (Yousefi and Gholipour, 2018). An average life of 30 years was therefore considered for the Middle-East.

The other regions suffer a lack of data. A 60-year value is considered for Latin America, which is lower than theoretical values of Heeren et al. (2015) and Deetman et al. (2020), and a lower value for the entire continent by Murakami et al. (2010). A life span of 50 years was used in Deetman et al. (2020), and is retained in this study for ASEAN and Other Asia. To the author's knowledge, no precise assessments of life span are available for Africa and India, an average value of 50 years was then considered. The final data are displayed in 4.2.

Area	Average current life span	Average saturation life span
Africa	50	70
ASEAN	50	70
China	35	55
Europe	70	90
India	40	60
Latin America	60	80
Middle East	30	50
North America	50	70
OECD Pacific	35	55
Other Asia	40	60

Table 4.2: Summary of the current and saturation regional building lifetimes considered in this study.

The selected average lifetime were then made dynamic over time. A four-parameter logistic function was used (eq 4.2.1). The parameters were designed assuming initial lifetimes of 10 years in 1900 and saturation values 20 years higher than the current values (Table 4.2). The resulting lifetimes are displayed in Figure 4.3.

$$L_t = L_{sat} + \frac{L_{init} - L_{sat}}{1 + \frac{t}{t_i}^\beta} \quad (4.2.1)$$

In this equation, L_t is the lifetime in the year t , L_{sat} is the saturation level of the lifetime, L_{init} its initial value, t_i is the inflection year and β influence the growth rate of the curve.

¹⁵The workshop "Life Expectancy of Buildings in the UAE" aimed at tackling the quality issue and thus increasing the buildings lifetime.

¹⁶Poor quality standards are assumed to be the source of this low life span.

¹⁷This average lifetime is even assumed to decrease as low quality standards actors represent an increasing market share.

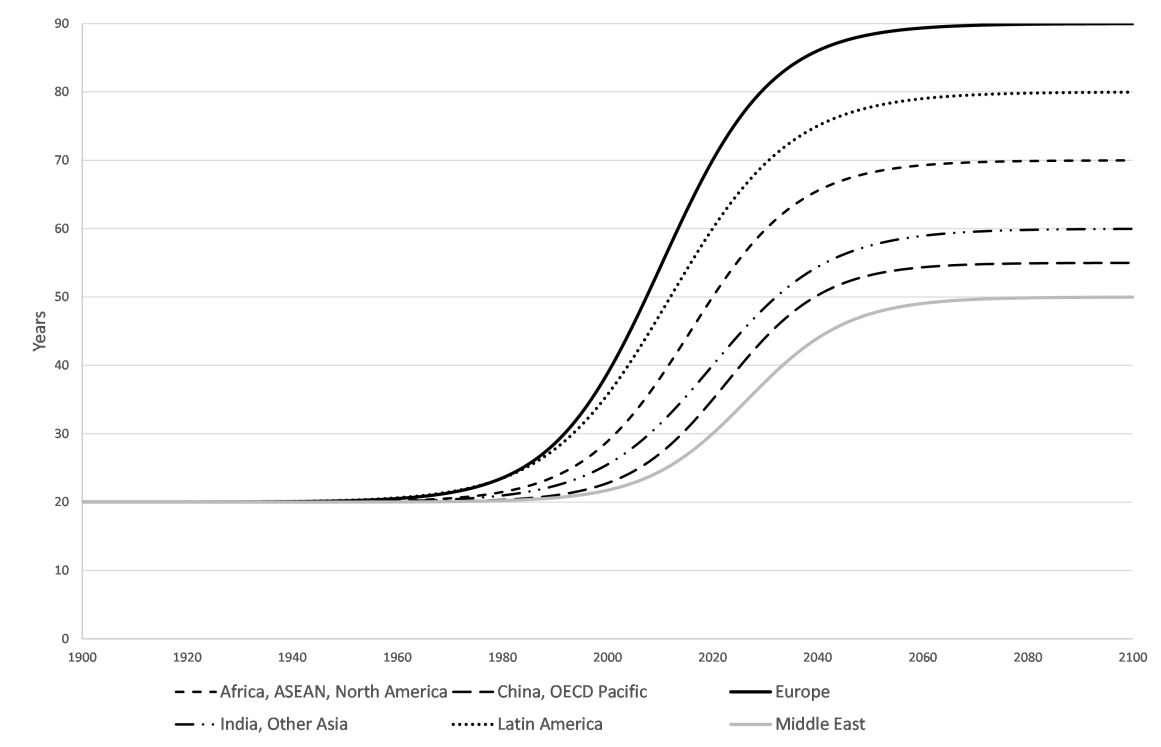


Figure 4.3: Regional average lifetimes between 1900 and 2100.

References	Distribution	Area	Building type	Mean lifetime	Standard deviation
Deetman et al. (2021b)	Weibull	Brazil	Urban residential	100	
Deetman et al. (2021b)	Weibull	Canada	Residential	51	
Hatayama et al. (2009)	Weibull	China	All	32.5	
Zhou et al. (2019)	Weibull	China	Urban residential	34.1	23.5
Cai et al. (2015)	Weibull	China	All	23.2	
Deetman et al. (2020)	Weibull	China	Residential	39	
Wang et al. (2015b)	Weibull	China	Residential	39	
Olaya et al. (2017)	Normal	Colombia	Residential	100	25
Vásquez et al. (2016)	Normal	Czech Republic	Residential	100	25
Deetman et al. (2020)	Weibull	Eastern Europe	Residential	78	
Hatayama et al. (2009)	Weibull	Europe	All	31.5	
Murakami et al. (2010)		Europe	All	75	
Vásquez et al. (2016)	Normal	Germany	Residential	150	40
Bradley and Kohler (2007)	Weibull	Germany	Urban residential		
Ciacchi et al. (2013)	Normal	Italy	All	40	14
Hatayama et al. (2009)	Log-normal	Japan	All	38.7	
Tanikawa et al. (2015)	Log-normal	Japan	All		
Hashimoto et al. (2007)	Log-normal and Weibull	Japan	All		
Deetman et al. (2020)	Weibull	Japan	Residential	34	
Murakami et al. (2010)		Japan	All	50	
Fishman et al. (2014)	Normal	Japan and USA	All		
Deetman et al. (2020)	Weibull	Mexico	Residential	56	
Murakami et al. (2010)		North, Middle and South America	All	50	
Brattebø et al. (2009)	Normal	Norway	All	180 down to 95	
Deetman et al. (2020)	Weibull	Oceania	Residential	83	
Deetman et al. (2020)	Weibull	Rest of South America	Residential	60.5	
Deetman et al. (2020)	Weibull	Southeastern Asia	Residential	50	
Heeren et al. (2015)	Log-normal	Rest of South America	Residential and small offices	90	
Müller et al. (2014)	Normal	The Netherlands	Residential	60-90-120	20
Davis et al. (2007)	Weibull	UK	All	60	13.7
Davis et al. (2007)	Log-normal	UK	All	60	12.1
Deetman et al. (2020)	Weibull	USA	Residential	77	
Hatayama et al. (2009)	Weibull	USA	All	75	
Kapur et al. (2008)	Weibull, Gamma and log-normal	USA	All		
Aktas and Bilec (2012)	Weibull	USA	Residential	61	25
Ciacchi et al. (2013)	Normal	USA	All	50	15
Deetman et al. (2020)	Weibull	Western Europe	Residential	63	

Table 4.3: Summary of lifetime distributions, regional mean values and standard deviations in the literature.

In a third and last step, normal distribution were applied on the logistic-based average lifetimes (eq 4.2.2). As depicted in Table 4.3, a wide panel of standard deviation values are used in the existing studies. It also shows an evolution with the mean value, and the ratio $\frac{\mu}{\sigma}$ of the selected studies ranges from 2 to 4.6. The data of [Zhou et al. \(2019\)](#) and [Aktas and Bilec \(2012\)](#) were considered, respectively for China and North America, because of their estimation from historical data. Given the lack of data for the other areas, an average value of $0.3 \cdot \mu$ was selected in this study. This is however a first order estimation, and it does not provide any overall pattern. Given the dynamic nature of the mean lifetimes, the standard deviation also varies over time.

$$f(L) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \exp\left(-\frac{1}{2} \cdot \left(\frac{L - \mu}{\sigma}\right)^2\right) \quad (4.2.2)$$

With $f(L)$ the probability density function depending on the lifetime, σ the standard deviation and μ the mean lifetime. The final probability density functions of Europe, China, India and North America in 2000, 2020 and 2050 are displayed in Figures 4.4a to 4.4d.

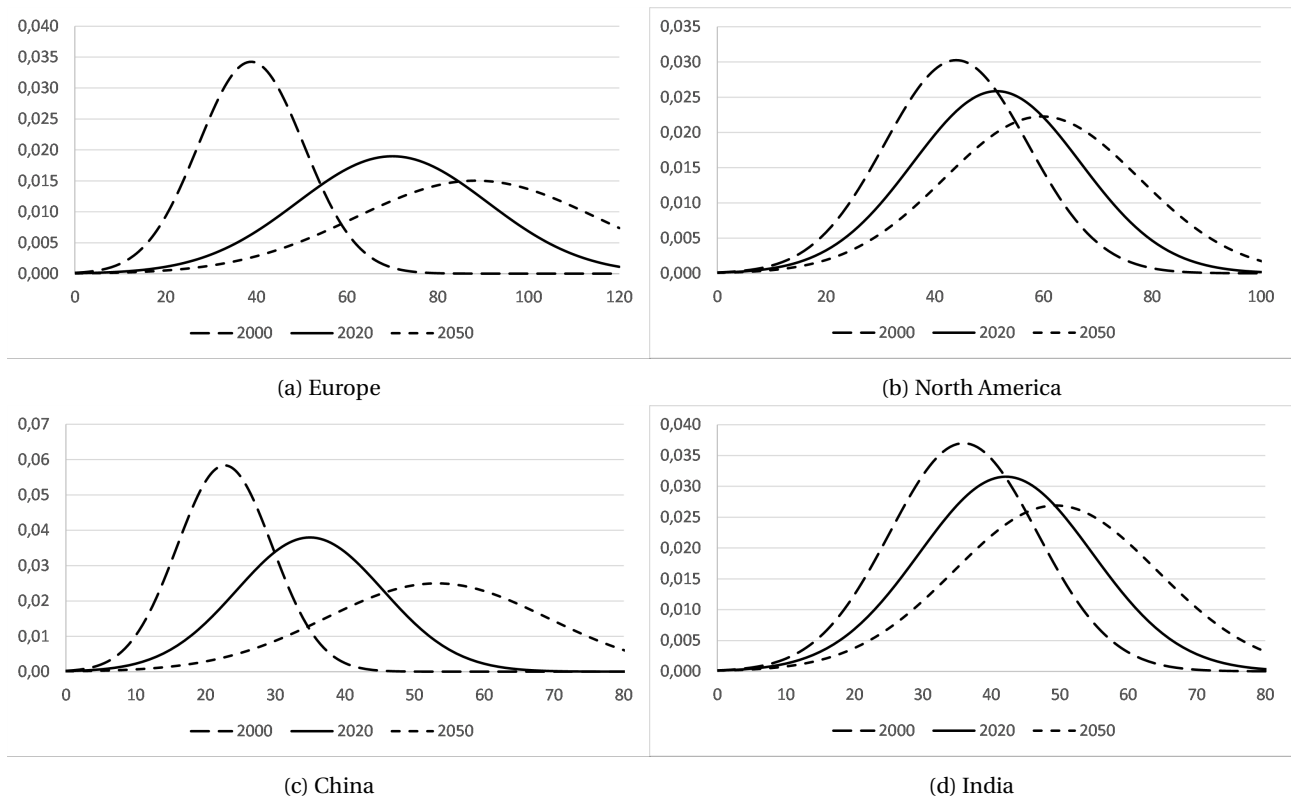


Figure 4.4: Normal distribution of the European, North American, Chinese and Indian buildings lifetimes in 2000, 2020 and 2050.

Regional raw materials, energy and CO₂ intensities

Some material modeling studies consider static materials intensities ([Marinova et al., 2020a](#); [Deetman et al., 2020](#); [Hong et al., 2016](#); [Schebek et al., 2017](#); [Yang and Kohler, 2008](#)), and other provide useful data about their evolution over time. [Hu et al. \(2010\)](#) assumed a dynamic steel material intensities in rural residential building in China, and dynamic concrete intensities are displayed in Figure 4.5. An increase of concrete and steel intensities is generally observed over time, except in Sweden ([Gontia et al., 2018](#)). Two reasons can explain this upward trend. Firstly, a change in the construction mix occurred in Europe and Japan after the World War II. Concrete increased its domination over material use in a context of rapid and economical reconstruction of destroyed cities ([Steele, 2017](#); [Diefendorf, 1989](#); [Chemillier, 1997](#)). The rises represented in Figure 4.5 may thus provide insight about an evolution toward more concrete in the construction mix rather than a higher use of materials in concrete buildings. A further evolution of the mix (e.g. wood building development) is considered in this study. Higher steel, aluminum and copper intensities over

time draw a different trend, such as an increasing use of reinforced concrete, or higher electrification of buildings. This research field is not well studied in the literature, and no quantitative regional trends are available to the author knowledge.

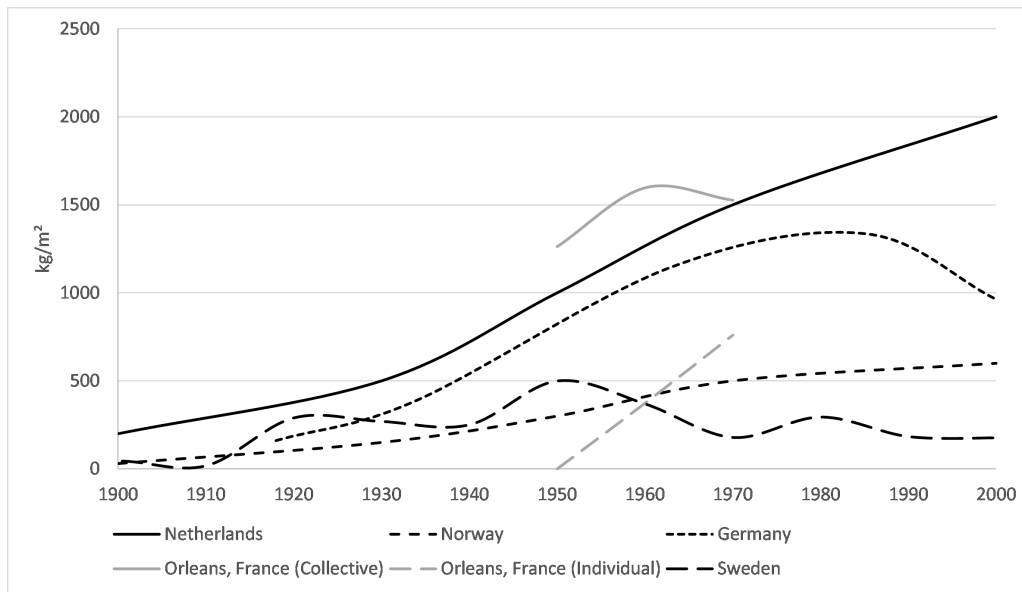


Figure 4.5: Dynamic residential concrete intensity values observed in the literature. Netherlands data from [B. Müller \(2006\)](#), Norway data from [Bergsdal et al. \(2007\)](#), Germany data from [Ortlepp et al. \(2018\)](#), French data from [Serrand et al. \(2013\)](#) and Sweden data from [Gontia et al. \(2018\)](#). The decrease of intensity observed in [Ortlepp et al. \(2018\)](#) could be explained by a recent rise of masonry use.

In this study, dynamic material intensities were considered. [IEA \(2018a\)](#) distinguished five building structures in nine major regions: composite, wood, steel, masonry and concrete. While wood structures accounted for nearly 80% of the residential stock in North America, Oceania and Africa, concrete was chosen in the rest of the world. The share of concrete structures reaches nearly 60% in Europe, China, India, ASEAN and most Asian countries residential buildings, as well as in Latin America, while wood and masonry are the secondary structures. The situation is more homogeneous in the non-residential sector. A majority of the stock relies on concrete structures - ahead of steel and masonry - except in North America. Along with those market shares, [IEA \(2018a\)](#) specify regional material intensities for concrete and steel. The concrete material intensities provided by the [IEA \(2018a\)](#) exceed more than 1000 kg/m² for residential in regions with concrete as the main building material. This is in agreement with [Liu \(2010\)](#) for China, [Kleemann et al. \(2016\)](#) for the Austrian capital, [B. Müller \(2006\)](#) for the Netherlands, [Ortlepp et al. \(2016\)](#) for Germany or [Serrand et al. \(2013\)](#) for the city of Orleans. However, the values observed in the literature vary and are mainly focused on European countries, which prevents the comparison of data from the majority of regions. Tertiary material intensities of concrete are higher than residential in all regions in [IEA \(2018a\)](#). Moreover, while concrete does not exceed 20% of the residential market in North America, Oceania and Africa, its share of the tertiary market in these regions is increasing significantly. It reaches 40% in North America, 60% in Oceania, and nearly 90% in Africa. Conversely, the market shares of steel show little differences in material intensities between regions.

[IEA \(2018a\)](#) did not specify aluminum and copper consumption of the global building stock. Less data are available for those two materials than for concrete and steel in the literature. [Dong et al. \(2019\)](#) estimated dynamic residential and non-residential copper intensities from 1980 to 2050 for China. [Koutamanis et al. \(2018\)](#) compiled copper intensities in kg/capita from [Drakonakis et al. \(2007\)](#); [van Beers and Graedel \(2007\)](#); [Wittmer et al. \(2007\)](#); [Huang et al. \(2013\)](#); [Cochran et al. \(2007\)](#); [Mália et al. \(2013\)](#) and [Li et al. \(2013\)](#) for Florida, the USA, China, Korea, Norway, Switzerland, Australia, New Heaven, and Cape Town. The authors showed significant differences between buildings, even within the same perimeter and emphasize the difficulty to estimate copper intensity over large areas. [Schipper et al. \(2018\)](#) reported material intensities of copper in residential building range from 0.92 to 3.18 kg/m², and from 0.46 to 1.58 kg/m² for non-residential buildings. Copper is consumed in the building sector for wiring, air conditioning, plumbing and

roof building (Koutamanis et al., 2018). This large range of uses and their regional disparities explain the significant heterogeneity observed in the copper intensities. Residential aluminum intensity varies between 0.37 kg/m² and 0.73 kg/m² in Vienna, Austria (Kleemann et al., 2016), and between 0.6 kg/m² and 3.6 kg/m² in France depending on the type of building (ADEME et al., 2018a). Hong et al. (2016) estimated dynamic residential and commercial aluminum intensity from 2010 to 2025 in China, while Marinova et al. (2020b) and Deetman et al. (2020) provided values for both the residential and the non-residential sectors at a multi-regional scale. In order to show the link between material intensities and living standards, copper and aluminum intensities were differentiated with GDP/capita values in this study. The ten selected areas were segmented in three groups depending on their GDP/capita value in 2020. Maximum values were estimated based on the data summarized in Table 4.4. They were considered for the first group, the minimum value for the third group and an intermediate value was estimated for the second group. As described in Schipper et al. (2018), the non-residential copper intensity are half the residential values. The current regional values finally selected in this study are summarized in the Table 4.5.

References	Aluminum	Copper	Year	Area	Building type
Ortlepp et al. (2018)	1.07			Germany	Non-residential
Ortlepp et al. (2016)				Germany	Residential
Gontia et al. (2018)		3.3		Sweden	Residential
Hong et al. (2016)	2.02		2010	China	Residential
Hong et al. (2016)	2.2		2025	China	Residential
Hong et al. (2016)	4.9		2010	China	Commercial
Hong et al. (2016)	5.34		2025	China	Commercial
Marinova et al. (2020b)	2.53	0.94		Average of studies for various countries	Residential
Deetman et al. (2020)	4.2	3.2		Average of studies for mainly developed countries	Non-residential
Dong et al. (2019)		0.11	1980	China	Residential
Dong et al. (2019)		0.43	2010	China	Residential
Dong et al. (2019)		0.59	2020	China	Residential
Dong et al. (2019)		0.88	2050	China	Residential
Dong et al. (2019)		0.05	1980	China	Non-residential
Dong et al. (2019)		0.21	2010	China	Non-residential
Dong et al. (2019)		0.3	2020	China	Non-residential
Dong et al. (2019)		0.43	2050	China	Non-residential
ADEME et al. (2018a)	0.6	0.7	2020	France	Residential
ADEME et al. (2018a)	3.6	0.6	2020	France	Non-residential
Kleemann et al. (2016)	0.73	0.37	1970	Austria	Residential
Kleemann et al. (2016)	0.97	1.1	2003	Austria	Hospital
Schipper et al. (2018)		0.92-3.18		Previous studies for various countries	Residential
Schipper et al. (2018)		0.46-1.59		Previous studies for various countries	Non-residential

Table 4.4: Summary of buildings residential and non-residential materials intensities (kg/m²).

Building type	Material	North America	Europe	China	India	ASEAN	Africa	Latin America	Other Asia	Middle East	OECD Pacific
R	Concrete	400	1000	1100	1100	1100	400	1100	1100	1100	1000
	Steel	12	37	39	37	37	14	37	37	37	33
	Copper	3.2	3.2	0.6	0.3	0.6	0.3	0.6	0.6	0.6	3.2
	Aluminum	1.3	1.3	2	0.36	0.8	0.36	0.8	0.8	0.8	1.3
NR	Concrete	900	1200	1500	1200	1400	1400	1400	1300	1300	1300
	Steel	70	72	71	68	76	71	74	68	68	69
	Copper	1.6	1.6	0.3	0.15	0.3	0.15	0.3	0.3	0.3	1.6
	Aluminum	4.2	4.2	4.2	1.2	2.7	1.2	2.7	2.7	2.7	4.2

Table 4.5: Summary of the current residential and non-residential material intensities considered in this study in kg/m². R = Residential, NR = Non-Residential.

Dynamic materials intensities were then modeled using a logistic function depending on GDP (eq 4.2.3). An initial value of 120 kg/m² was assumed for concrete in 1900, in accordance to values observed in [B. Müller \(2006\)](#); [Ortlepp et al. \(2016\)](#) and [Gontia et al. \(2018\)](#). Initial values of 0.05 kg/m² were considered for aluminum and copper, and 2 kg/m² and 10 kg/m² for residential and non-residential steel in 1900. A better knowledge of past steel, copper and aluminum intensities are needed to design their evolution over time. The saturation levels considered are slightly higher than the current values of Europe for concrete, with 1,200 kg/m² for residential buildings in 2100. A renewal of residual non-concrete buildings was assumed, and a small increase of concrete market share in North America. Given the lack of data, the same level than in the North America was considered in Africa for residential concrete intensity. Other materials were assumed as less structural for building, and thus higher saturation levels are observed. The same saturation levels were considered for the nine selected areas.

$$I_t = \frac{I_{sat}}{1 + \frac{I_{sat}}{I_{1900}} \cdot \exp(-\beta(GDP_t - GDP_{1900}))} \quad (4.2.3)$$

In this equation, I_t is the material intensity in the year t , I_{sat} and I_{1900} are respectively the saturation level and the 1900 value of the material intensity, β is a parameter influencing the growth rate, GDP_t is the GDP value in the year t and GDP_{1900} is the 1900 value of GDP. The final results are displayed in Figures 4.6a to 4.6d for regional residential buildings, in Figures 4.7a to 4.7d for regional non-residential buildings. A higher steep of material intensities is observed for residential copper and non-residential aluminum. It lies in the assumption of almost no demand in 1900 and in the larger saturation values.

This study considers material flows for thermal renovation in addition to the construction related flows. The French data from [ADEME et al. \(2018b\)](#) are depicted thereafter, and are considered at the global scale due to the lack of data. This assumption covers high uncertainties, since various types of renovations could be implemented depending on the area. The implemented renovations in [ADEME et al. \(2018b\)](#) are insulation of exterior walls, floors, roofs, and replacement of doors, windows and closures. Along with the addition of material related to housing renovation, there is a high production of waste. Indeed, materials are removed upstream of the renovation process, while others are lost in the installation scraps ([ADEME et al., 2018b](#)). An average material intensity of the waste outputs was evaluated from the total mass of waste and the total surface area renovated until 2050. A balancing of the individual and collective share in the residential stocks was assumed ([ADEME, 2017](#)). The intermediate values of the "volontaire" scenario were considered, and the results are summarized in the Table 4.6.

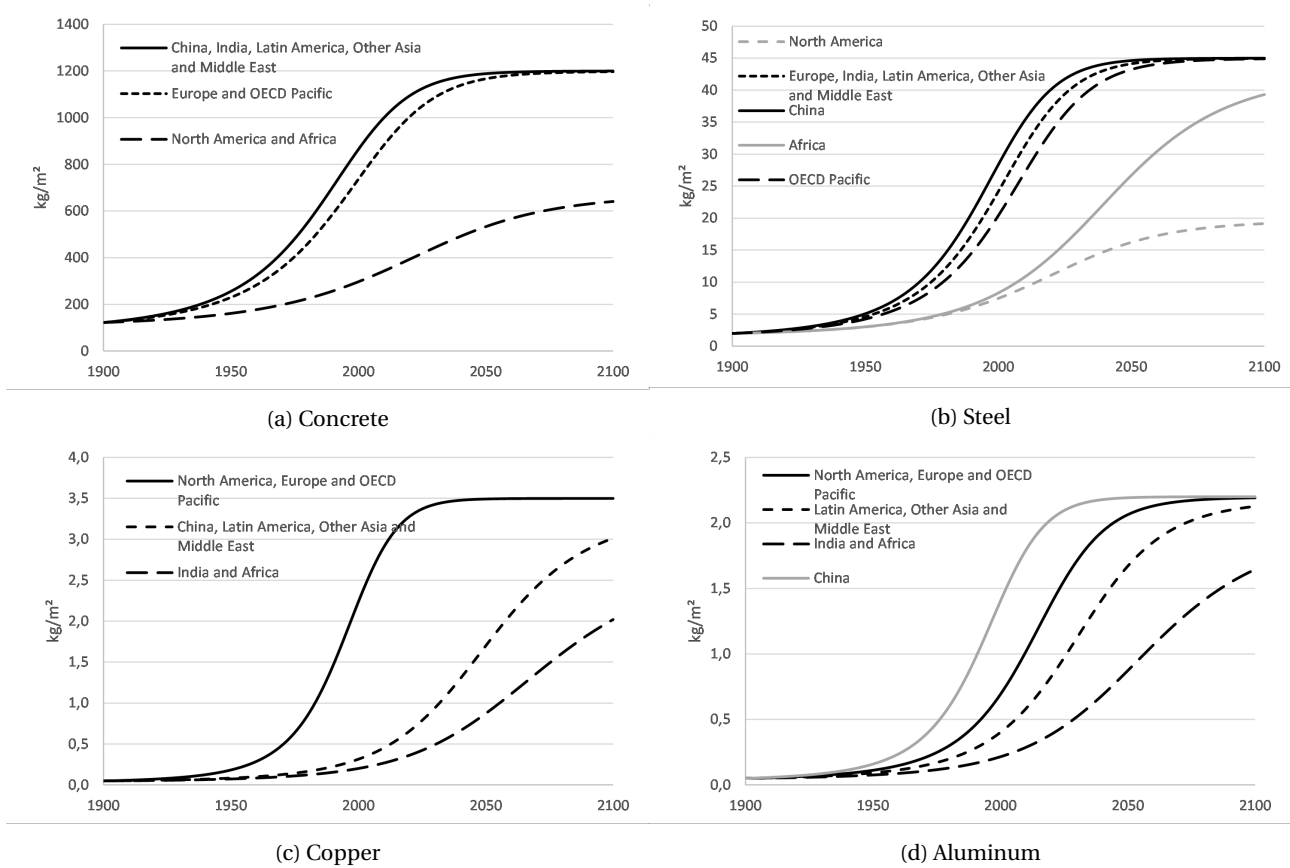


Figure 4.6: Dynamic and regional material intensities in concrete, steel, copper and aluminum in the residential building sector.

Renovation process	Aluminum	Concrete	Steel
Inflow	0.75	0.69	0.88
Waste outflow	0.003	0.47	0.016

Table 4.6: Materials intensities of renovation. The inflows and outflows per square meter of renovated floor area (kg/m^2).

Recycled aggregates concrete (RAC)

As described in the section S1.2, two types of recycled aggregates from construction and demolition waste (CDW) are considered: recycled aggregates (RA) and recycled concrete aggregates (RCA). The different applications of RA are described in [Reis et al. \(2021\)](#), and the authors outlined the growing number of encouraging pilot projects using recycled aggregate concrete (RAC). [Silva et al. \(2019\)](#) further provided a review of 31 constructions projects to demonstrate the technical and economic viability of recycled aggregates use. Among these projects, 11 are related to structural use of concrete in buildings. They carry substantial benefits through four reductions : financial, primary resources need, accumulation in landfills and environmental impacts. The RAC research field has been growing over the past years, and the specific impact of replacing natural aggregates by recycled concrete aggregates (RCA) on the properties of RAC was under focus. RCA is defined as aggregates recovered from concrete in which other materials represent less than few percents ([Marinković and Carević, 2019](#)), and it can be used for higher strength concrete than RA ([Purnell and Dunster, 2010](#)). However, [Behera et al. \(2014\)](#) showed lower mechanical and durability performance of RAC, and emphasized the need of further assessment of RA quality and its impact on concrete. In reviews on the RCA impacts on RAC production, [Silva et al. \(2014\)](#) and [Verian et al. \(2018\)](#) provided recommendations for an optimal use of recycled concrete aggregates (RCA) in concrete production. The authors showed different challenges depending on the

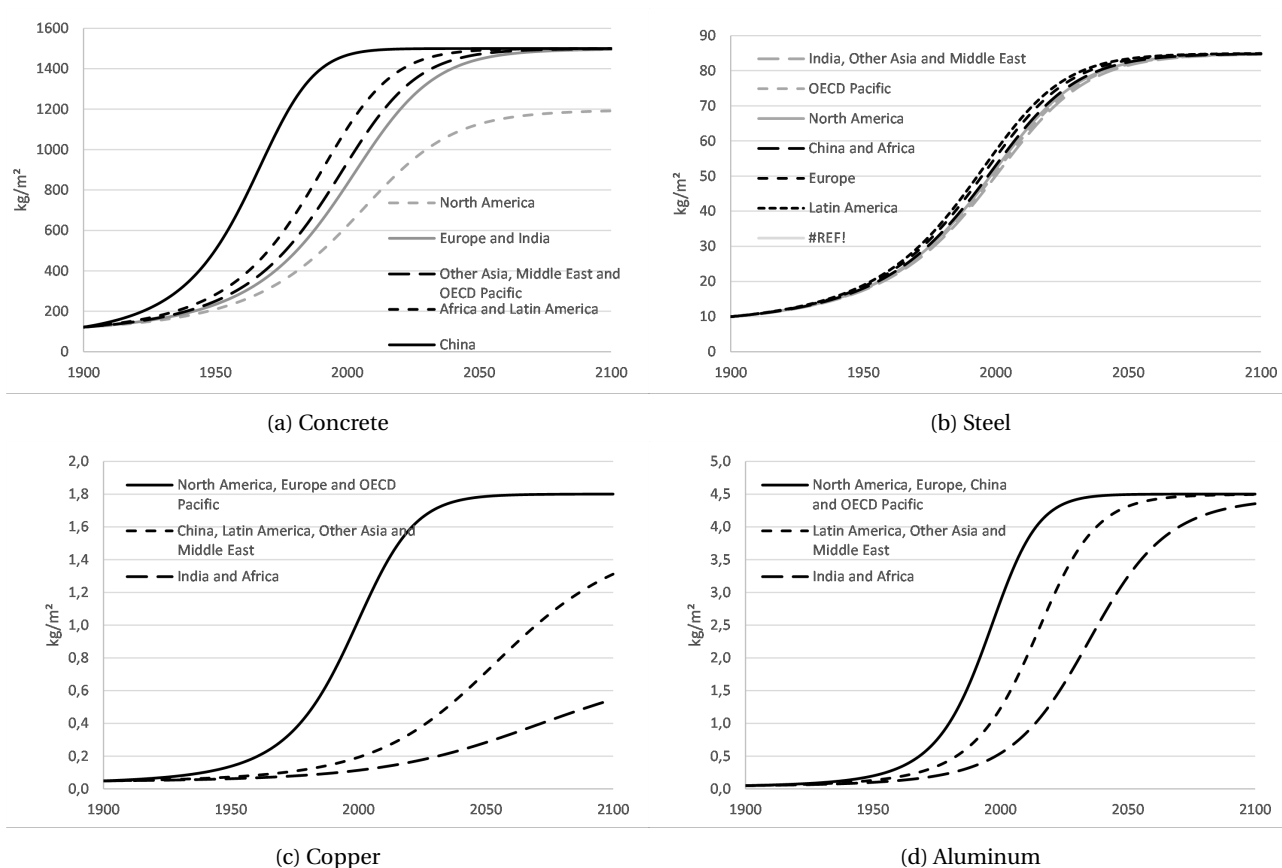


Figure 4.7: Dynamic and regional material intensities in concrete, steel, copper and aluminum in the non-residential building sector.

use of fine and coarse aggregates¹⁸, but a potential was identified for both types. The authors further reported that some researches estimate a 30% limit in the use of coarse RCA in concrete, but state that there could be no limit in its potential share if specific process conditions are respected¹⁹. Thomas et al. (2013) further outlined the need for more assessment of RAC in different exposure conditions. For moderate conditions, Thomas et al. (2018) estimated that a 25% replacement of NA by RCA displays viable strength results. Guo et al. (2018) and Verian et al. (2018) further identified the potential to enhance recycled aggregate concrete performances, using for example CO₂ treatment and pozzolanic materials (e.g. fly ash).

RCA replacement scenarios methodology

A significant increase in the EOL-CR of CDW was observed over the past decade in Europe (Villoria Sáez and Osmani, 2019). However, most of other regions display lower rates (Tam et al., 2018; Reis et al., 2021), and most of the CDW are disposed in landfills. The concrete lost stock amounted to about 45 Gt in 2020. The recycling of the accumulated concrete in landfills would allow to decrease the dependency on primary mineral production and a reduction of the storage burden. To provide a first-order estimate of the impact of a mass use of RCA replacement in concrete production on lost stock reduction, a methodology was developed and computed on the building stock of the IEA (2017) scenarios. It is based in the following assumptions :

1. No RCA replacement is observed at large scales until 2025;
2. It was assumed that both fine and coarse natural aggregates could be replaced by their related recycled aggregates;
3. The potential shares of RCA in RAC described in Verian et al. (2018); Tam et al. (2018) and Thomas et al. (2018)

¹⁸Bravo et al. (2015) found that fine aggregates use hampers concrete performance, but that a limited share of coarse aggregates is viable. This higher impact of fine RCA was also highlighted in Guo et al. (2018).

¹⁹Coarse and fine aggregates are defined by the size of their particles.

were used to develop a business-as-usual case and four scenarios of RCA replacement (Figure 4.8) :

- Business-as-usual case : 0% of RCA replacement from 2025 to 2060
 - Replacement scenario 1 (RS1) : progressive increase from 0% in 2025 to 20% of RCA replacement in 2060
 - Replacement scenario 2 (RS2) : progressive increase from 0% in 2025 to 50% of RCA replacement in 2060
 - Replacement scenario 3 (RS3) : progressive increase from 0% in 2025 to 20% of RCA replacement in 2040
4. A share of 60% to 75% of aggregates in concrete was considered²⁰.
5. Most of the current annual recovered flow annual of concrete is used in non-structural applications and the quality of the remaining wastes is unknown. It was assumed that RCA will be recovered from the concrete lost stock. However, RCA represent a small share of CDW, as most of the wastes are RA (Purnell and Dunster, 2010), but no estimation of the global overall share of RCA in CDW is available to the author's knowledge. Further estimations of RCA share in CDW will allow to calibrate the potential share of concrete inflow on which scenarios can be applied.
6. The scenarios of RCA replacement are considered on 20%, 50% and 100% of the concrete inflow to exhibit the limited geographical scale of RCA replacement in landfills.

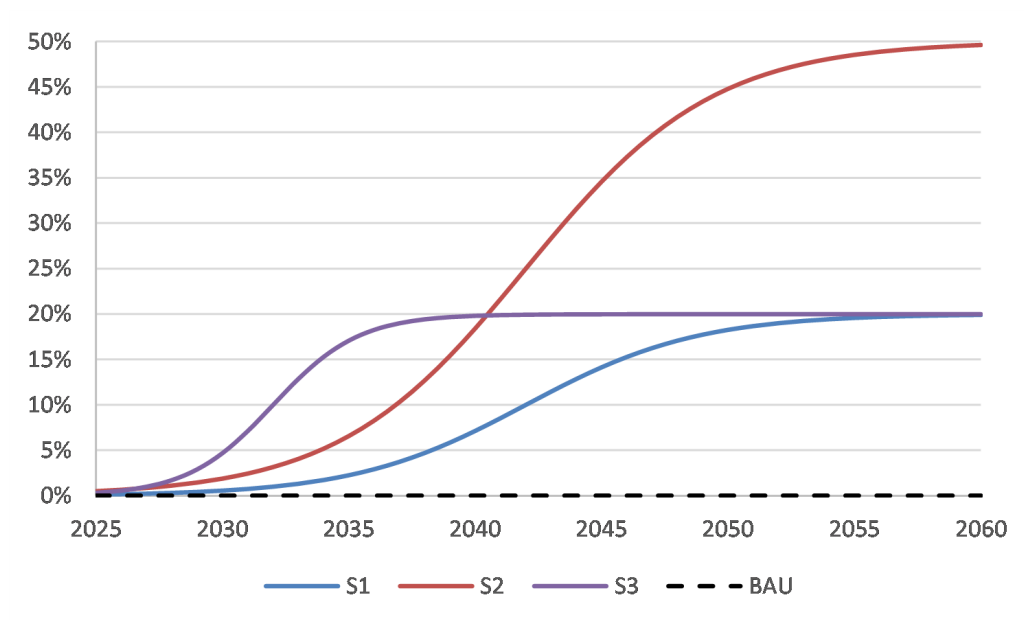


Figure 4.8: RCA replacement shares in the BAU case and the three replacement scenarios considered.

"Green" concrete

Fly ash generation

Coal combustion products (CCP) are the residues produced during the combustion of coal to generate electricity. They include fly ash, bottom ash, boiler slag and flue gas desulfurization materials (Kelly and Matos, 2017). Coal fly ash (CFA) represents most of the residues, and is mainly recycled to produce concrete (Luo et al., 2021; Marinina et al., 2021). Given that CFA is produced during with power generation, most countries display ash dumps and CFA is recycled for a local use. Marinina et al. (2021) reported various rate of use of the generated fly ash among countries, ranging from 10% in Russia and Africa to more than 90% in France, Japan, Germany and the UK. The future use of CFA to decrease concrete environmental impacts depends on national energy policies. A gradual shift from fossil fuels to renewable in the electricity mix will directly impact fly ash generation. CFA generation assessment in energy transition scenarios could therefore provide insights in the future viability of using CFA to decrease concrete environmental impacts. In this section, an estimation of CFA production is provided until to 2060 in the B2D and RT scenarios. It

²⁰The Portland Cement Association reports a rate of aggregates in concrete ranging from 60% to 75%.

relies on :

- Historical fly ash generation data for China (Luo et al., 2021), India (Bhawan and Puram, 2020), the USA (Kelly and Matos, 2017; AACA, 2016, 2017, 2018, 2019) and the UK (UKQAA, 2016);
- Historical coal demand (BP, 2021);
- Regional or global coal demand assumptions in the B2D and RT scenarios.

Historical fly ash generation intensity was firstly evaluated for the selected areas. They provide evolution of the CFA produced per coal consumed. The countries display values ranging from about 2.5 Mt/EJ for the USA to more than 11 Mt/EJ for India, and a stabilization of their values are observed since 2005. Given that 72% of coal was consumed by those countries in 2020 (Figure 4.9), these intensities allow to depict most of the global fly ash generation. The projected CFA generation was then estimated based on the evolution of coal demand in the B2D and RT scenarios (IEA, 2020b, 2021d) and constant future intensities were assumed until 2050. Their selected values are :

- 11 Mt/EJ for India;
- 6 Mt/EJ for China;
- 4 Mt/EJ for the UK;
- 2.5 Mt/EJ for the USA;
- 7 Mt/EJ for the rest of the world. This value was calibrated using the CFA production in 2016 reported in Jin et al. (2021).

The estimated CFA production between 2010 and 2050 is displayed in Figure 4.11. It shows a stabilization of CFA generation at about 1,150 Mt between 2010 and 2060 in the RTS. The reduction of coal demand in the B2DS substantially impact the CFA production. It drops to 530 Mt in 2030, and finally 250 Mt in 2060. At a regional level, the results are displayed in Figure 4.13 for China, Figure 4.14 for India and Figure 4.12 for the USA between 2002 and 2060 in the RT and B2D scenario. A significant increase of the fly ash production is observed between 2002 and 2020 in China. It raised from 180 Mt to 580 Mt, and then experiences a reduction to 370 Mt in 2060 in the RT scenario, and 90 Mt in the B2DS. An almost monotonous rise from 83 Mt in 2002 to 490 Mt in 2060 is showed for India in the RT scenario, while it decreases to 60 Mt in 2060 in the B2D scenario. The USA production decreases from 69 Mt in 2002 to 30 Mt in 2060 in the RT scenario, and drops to 7 Mt in 2060 in the B2D scenario (Figure 4.11). The utilization rate of CFA reached more than 66% in China in 2015 (Luo et al., 2021), 54% in the USA (Kelly and Matos, 2017) and 56% in India (Bhawan and Puram, 2020). Globally, this rate was only 25% in the early 2000s (Iyer and Scott, 2001), and experienced a growth to 60% in 2016 (Jin et al., 2021). Based on this evolution, a global utilization rate was estimated between 2002 and 2019 (Figure 4.15). Finally, the accumulation of unused CFA was calculated between 2002 and 2019 (Figure 4.16), and the initial lost stock in 2002 is unknown. It was found that the accumulated fly ash in landfills increased by 9.2 Gt between 2002 and 2019, which represents 15.5 years of current use, with strong regional disparities. The additional stock reached 2.8 Gt in China during the period, 1.1 Gt in India, 0.5 Gt in the USA and 4.8 Gt in the rest of the world (Figure 4.16). In the perspective of a progressive decrease in coal consumption, these stocks could become valuable reserves. They could provide materials to the industries many years after the shutdown of coal-fired power plants. Given that the CFA intensities are based on a stabilization assumption, the results carry high uncertainties. Moreover, lower values were observed in the past²¹ and no reliable retrospective CFA generations can be estimated from the intensities.

²¹The coal ash production in 1992 by country is provided Manz (1997)

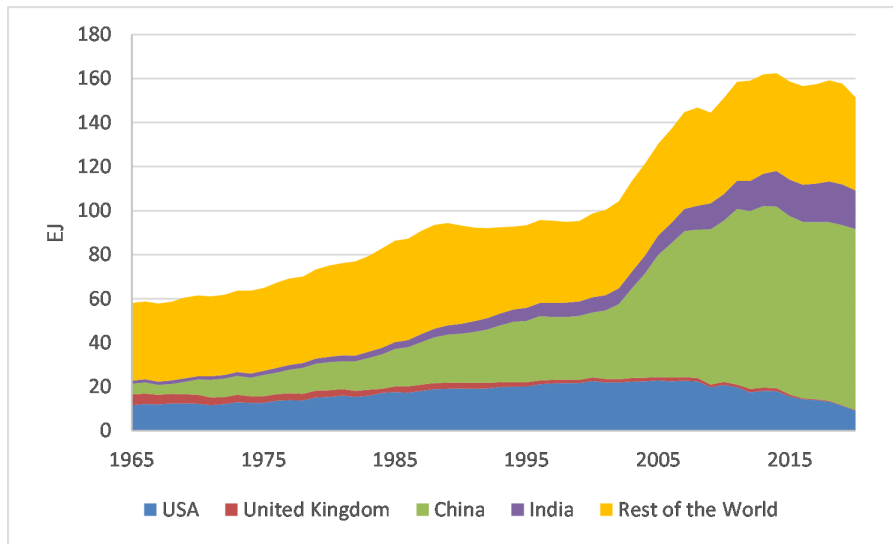


Figure 4.9: Historical coal consumption (BP, 2021)

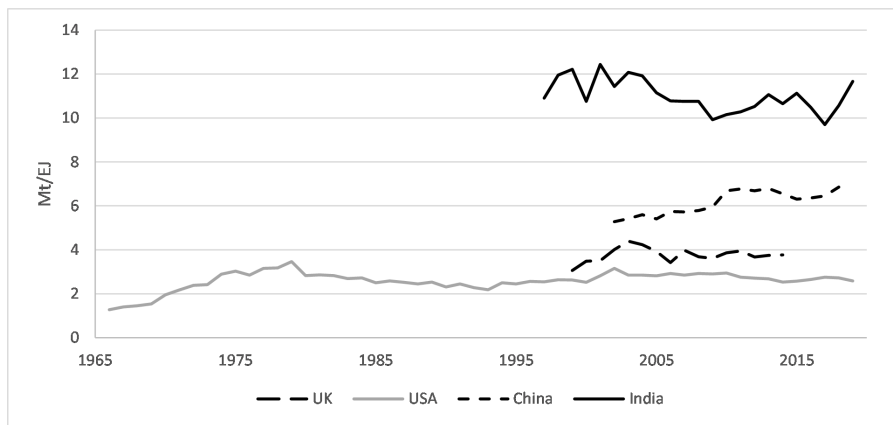


Figure 4.10: Historical regional coal fly ash generation per EJ of coal consumed. Estimated from (UKQAA, 2016; Luo et al., 2021; Kelly and Matos, 2017; AACA, 2017, 2018, 2019; Bhawan and Puram, 2020) and (BP, 2021).

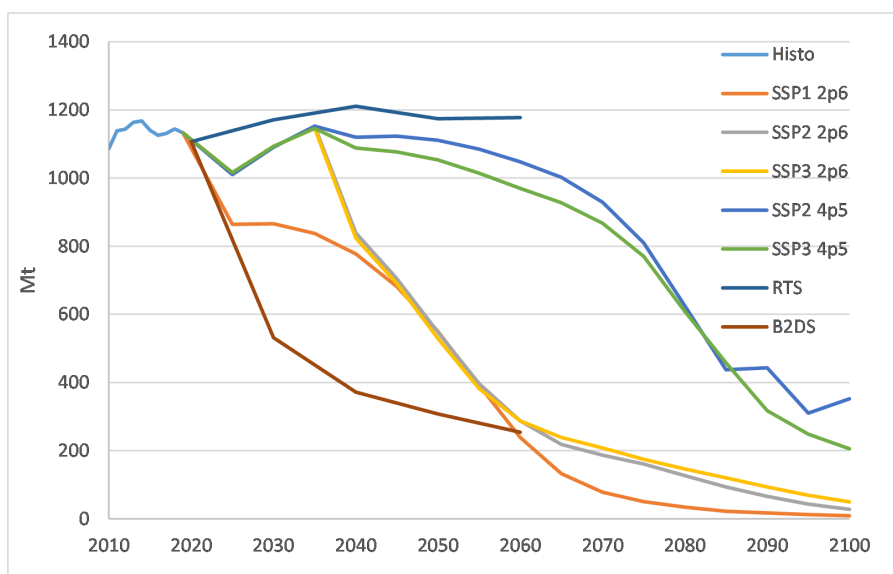


Figure 4.11: CFA production between 2010 and 2100. Estimated historical global data are displayed between 2010 and 2019 and prospective results are showed for the SSPs and the RTS and B2DS between 2020 and 2100 (or 2060 for the RTS and B2DS).

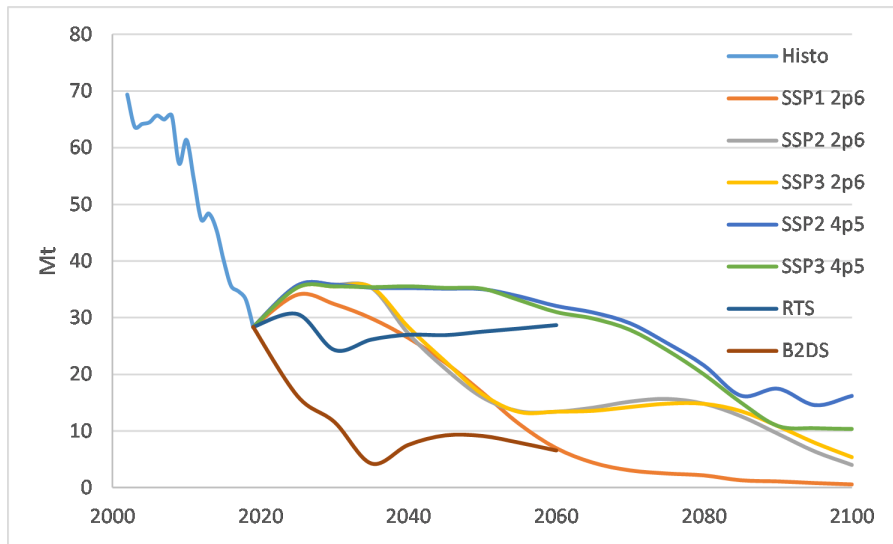


Figure 4.12: Estimated CFA production in the USA between 2002 and 2100. Historical data are displayed between 2002 and 2015, estimated historical data are depicted between 2016 and 2019, and modeled data are shown between 2020 and 2100.

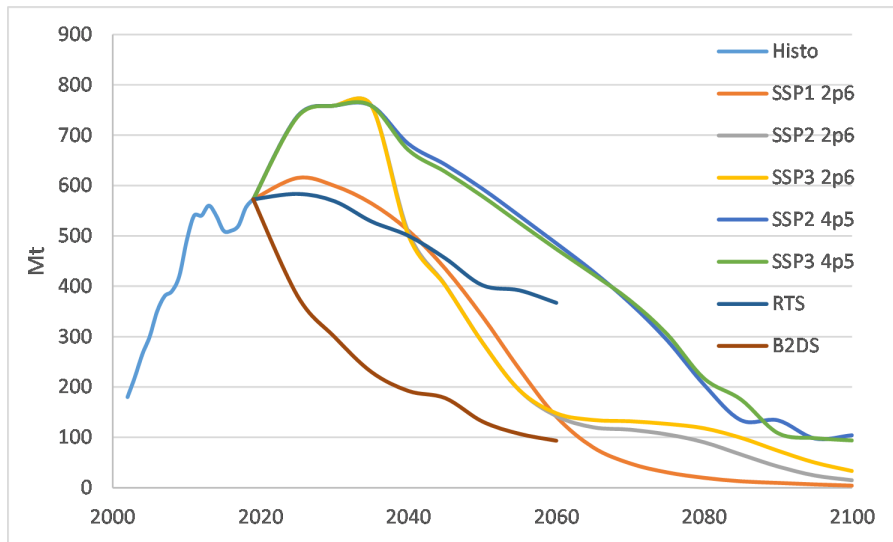


Figure 4.13: Estimated CFA production in China between 2002 and 2100. Historical data are displayed between 2002 and 2015 for the USA, estimated historical data are depicted in 2019 and 2019 and modeled data are shown between 2020 and 2100.

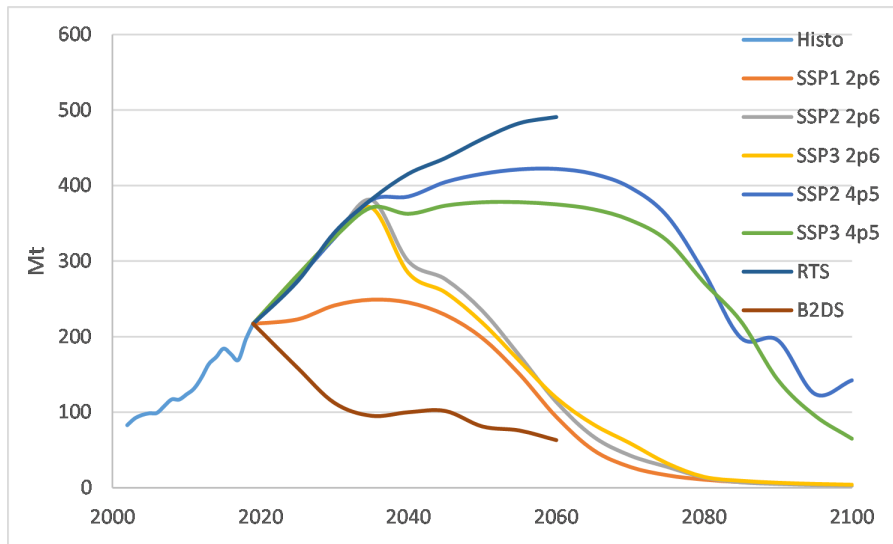


Figure 4.14: Estimated CFA production in India between 2002 and 2019. Historical data are displayed between 2002 and 2019 for India, estimated historical data are depicted in 2019 for India and modeled data are showed between 2021 and 2100.

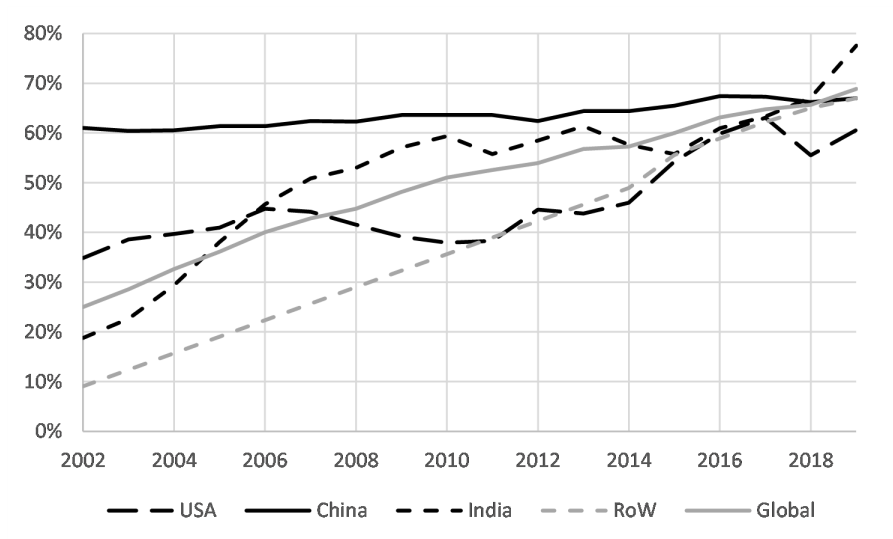


Figure 4.15: Historical utilization rate in China, India and the USA, and estimated values at the global level and for the rest of the world.

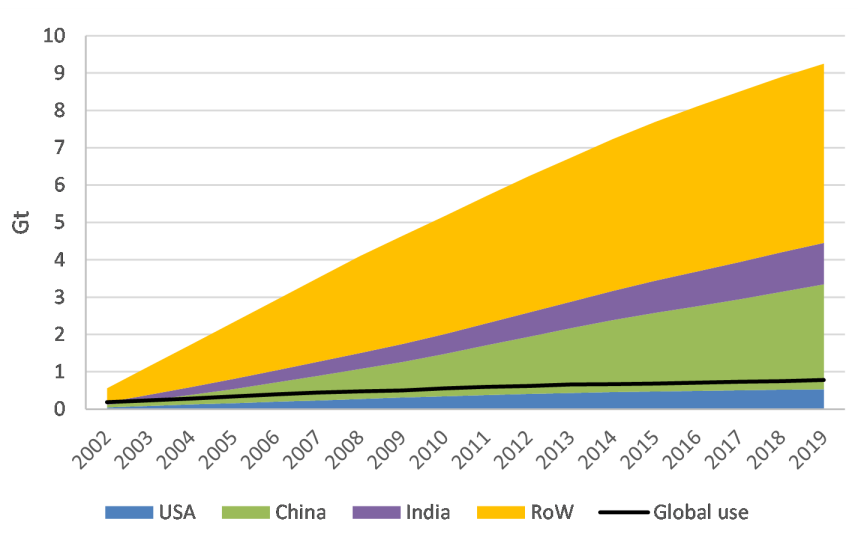


Figure 4.16: Estimated global additional stock of unused coal fly ash between 2002 and 2019.

"Green" concrete composition

Three studies were considered to compute the energy and environmental effects of using by-products and/or recycled materials in concrete. The resulting materials is referred to as "green" concrete. Two types of replacements are considered in the studies :

- Replacement of natural aggregates, by various (fine and coarse) recycled concrete aggregates (RCA), fine RCA, coarse RCA or Electric Arc Furnace Steel Slag (EAFSS);
- Replacement of Ordinary Portland cement, by coal fly ash (CFA) or blast furnace slag (BFS).

Flower and Sanjayan (2007) considered CFA and BFS replacement, and found potential CO₂ emissions reduction by 22% for BFS and 13% to 15% for CFA. Turk et al. (2015) analysed natural aggregate replacement by EAFSS, cement replacement by CFA, and combined EAFSS or CFA with RCA. The results display higher reductions for CFA replacement than for EAFSS, and a positive impact of an additional RCA use. Kurda et al. (2018) analyzed a large panel of single and combined replacements of fine RCA, coarse RCA and CFA (and additional superplasticizer not considered in this study). The authors showed significant reduction potential of CFA and a higher reduction when combined with coarse RCA than with fine RCA. The emissions decrease could reach 60% with a replacement CFA of 60% combined with a 100% coarse replacement. The results of the three studies are displayed in Table 4.7.

References	Concrete mix						Impact and potential reduction				
	Various RCA	Fine RCA	Coarse RCA	CFA	BFS	EAFSS	Production energy (MJ/t)	CO ₂ em. (kgCO ₂ /t)	Energy reduction	Emissions reduction	
Kurda et al. (2018)							1,950	362			
		50%					1,940	361	0.5%	0.3%	
		100%					1,940	360	0.5%	0.6%	
				30%			1,580	269	19%	26%	
		50%		30%			1,570	268	19%	26%	
		100%		30%			1,560	267	20%	26%	
				60%			1,210	176	38%	51%	
		50%		60%			1,190	174	39%	52%	
		100%		60%			1,190	174	39%	52%	
			100%				1,530	331	22%	8.6%	
		50%	100%				1,530	331	22%	8.6%	
		100%	100%				1,530	330	22%	8.8%	
				100%	30%		1,160	330	41%	34%	
		50%	100%	30%			1,150	238	41%	34%	
		100%	100%	30%			1,150	237	41%	35%	
	Turk et al. (2015)							1,690	260		
					25%			1,300	195	23%	25%
						5.6%	1,400	250	17%	4%	
		30%		25%			1,150	190	32%	27%	
		28%				5.6%	1,230	242	27%	7%	
Flower and Sanjayan (2007)							290-322				
				25%			253-273		13-15%		
					40%		225-251		22%		

Table 4.7: Energy and environmental impacts of various concrete mixes. RCA = Recycled Concrete Aggregates, CFA = Coal Fly Ash, BFS = Blast Furnace Slag and EAFSS = Electric Arc Furnace Steel Slag.

The energy and environmental impact of an increase of "green" concretes based on CFA, BFS and combined CFA and coarse RCA was computed in the B2D and RT scenario. The traditional concrete considered in Kurda et al. (2018) was used (Table 4.8)²². Four "green" concretes were computed (Table 4.9) and used in 20%, 50% and 100% of concrete demand.

Materials	Fine aggregates	Coarse aggregates	Cement	Water	Total
	763	1,060	350	186	2,359

Table 4.8: Traditional concrete mix materials in kg for 1 m³ (Kurda et al., 2018)

²²A modification of a material used in a concrete mix display side effect on other contents (Kurda et al., 2018). For example, the fine aggregates composition of a concrete mix changes when CFA is used. In this study, no side effects are considered.

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 4.9: Considered replacements in "green" concretes.

4.2.3 Further results

Regional materials stocks and flows

The regional materials stocks and flows results are displayed in this section for the selected scenarios.

SSPI

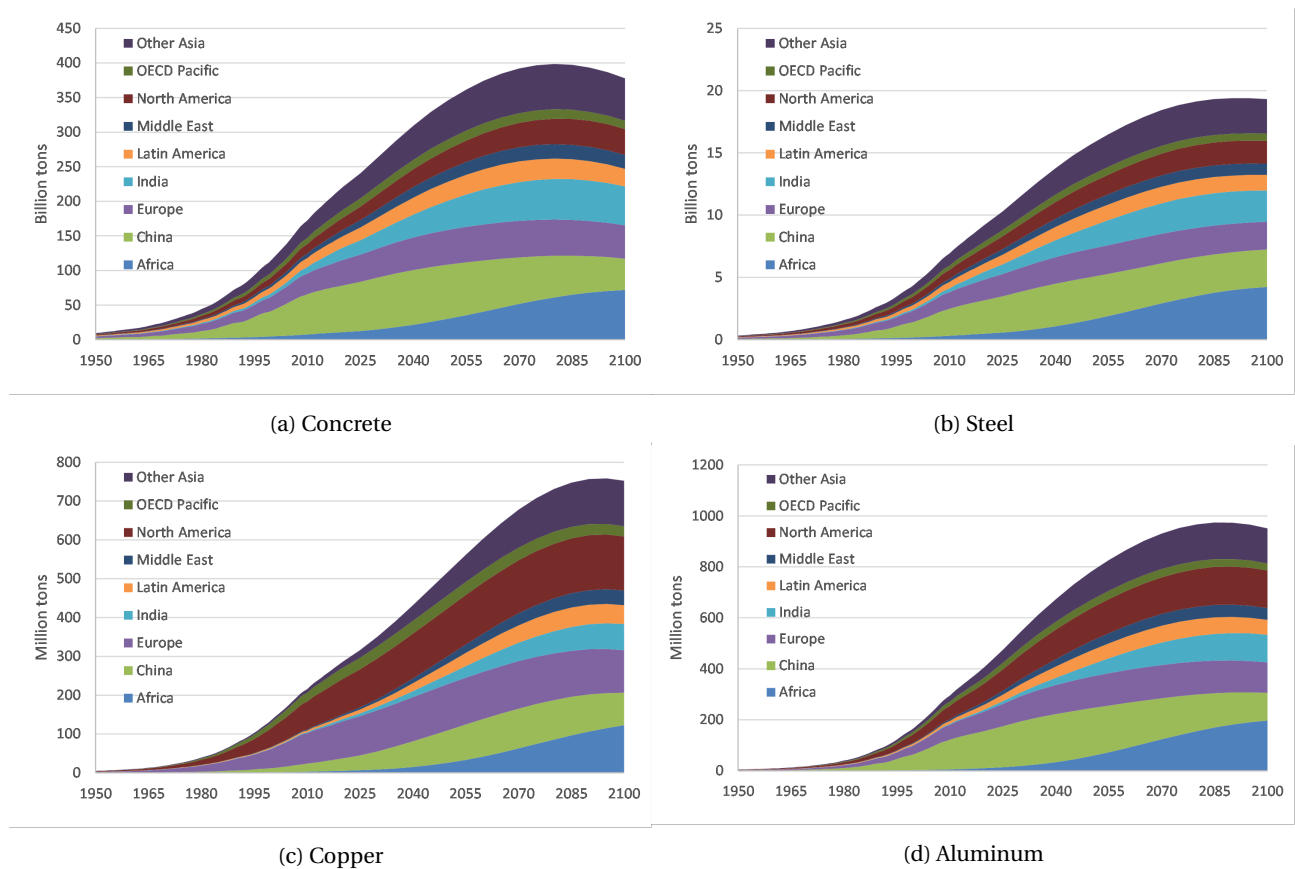


Figure 4.17: Regional in-use stocks of concrete, steel, copper and aluminum in the SSP1. The residential and non-residential segments are aggregated.

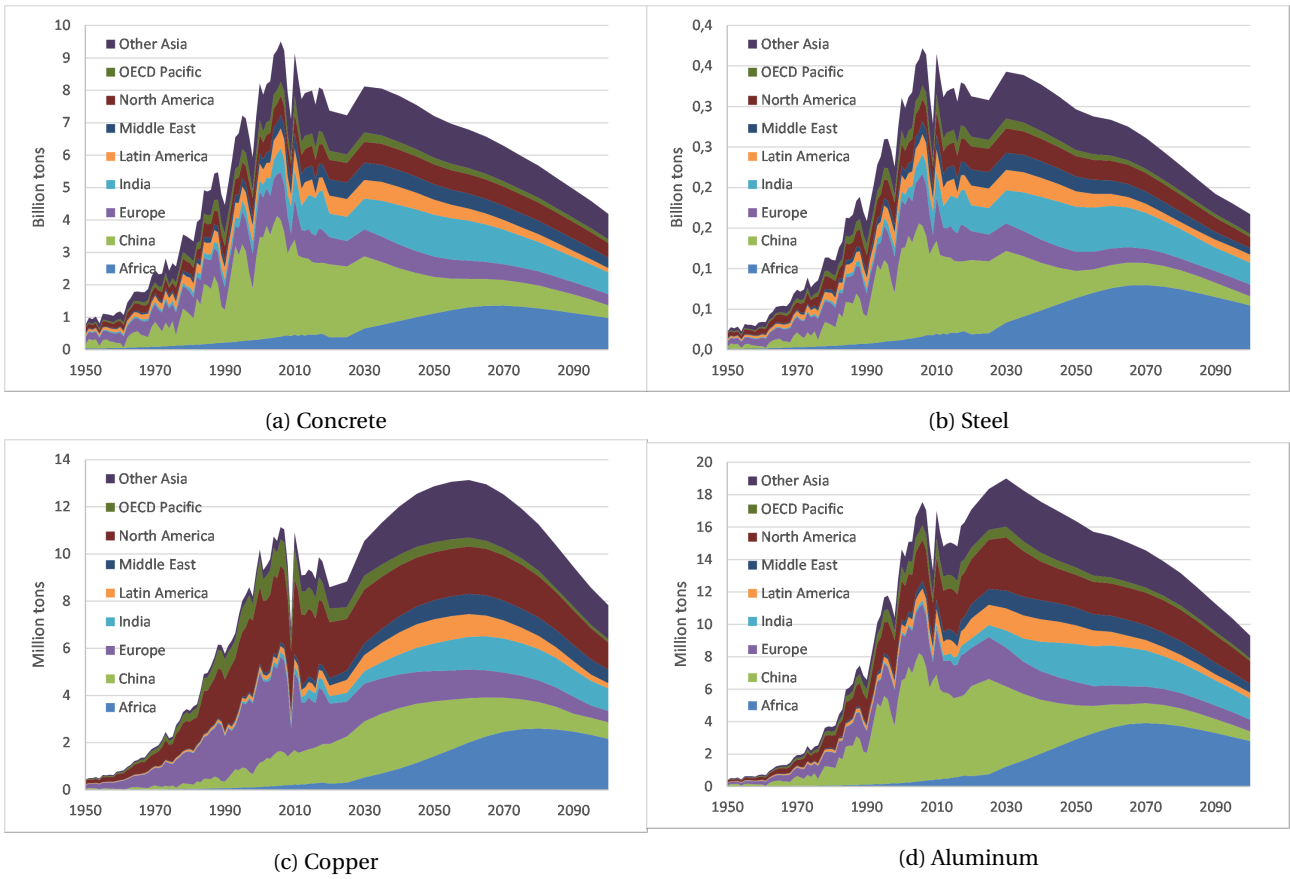


Figure 4.18: Regional inflows of concrete, steel, copper and aluminum in the SSP1. The residential and non-residential segments are aggregated.

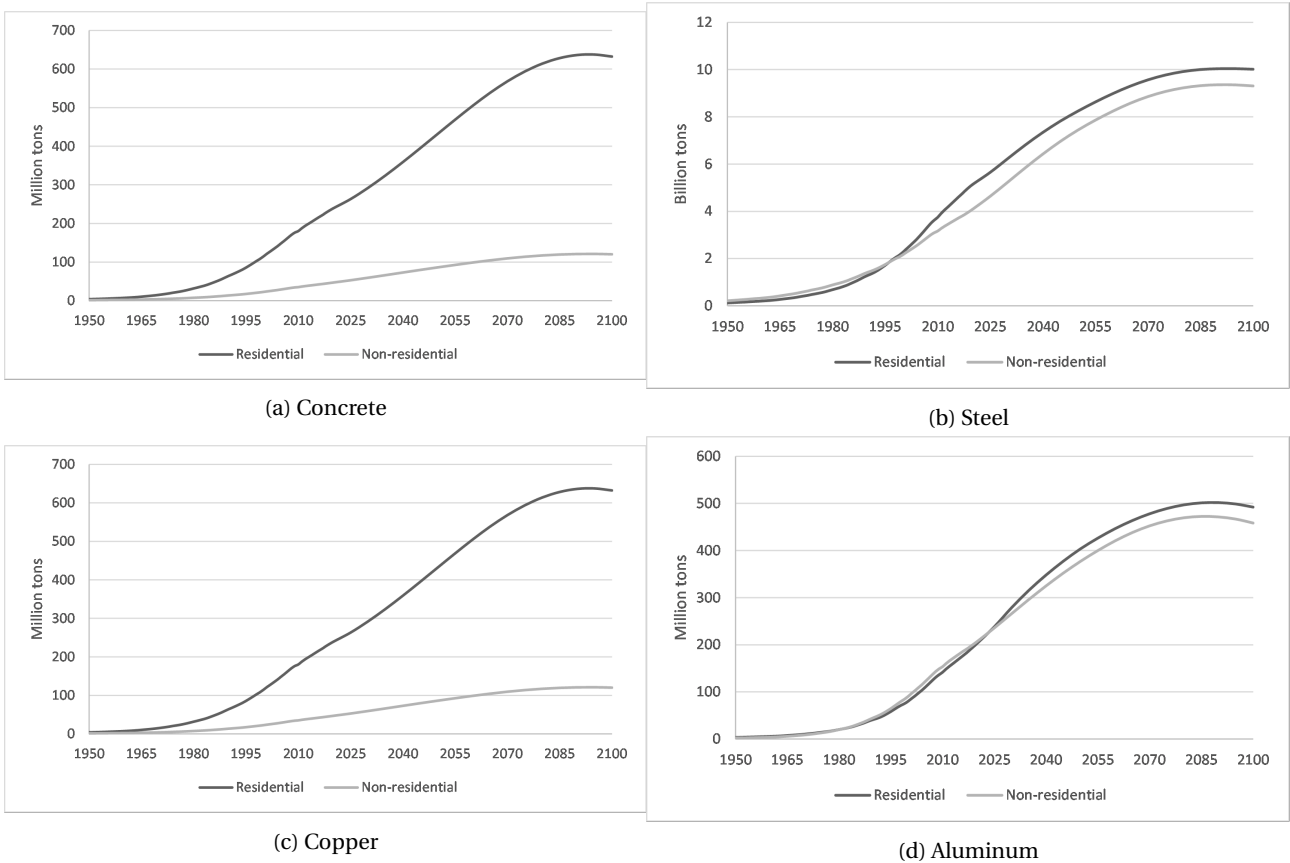


Figure 4.19: Global stocks of concrete, steel, copper and aluminum in the residential and non-residential segments in the SSP1.

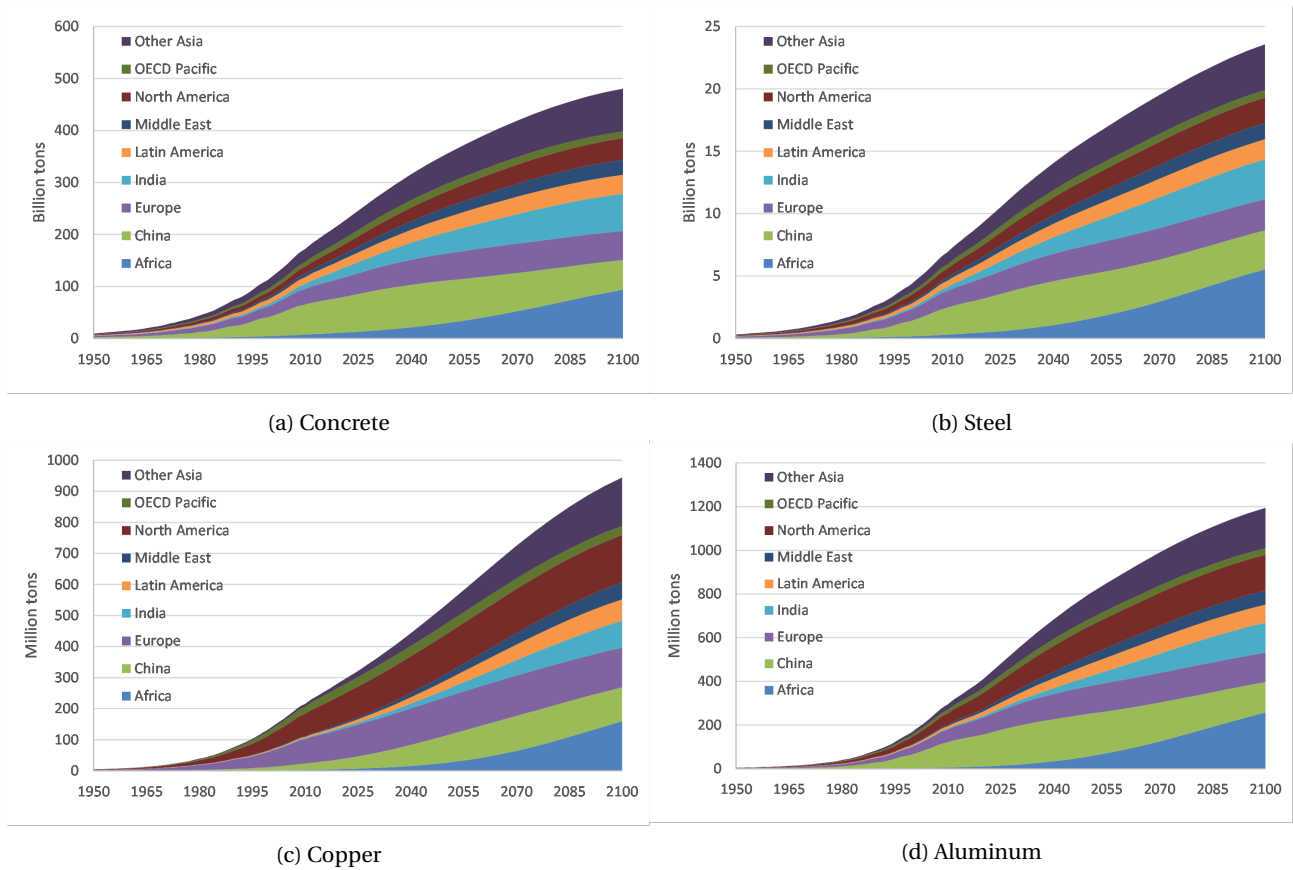
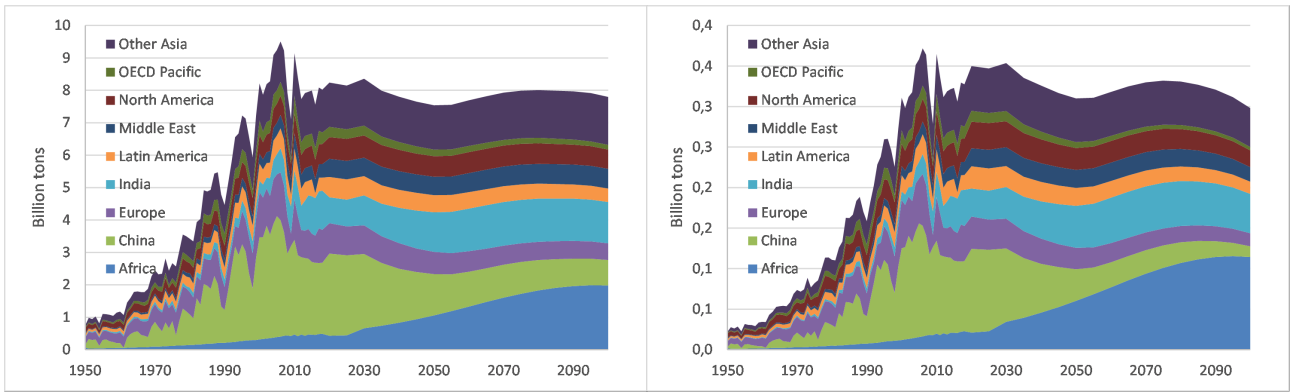
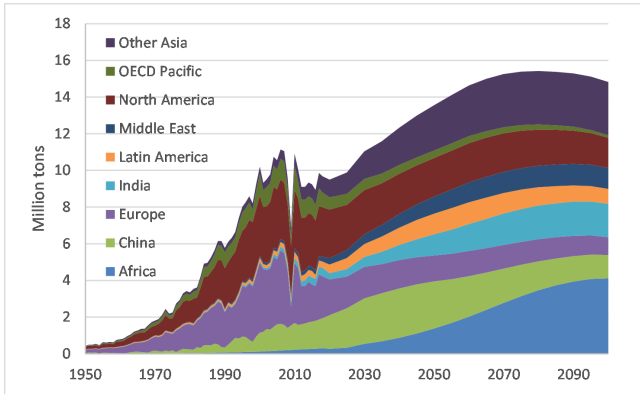


Figure 4.20: Regional in-use stocks of concrete, steel, copper and aluminum in the SSP2. The residential and non-residential segments are aggregated.

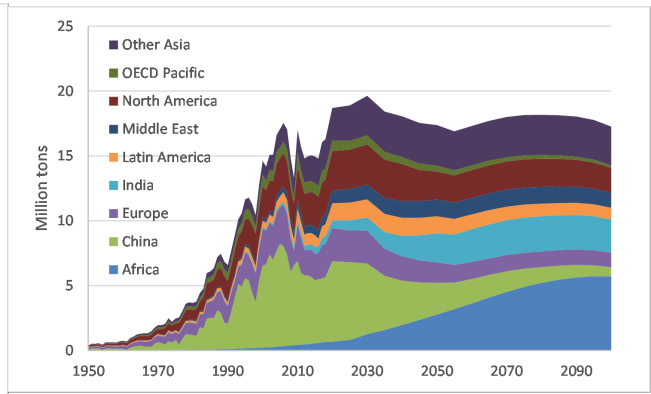


(a) Concrete

(b) Steel

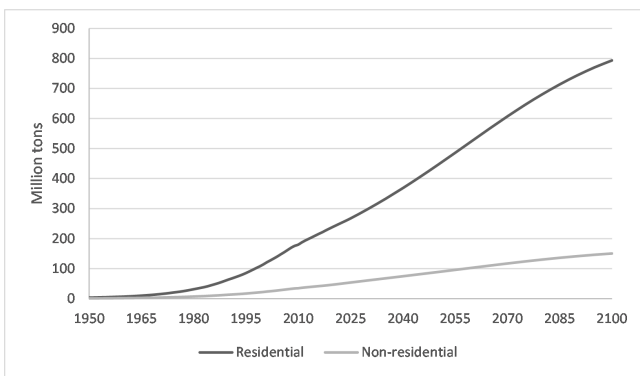


(c) Copper

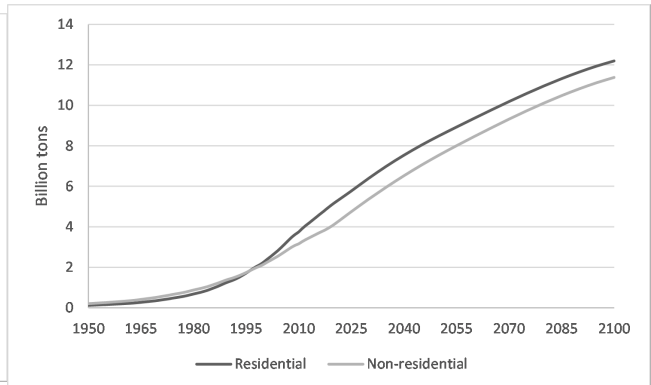


(d) Aluminum

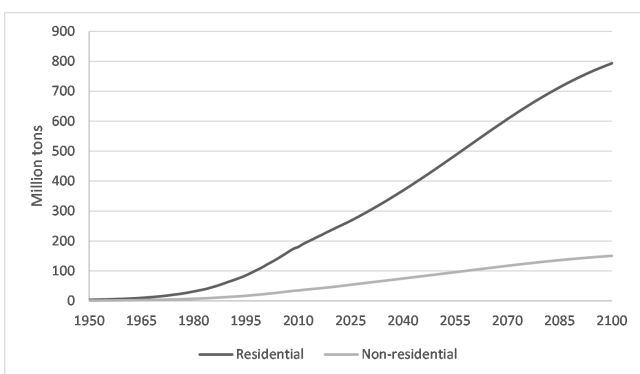
Figure 4.21: Regional inflows of concrete, steel, copper and aluminum in the SSP2. The residential and non-residential segments are aggregated.



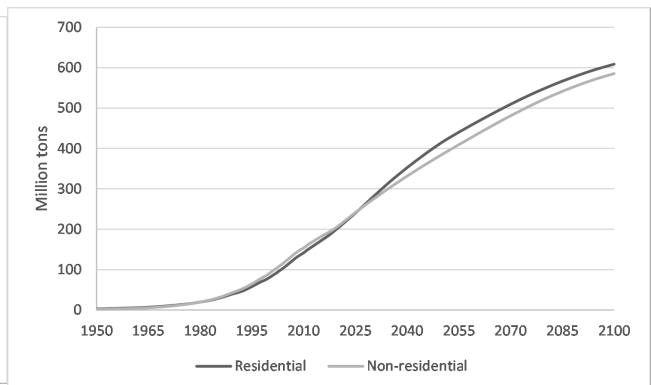
(a) Concrete



(b) Steel



(c) Copper



(d) Aluminum

Figure 4.22: Global stocks of concrete, steel, copper and aluminum in the residential and non-residential segments in the SSP2.

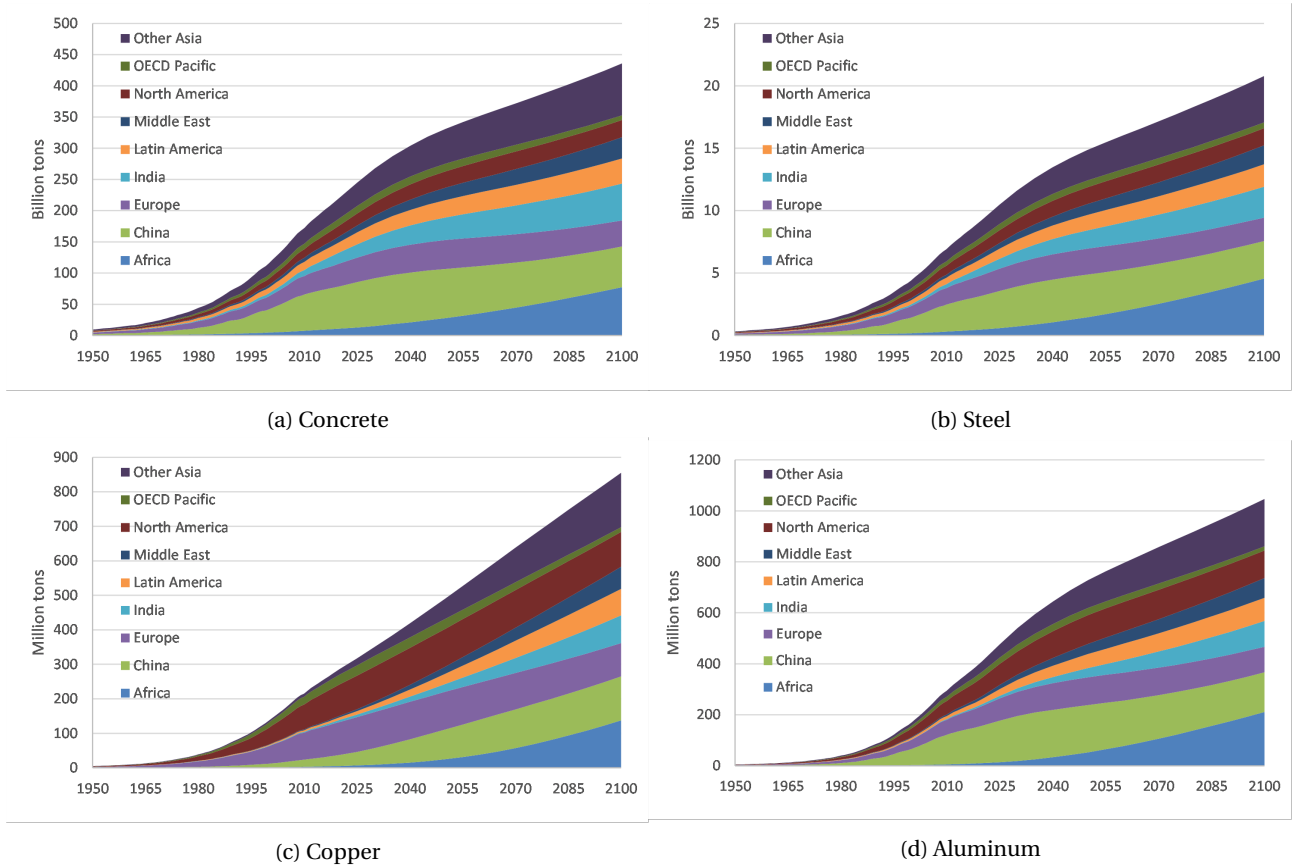
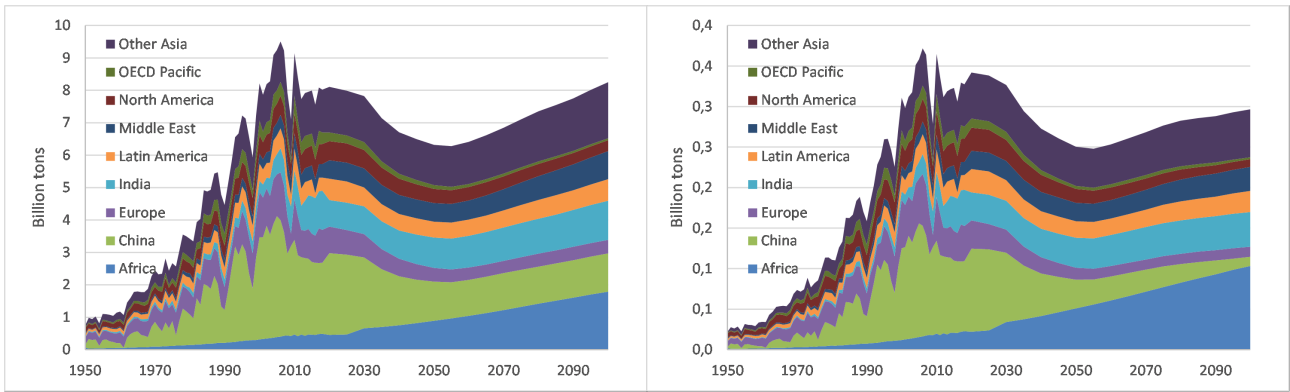
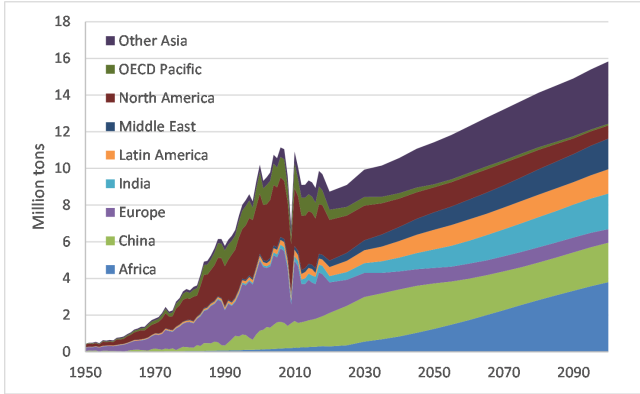


Figure 4.23: Regional in-use stocks of concrete, steel, copper and aluminum in the SSP3. The residential and non-residential segments are aggregated.

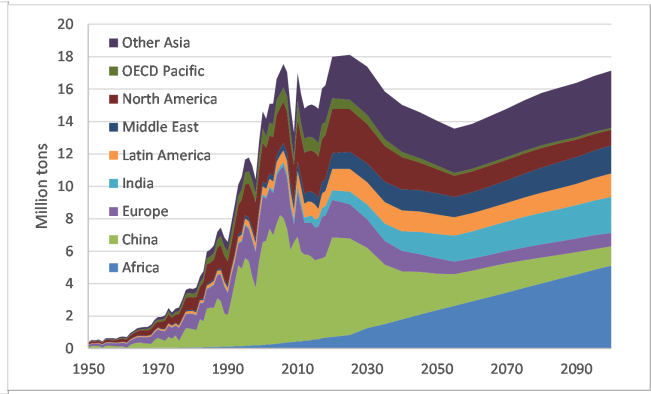


(a) Concrete

(b) Steel

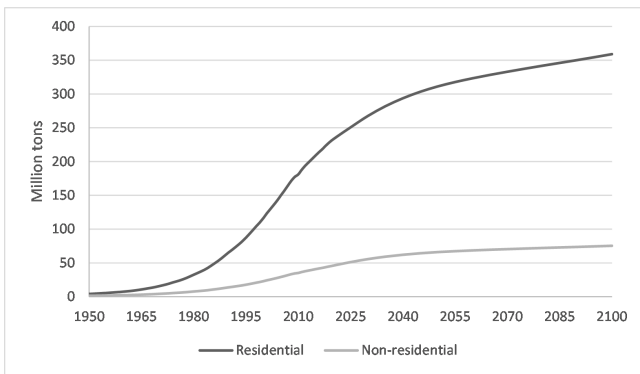


(c) Copper

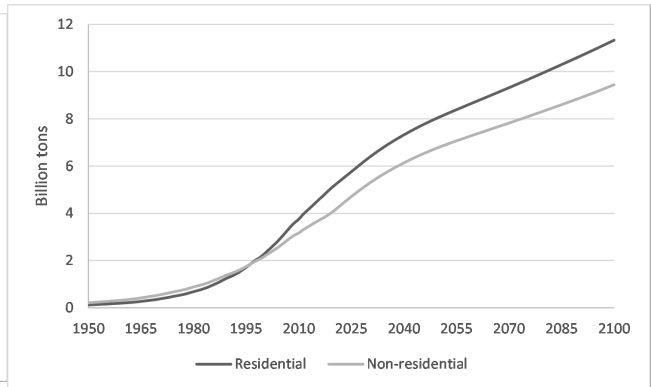


(d) Aluminum

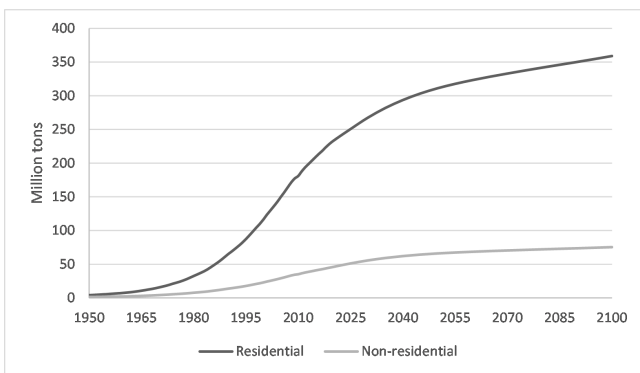
Figure 4.24: Regional inflows of concrete, steel, copper and aluminum in the SSP3. The residential and non-residential segments are aggregated.



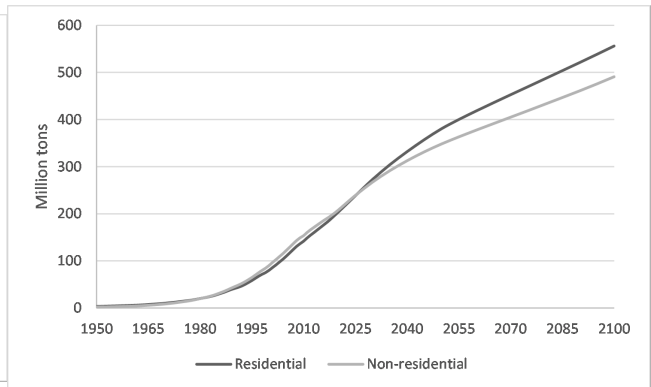
(a) Concrete



(b) Steel

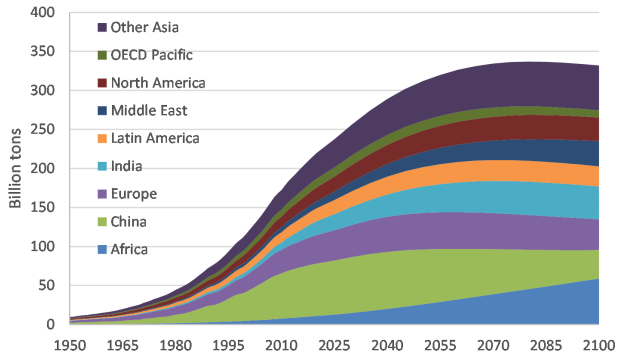


(c) Copper

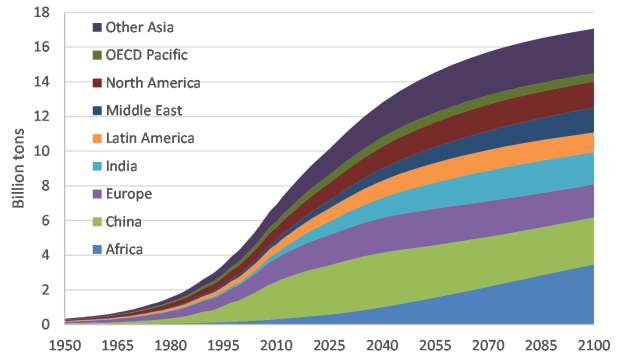


(d) Aluminum

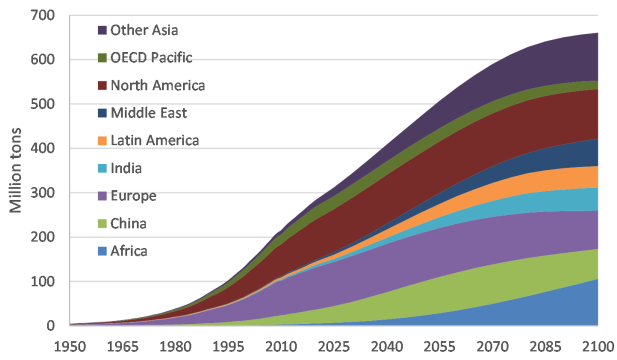
Figure 4.25: Global stocks of concrete, steel, copper and aluminum in the residential and non-residential segments in the SSP3.



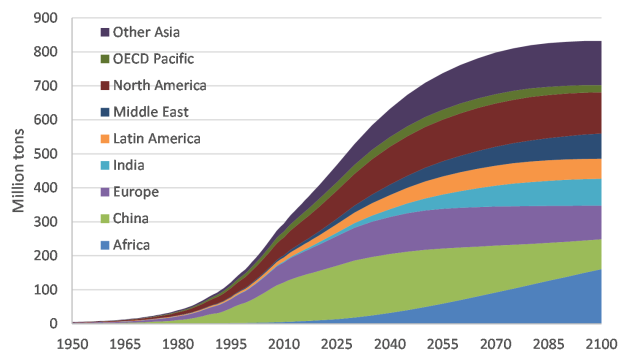
(a) Concrete



(b) Steel



(c) Copper



(d) Aluminum

Figure 4.26: Regional in-use stocks of concrete, steel, copper and aluminum in the SSP4. The residential and non-residential segments are aggregated.

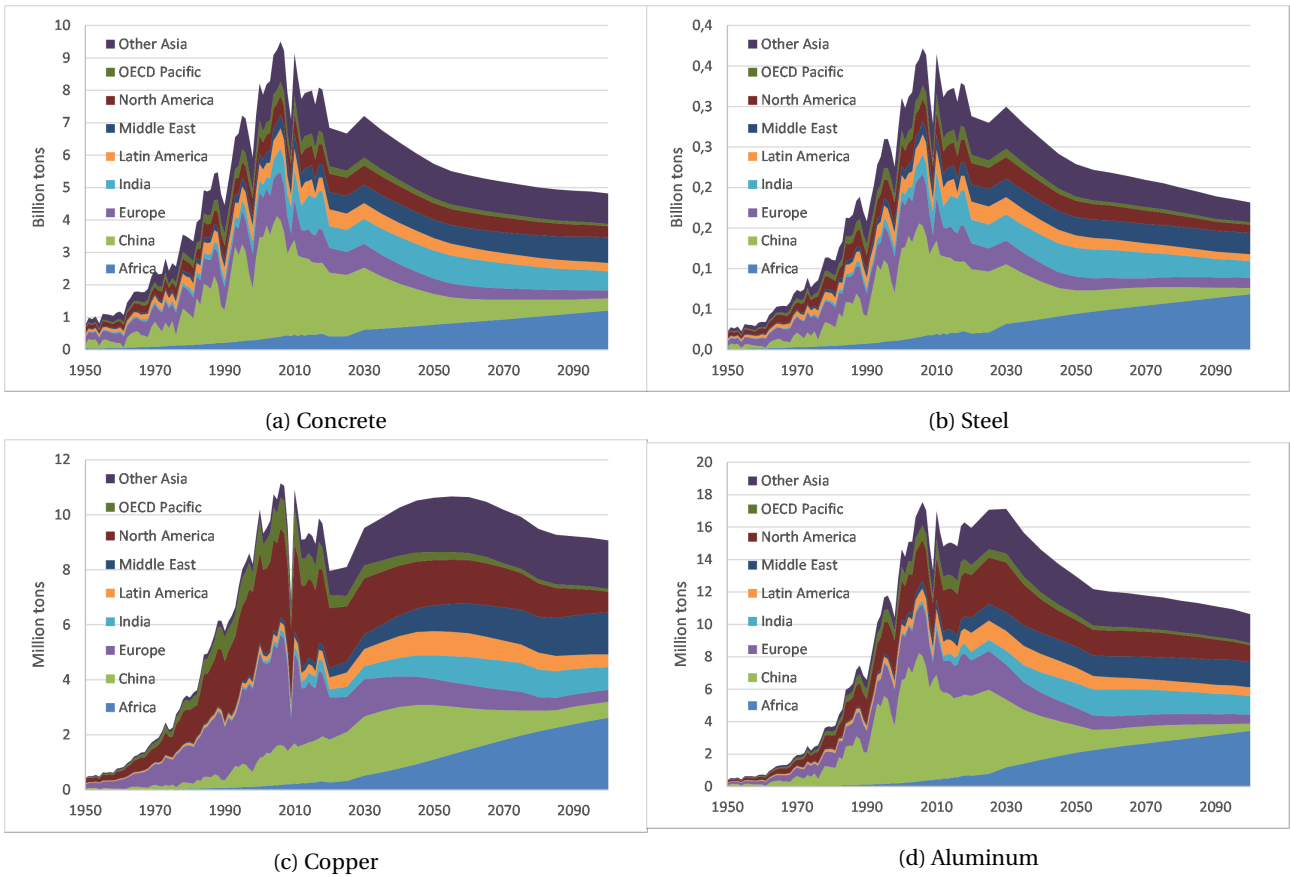


Figure 4.27: Regional inflows of concrete, steel, copper and aluminum in the SSP4. The residential and non-residential segments are aggregated.

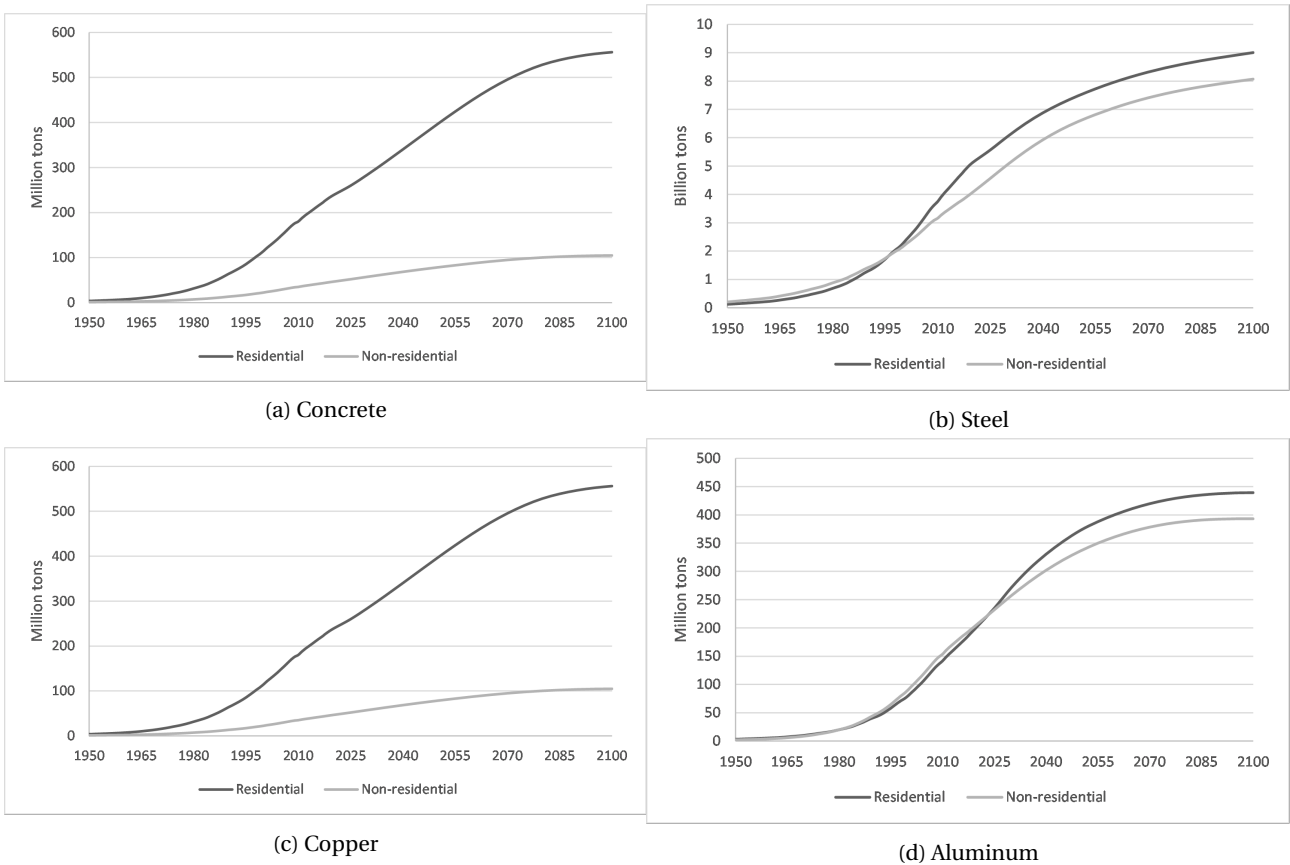


Figure 4.28: Global stocks of concrete, steel, copper and aluminum in the residential and non-residential segments in the SSP4.

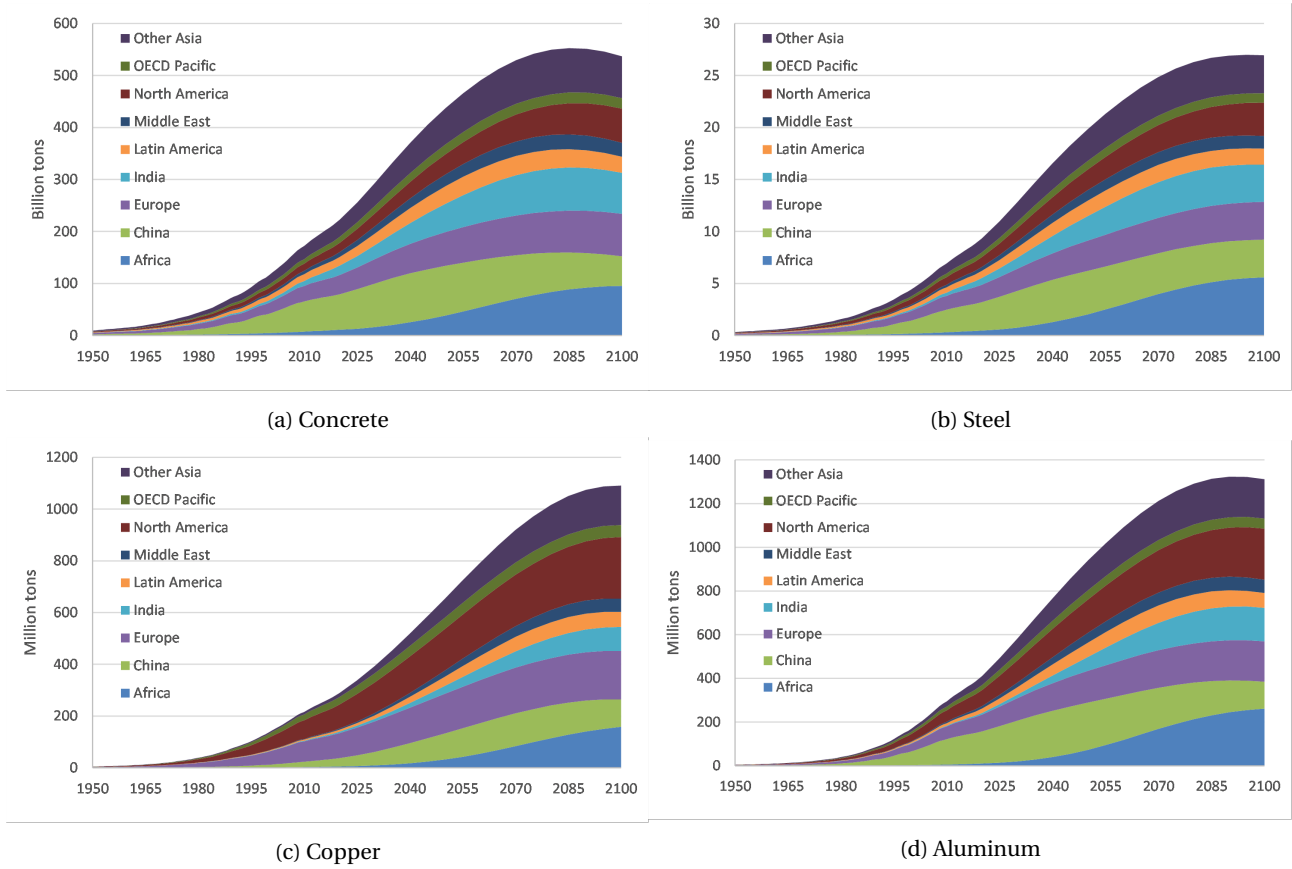


Figure 4.29: Regional in-use stocks of concrete, steel, copper and aluminum in the SSP5. The residential and non-residential segments are aggregated.

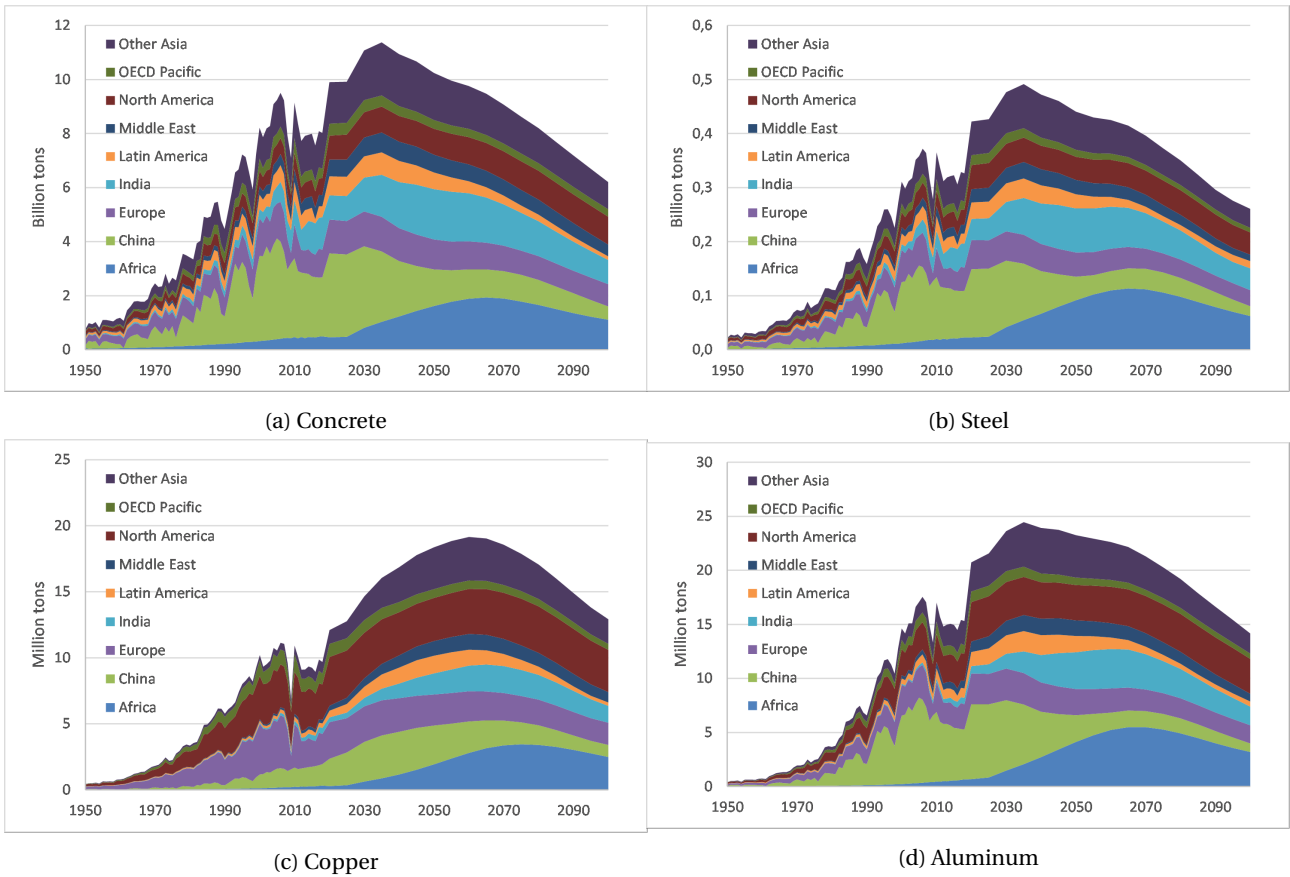


Figure 4.30: Regional inflows of concrete, steel, copper and aluminum in the SSP5. The residential and non-residential segments are aggregated.

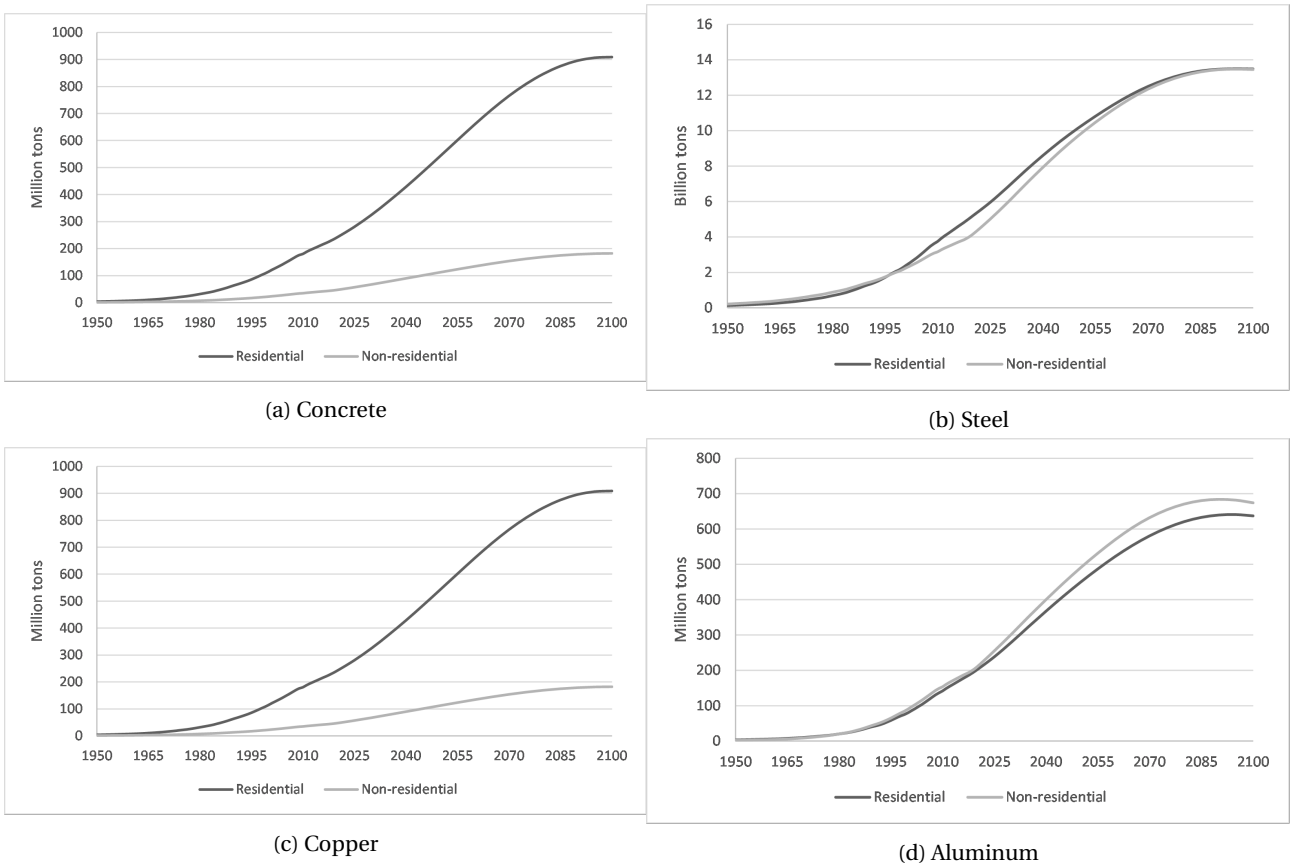


Figure 4.31: Global stocks of concrete, steel, copper and aluminum in the residential and non-residential segments in the SSP5.

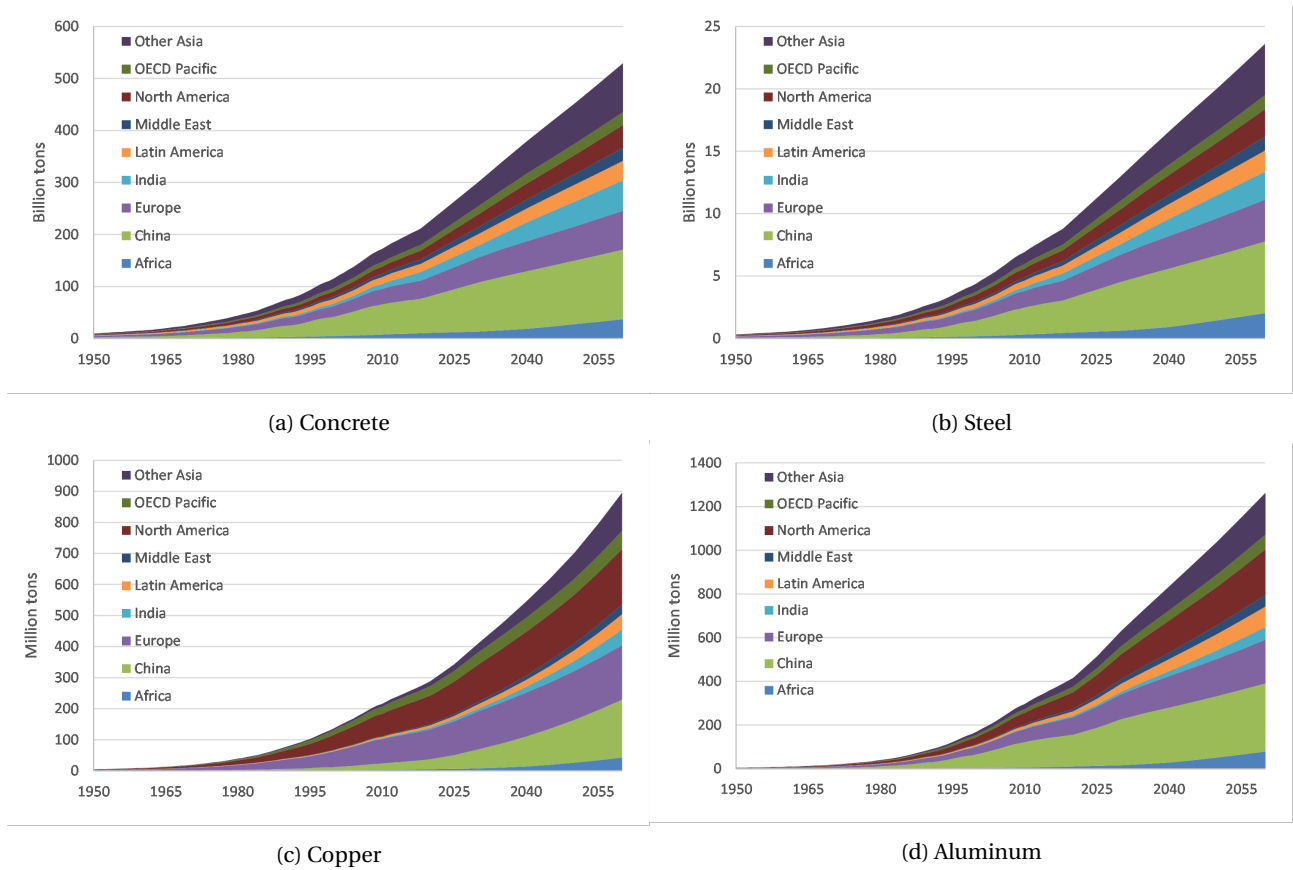


Figure 4.32: Regional in-use stocks of concrete, steel, copper and aluminum in the B2DS. The residential and non-residential segments are aggregated.

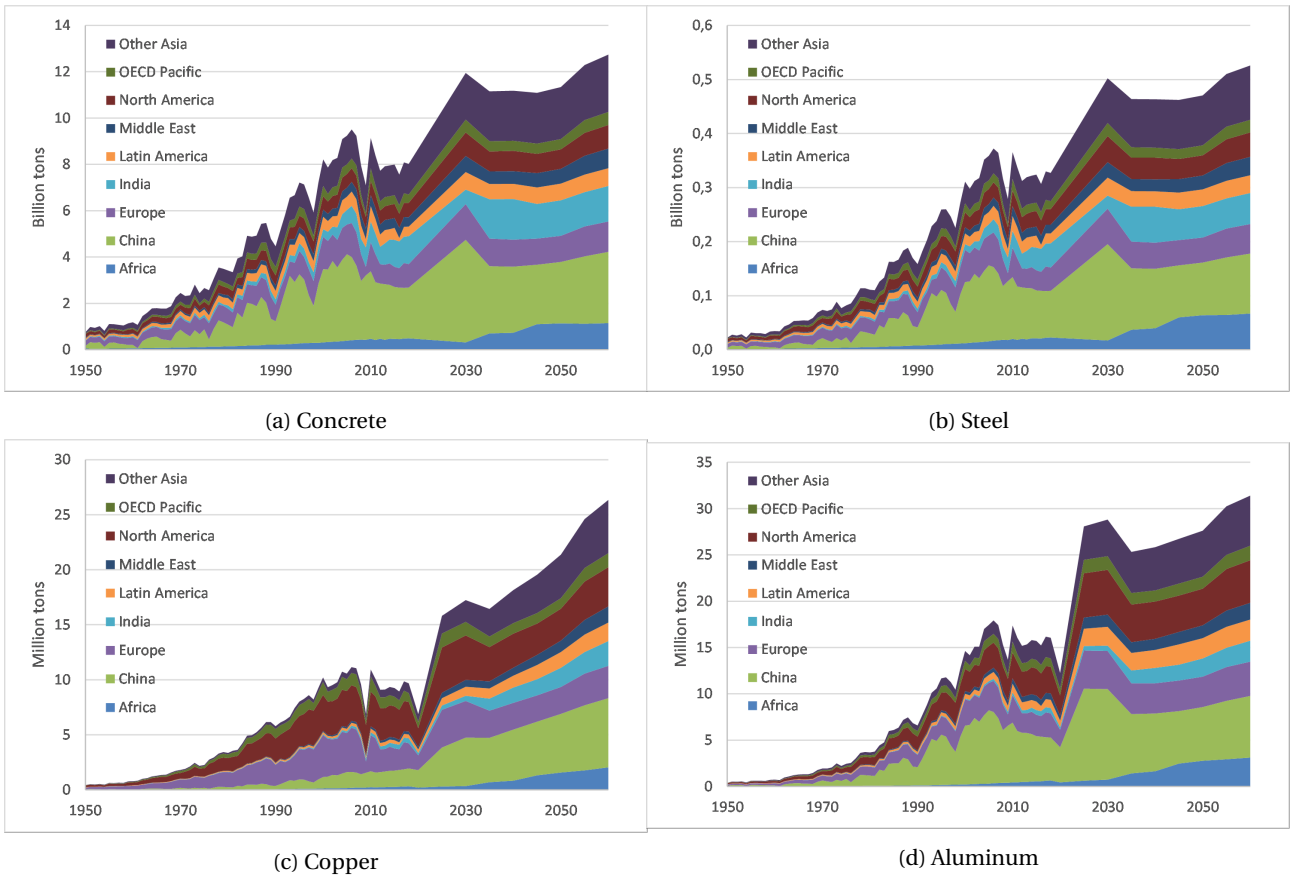


Figure 4.33: Regional inflows of concrete, steel, copper and aluminum in the B2DS. The residential and non-residential segments are aggregated.

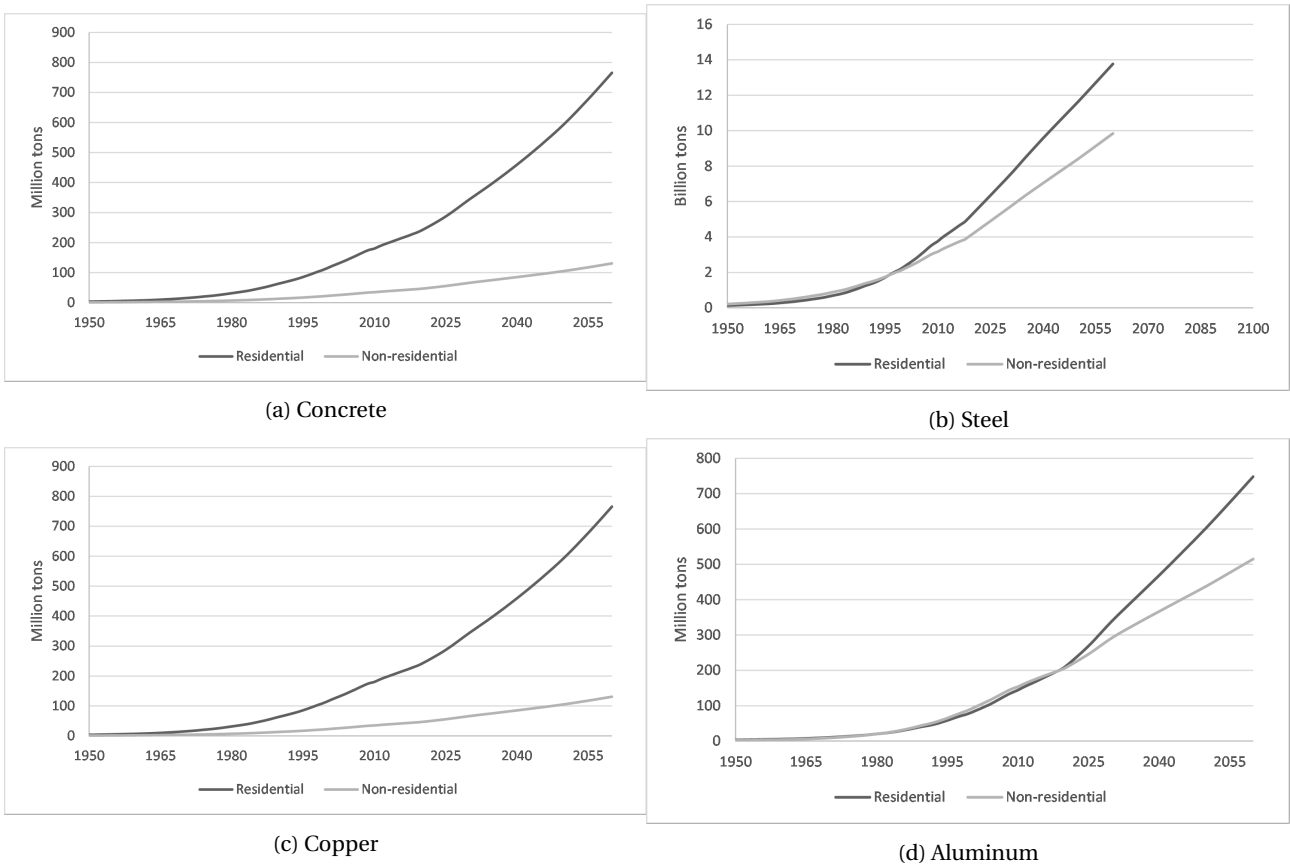


Figure 4.34: Global stocks of concrete, steel, copper and aluminum in the residential and non-residential segments in the B2DS.

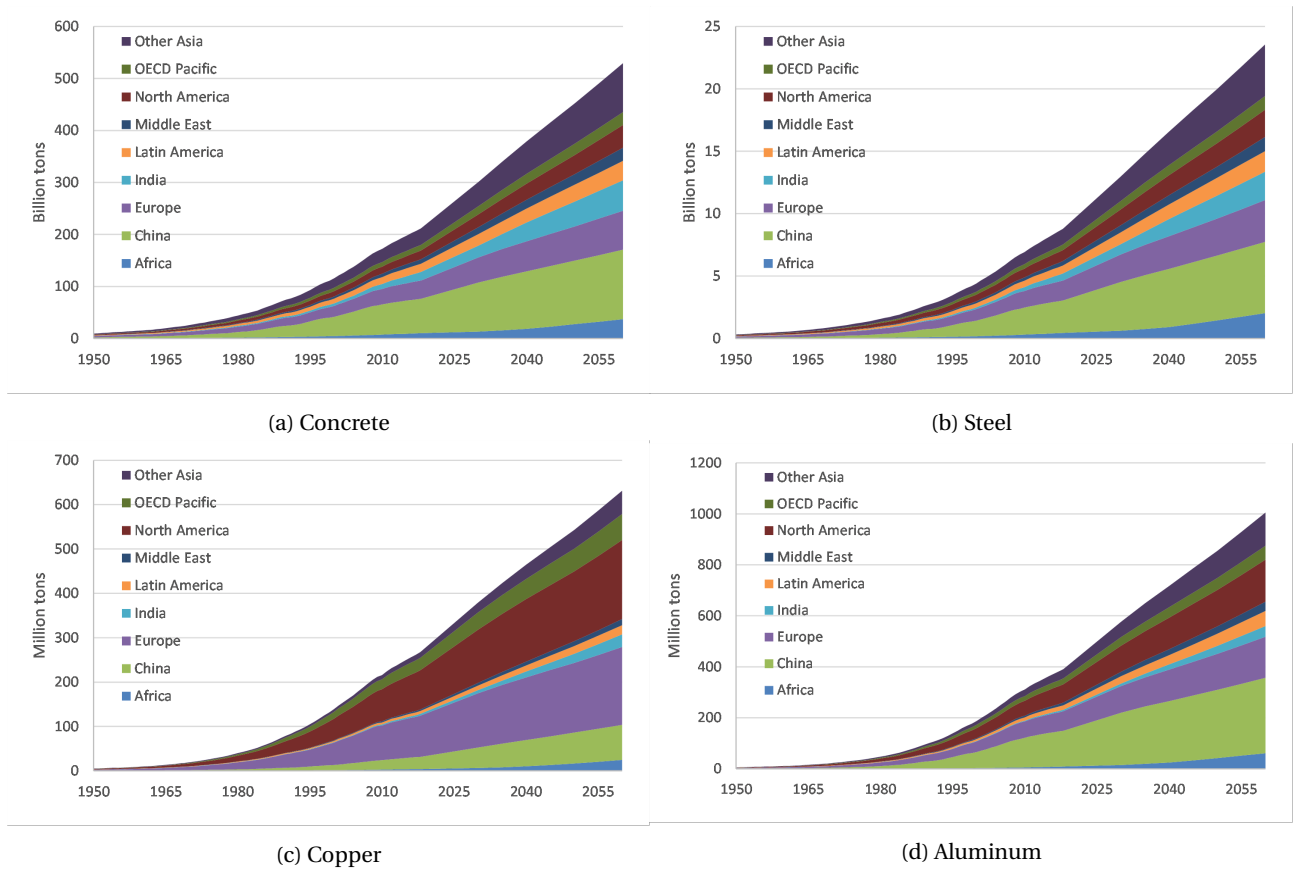


Figure 4.35: Regional in-use stocks of concrete, steel, copper and aluminum in the RTS. The residential and non-residential segments are aggregated.

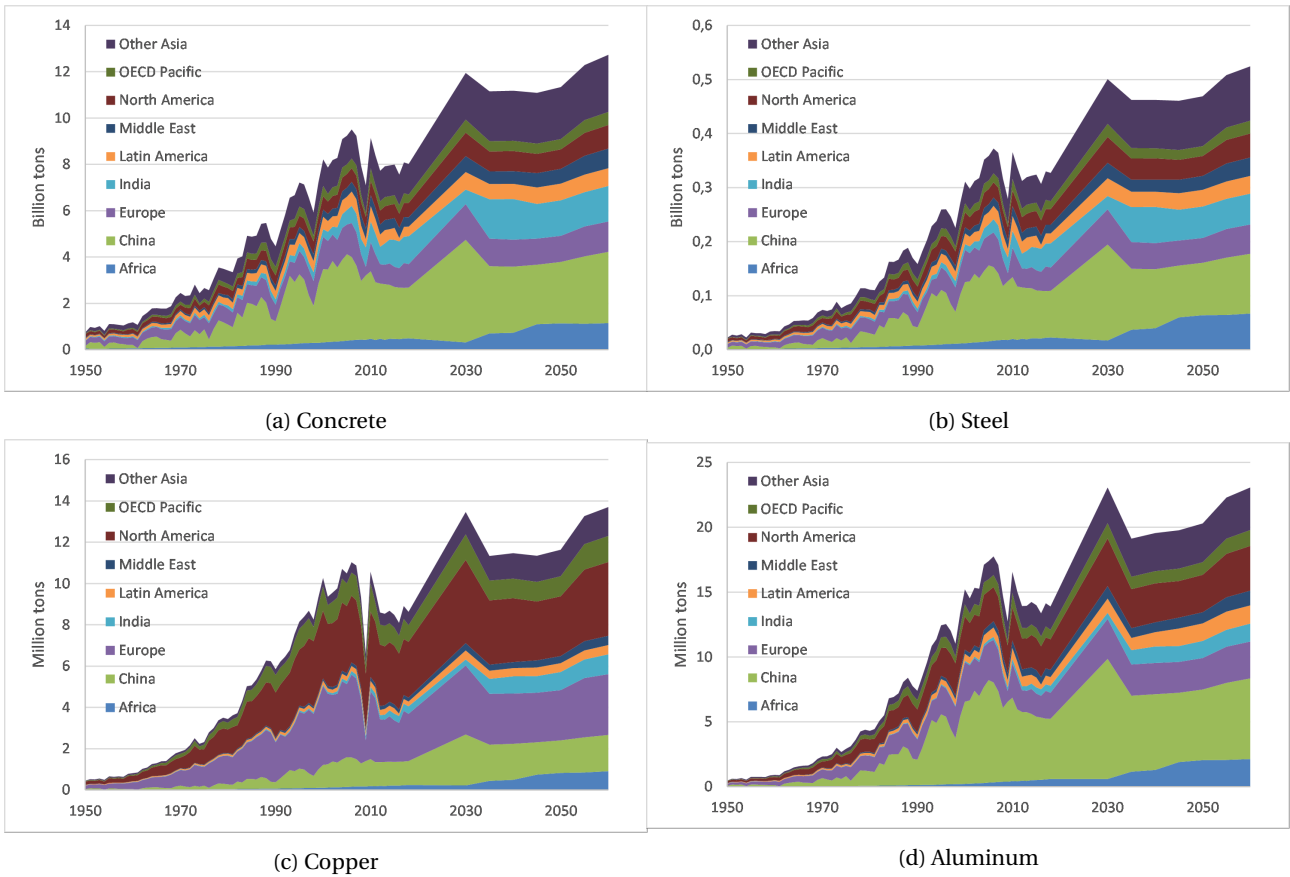


Figure 4.36: Regional inflows of concrete, steel, copper and aluminum in the RTS. The residential and non-residential segments are aggregated.

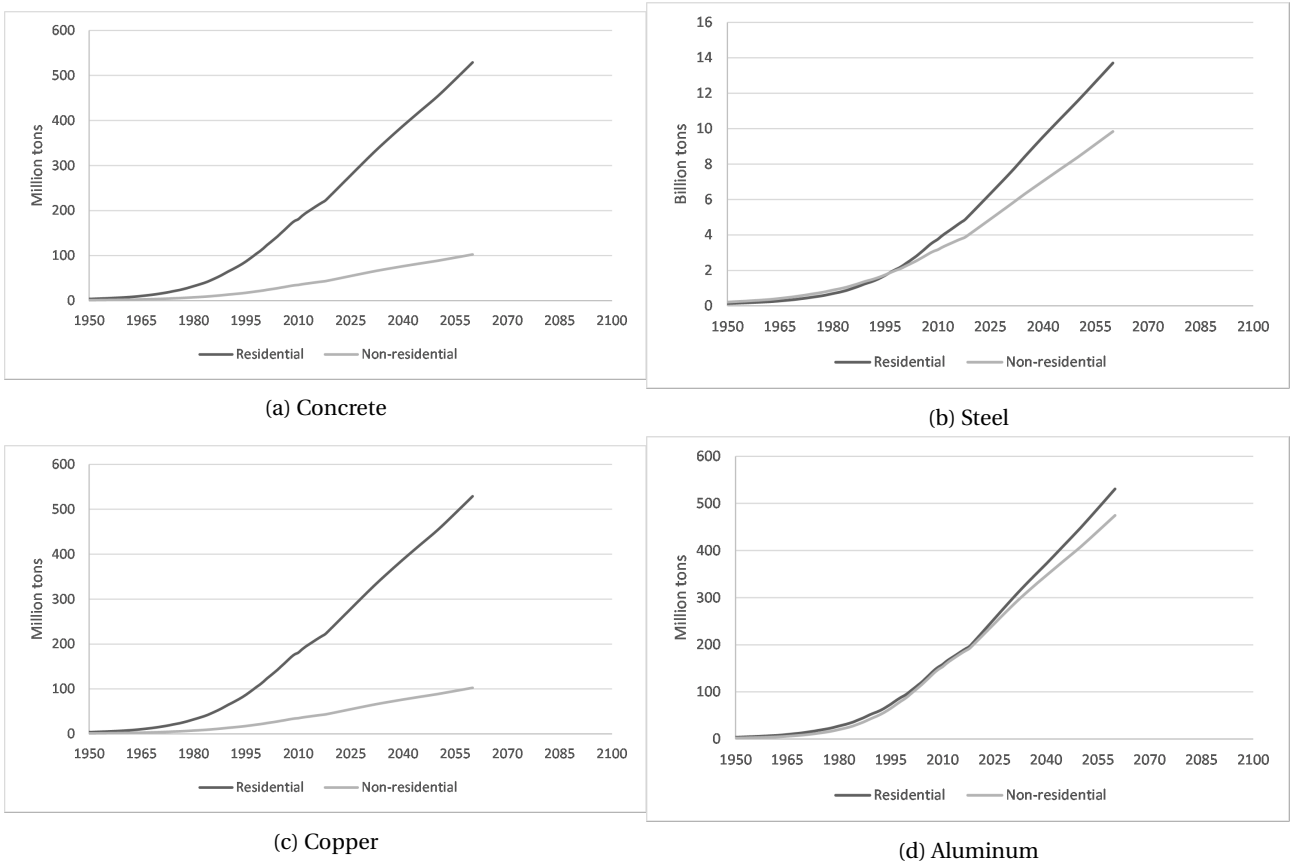


Figure 4.37: Global stocks of concrete, steel, copper and aluminum in the residential and non-residential segments in the RTS.

Materials weight of thermal renovation

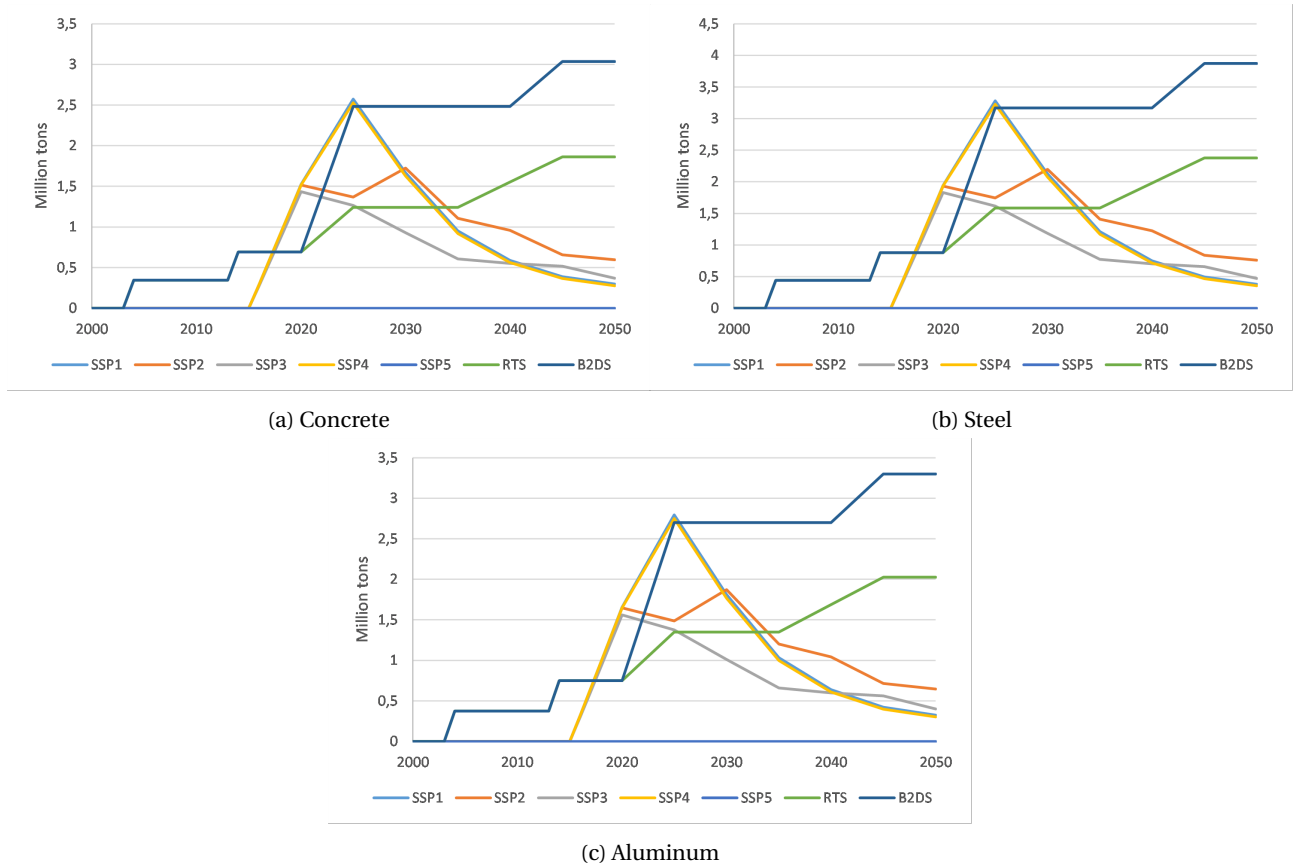


Figure 4.38: Materials flows needed for the renovated surfaces in the building sector for the selected scenarios. Renovation is only considered in the residential segment.

Concrete recovery and recycling

SSP1

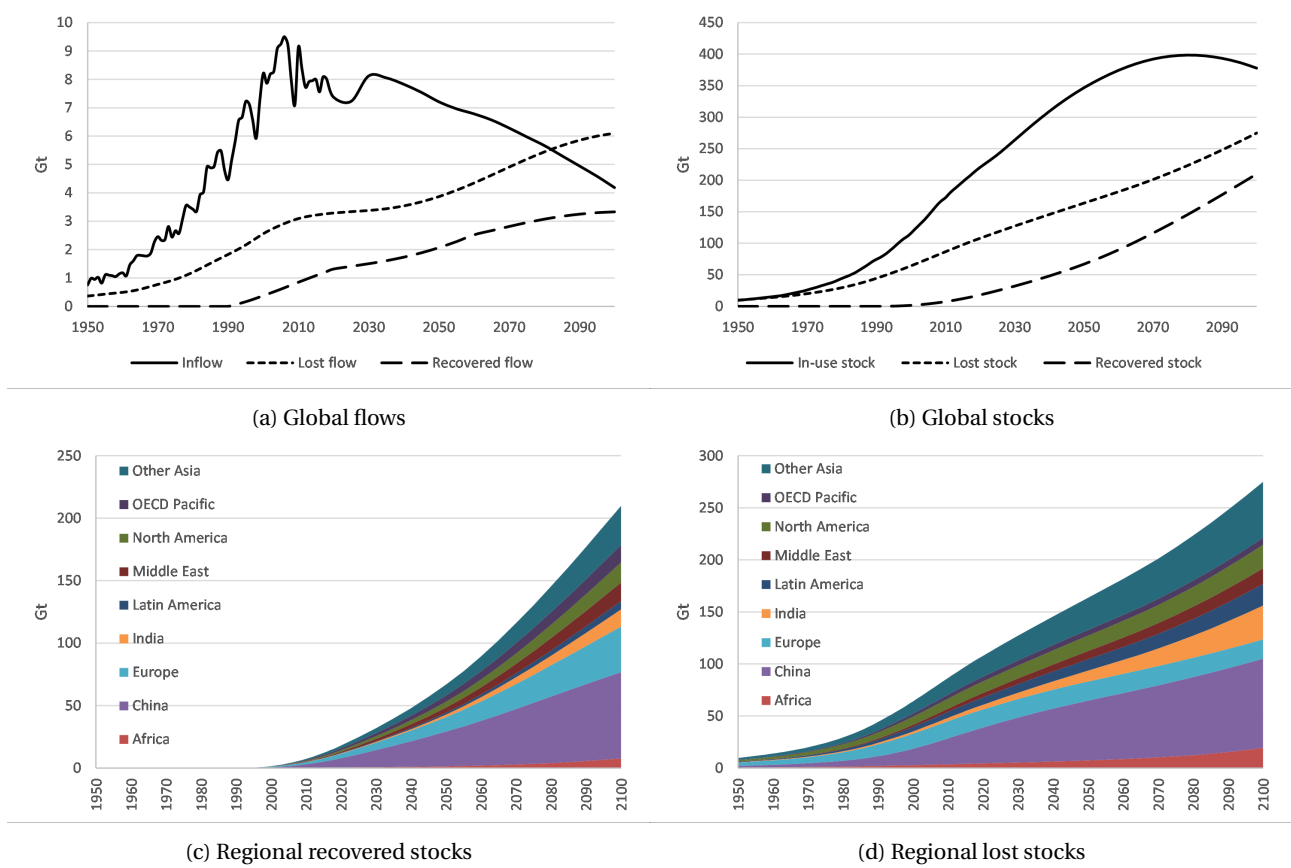
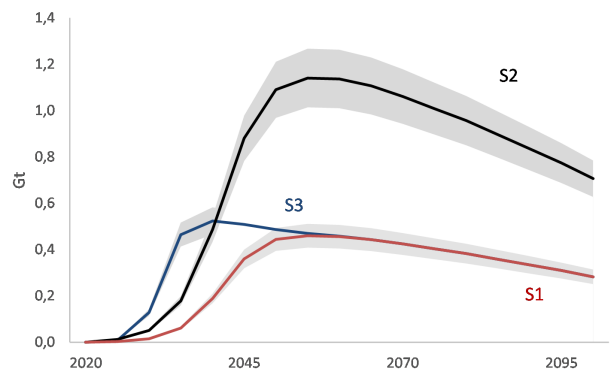
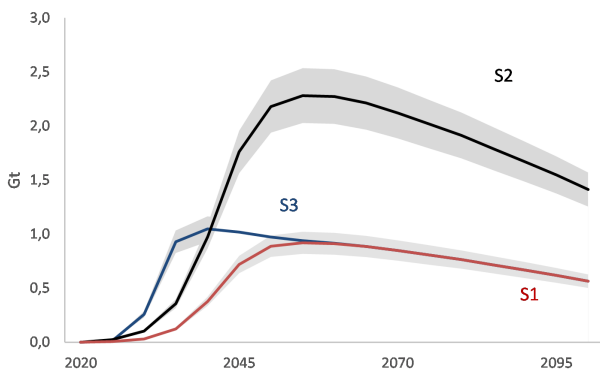
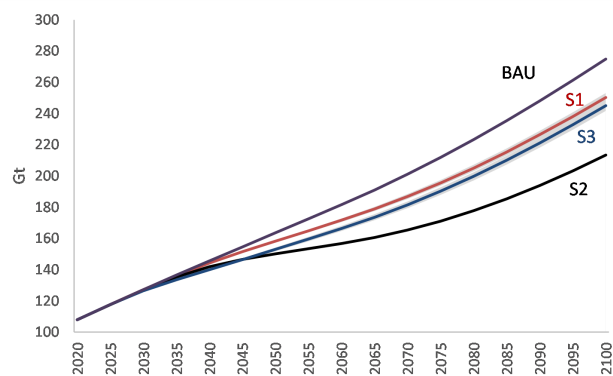
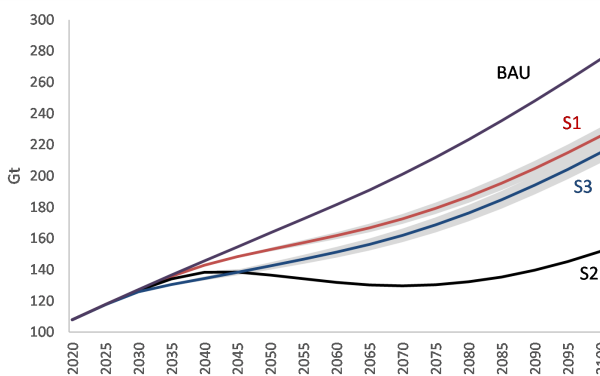


Figure 4.39: Global in-use, recovered and lost flows (a) and stocks (b) in the SSP1. The regional recovered stocks are displayed in the Figure (c) and the lost stocks in the Figure (d).



(a) Annual demand in the S1, S2 and S3 computed on 100% of the inflow

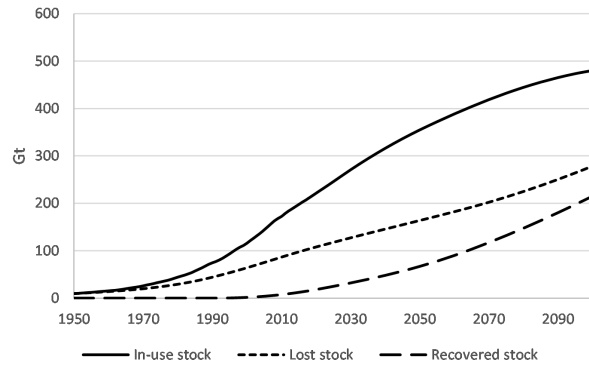
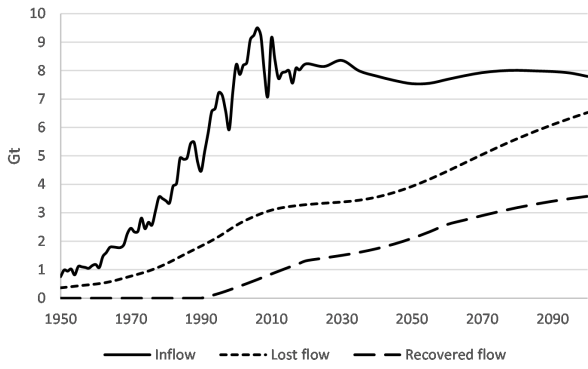
(b) Annual demand in the S1, S2 and S3 computed on 50% of the inflow



(c) Lost stock in the S1, S2 and S3 computed on 100% of the inflow

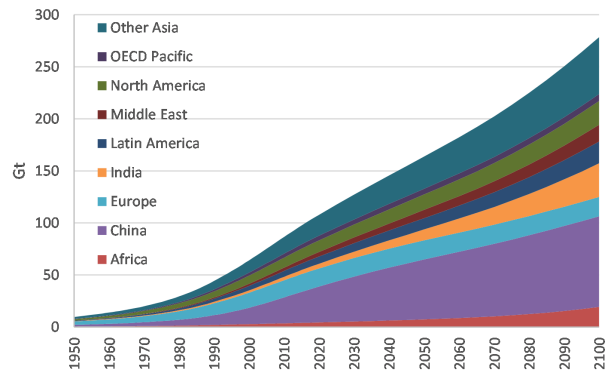
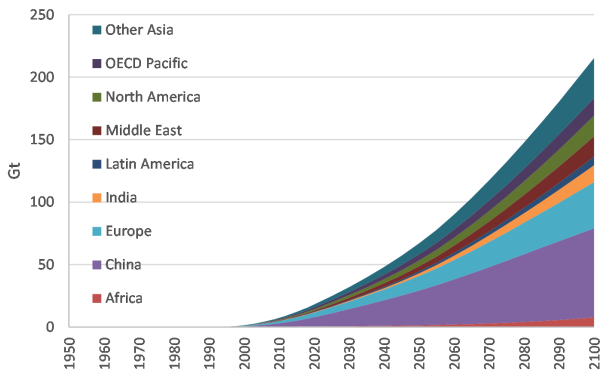
(d) Lost stock in the S1, S2 and S3 computed on 50% of the inflow

Figure 4.40: Global annual demand of RCA for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP1, and lost stocks of concrete for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP1.



(a) Global flows

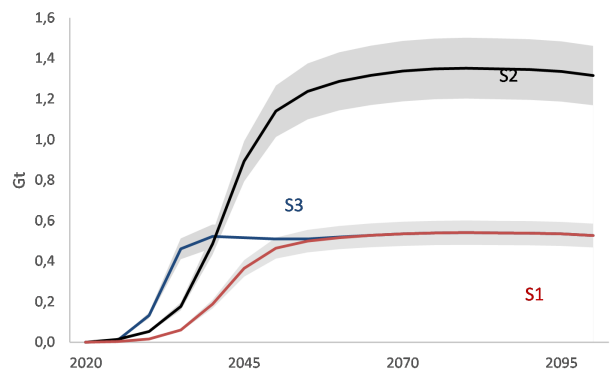
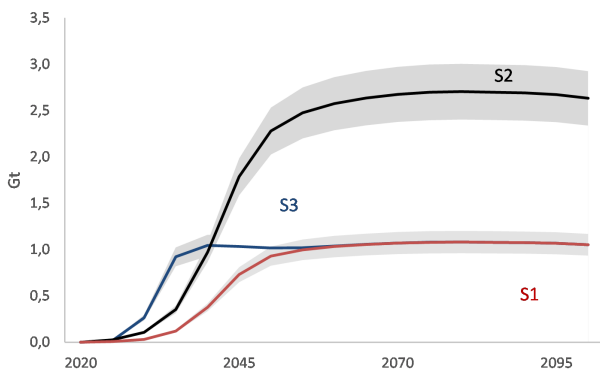
(b) Global stocks



(c) Regional recovered stocks

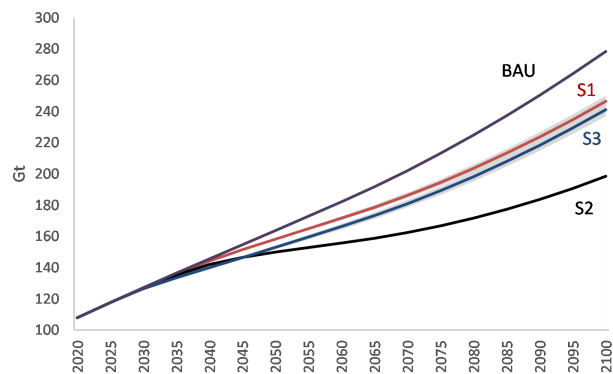
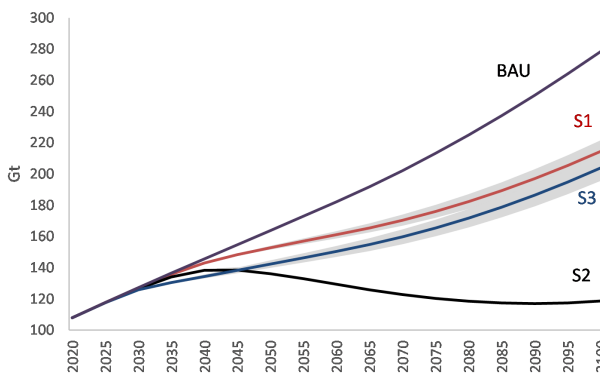
(d) Regional lost stocks

Figure 4.41: Global in-use, recovered and lost flows (a) and stocks (b) in the SSP2. The regional recovered stocks are displayed in the Figure (c) and the lost stocks in the Figure (d).



(a) Annual demand in the S1, S2 and S3 computed on 100% of the inflow

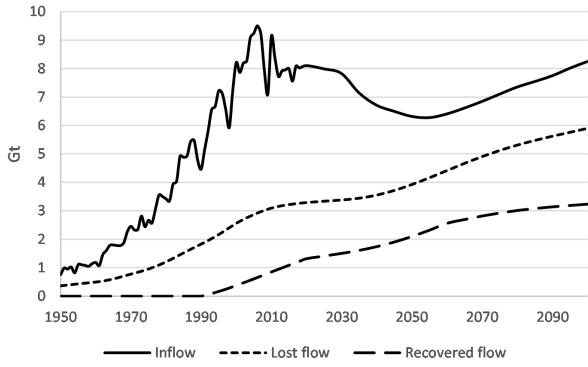
(b) Annual demand in the S1, S2 and S3 computed on 50% of the inflow



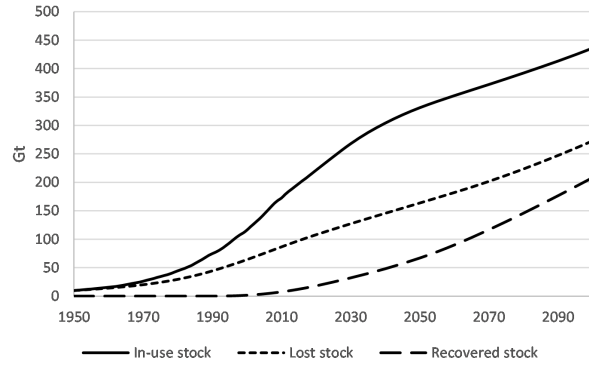
(c) Lost stock in the S1, S2 and S3 computed on 100% of the inflow

(d) Lost stock in the S1, S2 and S3 computed on 50% of the inflow

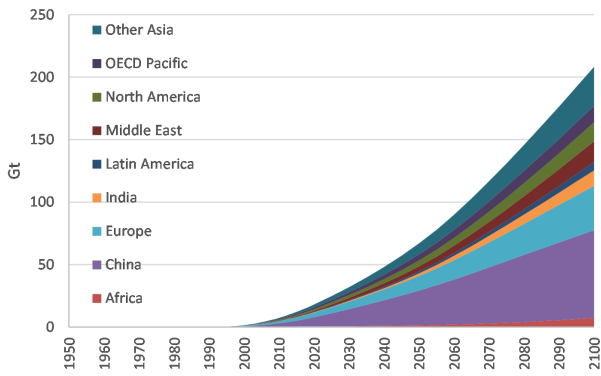
Figure 4.42: Global annual demand of RCA for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP2, and lost stocks of concrete for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP2.



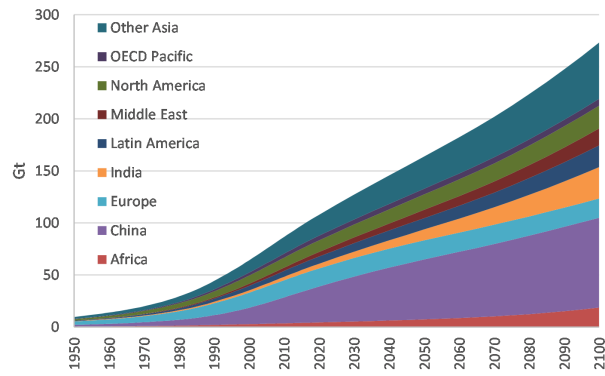
(a) Global flows



(b) Global stocks

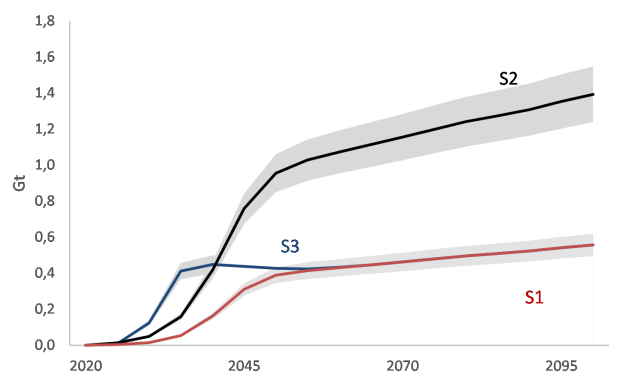
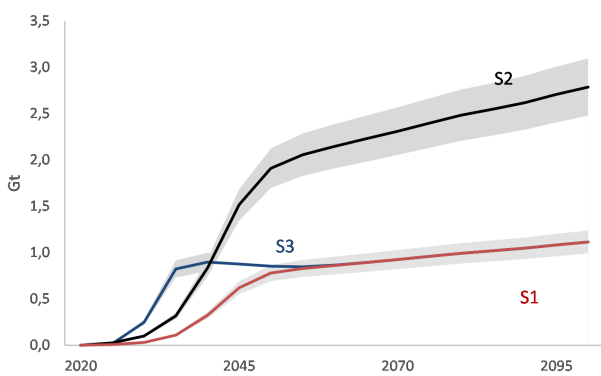


(c) Regional recovered stocks



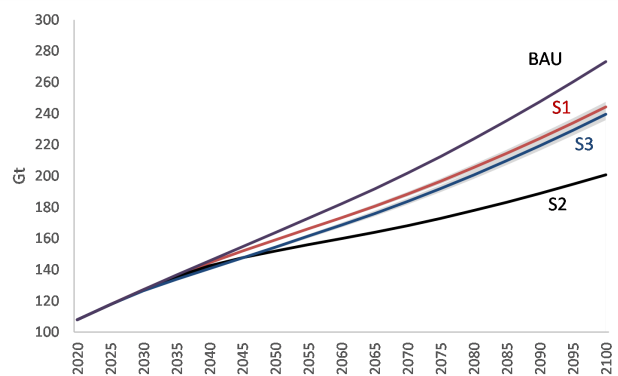
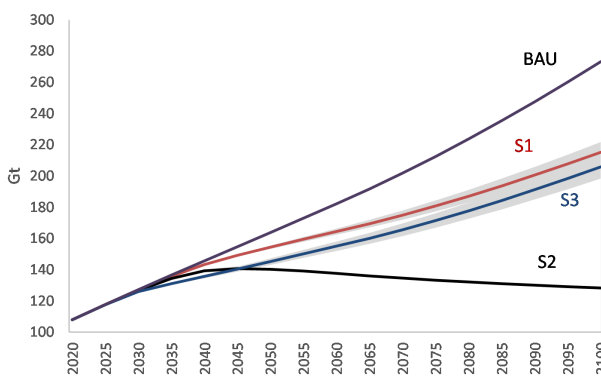
(d) Regional lost stocks

Figure 4.43: Global in-use, recovered and lost flows (a) and stocks (b) in the SSP3. The regional recovered stocks are displayed in the Figure (c) and the lost stocks in the Figure (d).



(a) Annual demand in the S1, S2 and S3 computed on 100% of the inflow

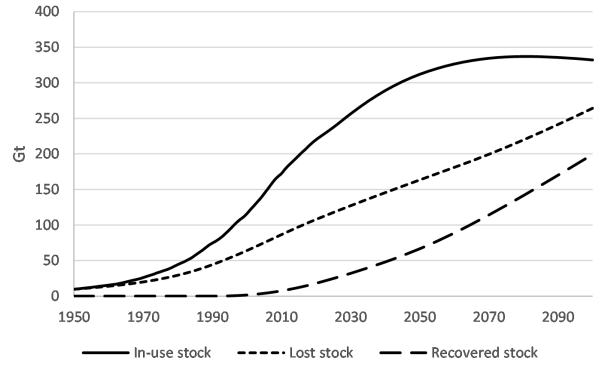
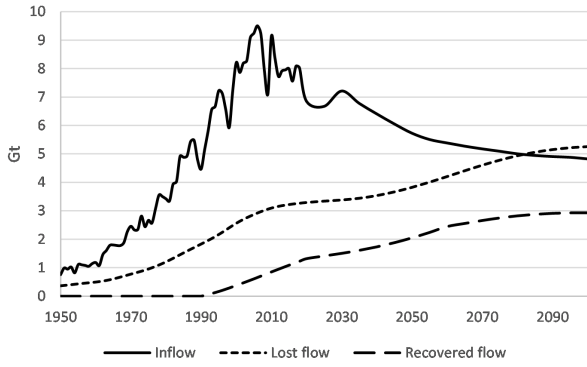
(b) Annual demand in the S1, S2 and S3 computed on 50% of the inflow



(c) Lost stock in the S1, S2 and S3 computed on 100% of the inflow

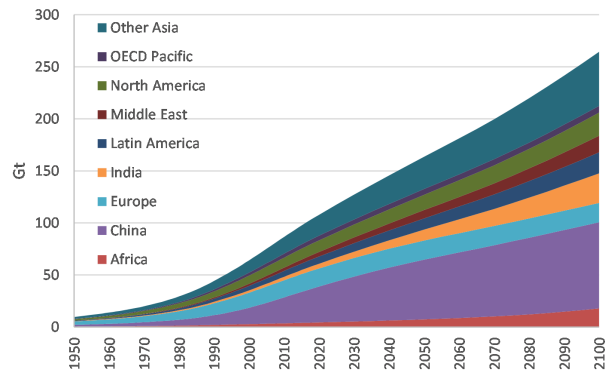
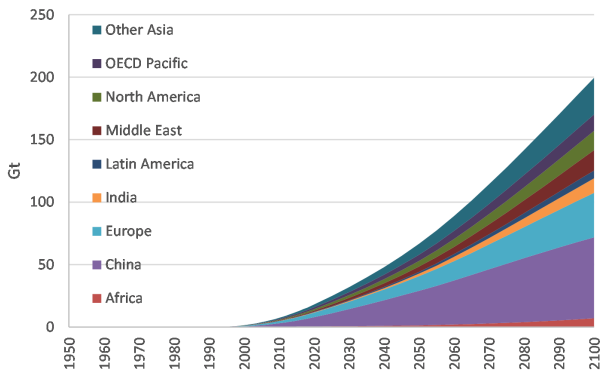
(d) Lost stock in the S1, S2 and S3 computed on 50% of the inflow

Figure 4.44: Global annual demand of RCA for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP3, and lost stocks of concrete for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP3.



(a) Global flows

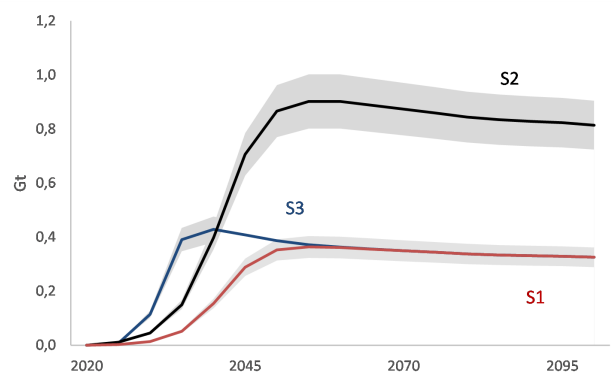
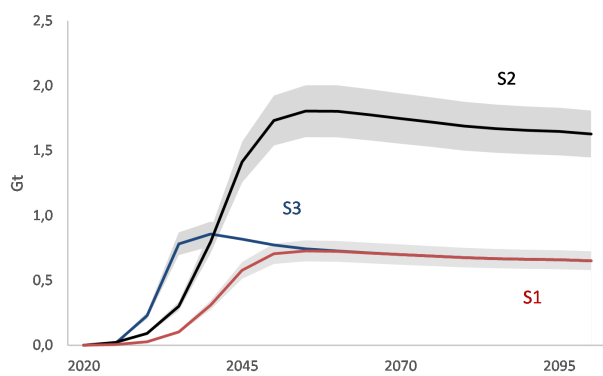
(b) Global stocks



(c) Regional recovered stocks

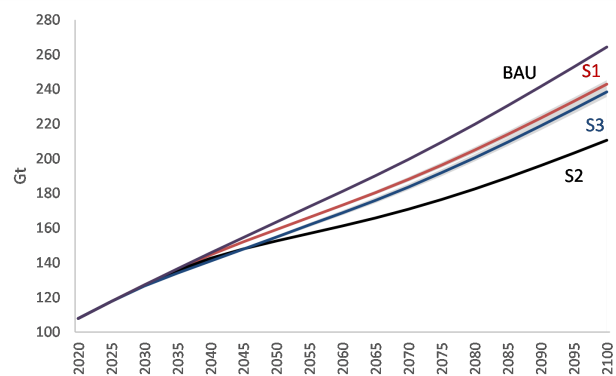
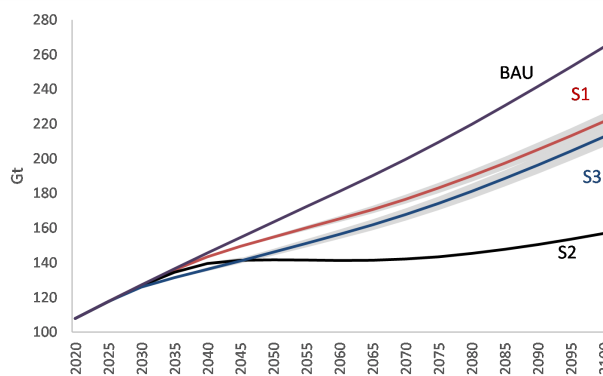
(d) Regional lost stocks

Figure 4.45: Global in-use, recovered and lost flows (a) and stocks (b) in the SSP4. The regional recovered stocks are displayed in the Figure (c) and the lost stocks in the Figure (d).



(a) Annual demand in the S1, S2 and S3 computed on 100% of the inflow

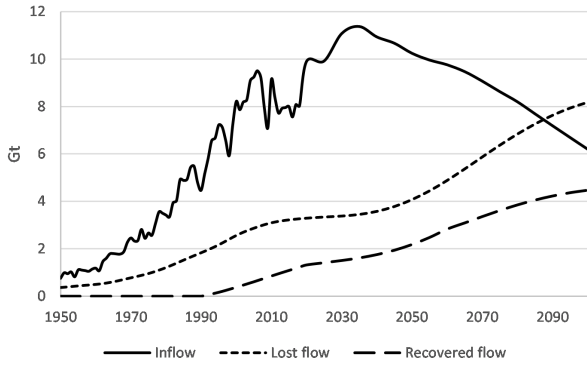
(b) Annual demand in the S1, S2 and S3 computed on 50% of the inflow



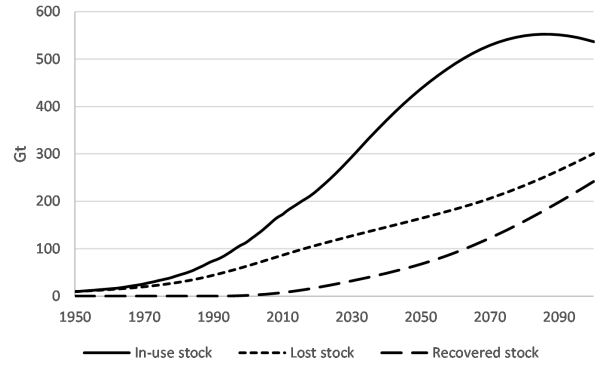
(c) Lost stock in the S1, S2 and S3 computed on 100% of the inflow

(d) Lost stock in the S1, S2 and S3 computed on 50% of the inflow

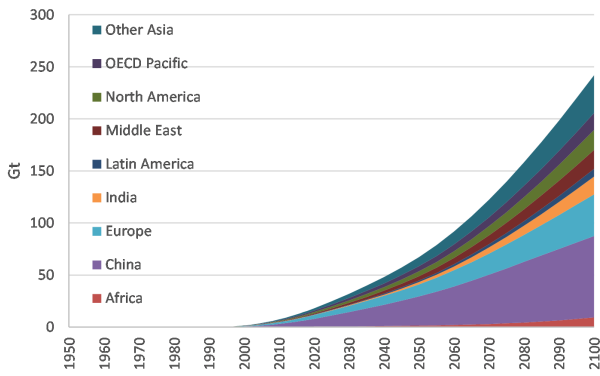
Figure 4.46: Global annual demand of RCA for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP4, and lost stocks of concrete for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP4.



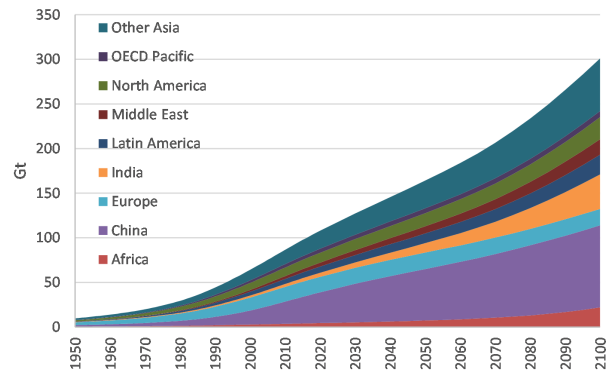
(a) Global flows



(b) Global stocks

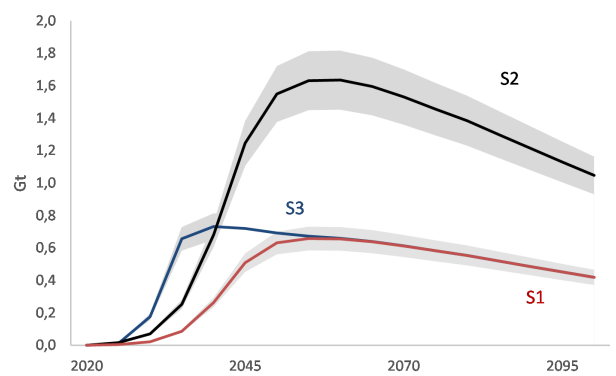
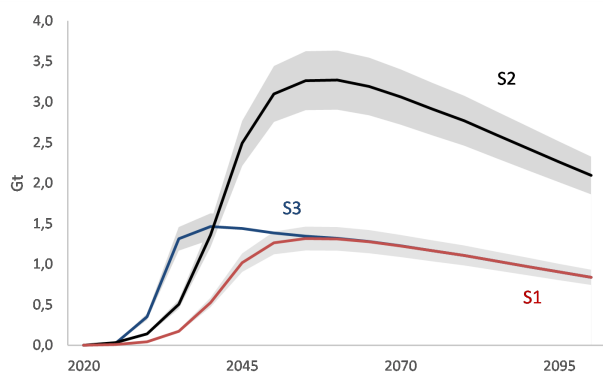


(c) Regional recovered stocks



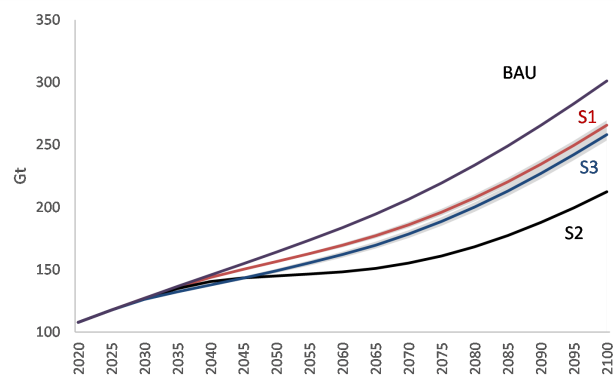
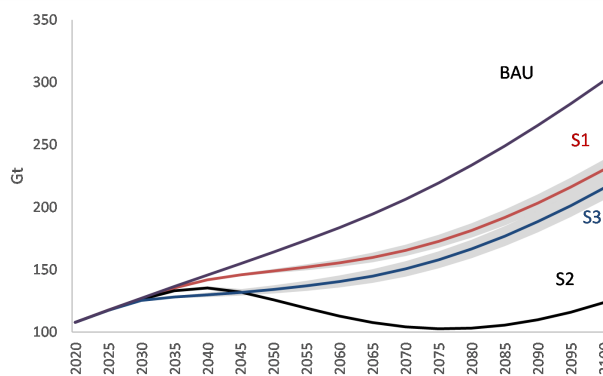
(d) Regional lost stocks

Figure 4.47: Global in-use, recovered and lost flows (a) and stocks (b) in the SSP5. The regional recovered stocks are displayed in the Figure (c) and the lost stocks in the Figure (d).



(a) Annual demand in the S1, S2 and S3 computed on 100% of the inflow

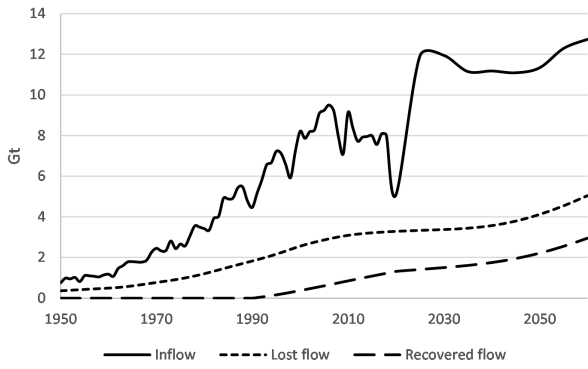
(b) Annual demand in the S1, S2 and S3 computed on 50% of the inflow



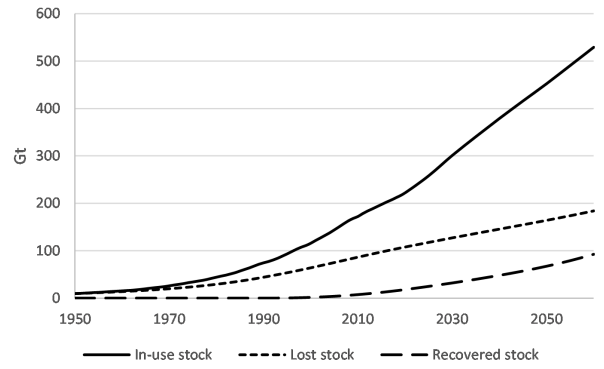
(c) Lost stock in the S1, S2 and S3 computed on 100% of the inflow

(d) Lost stock in the S1, S2 and S3 computed on 50% of the inflow

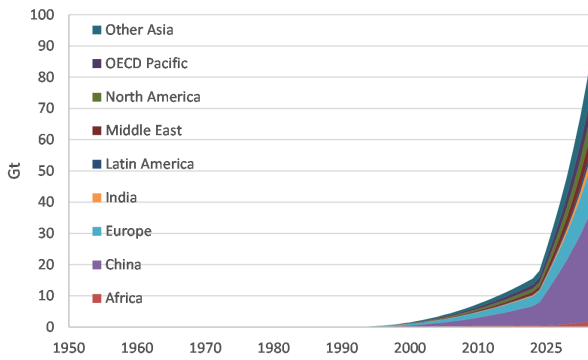
Figure 4.48: Global annual demand of RCA for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP5, and lost stocks of concrete for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the SSP5.



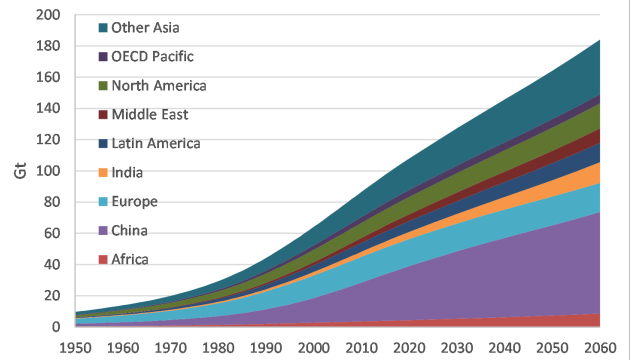
(a) Global flows



(b) Global stocks

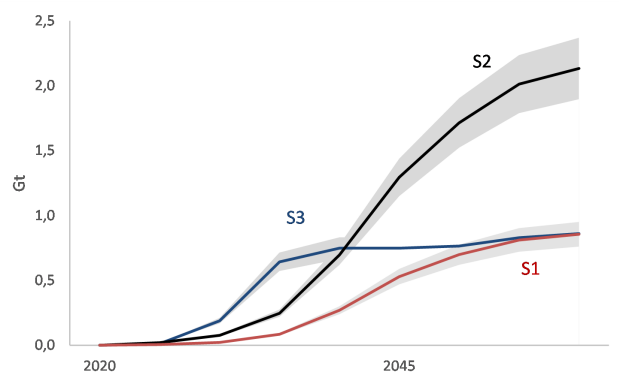
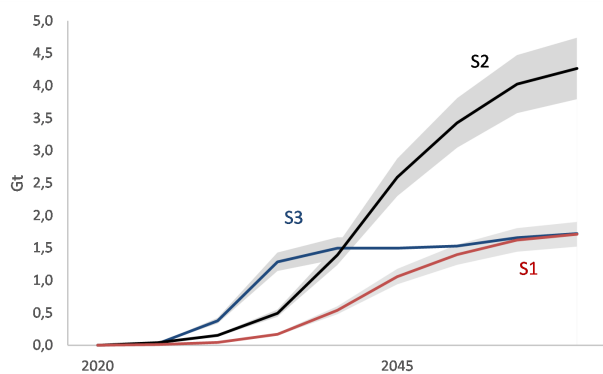


(c) Regional recovered stocks

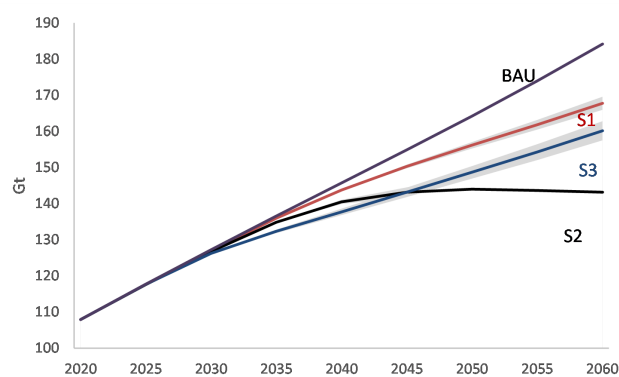
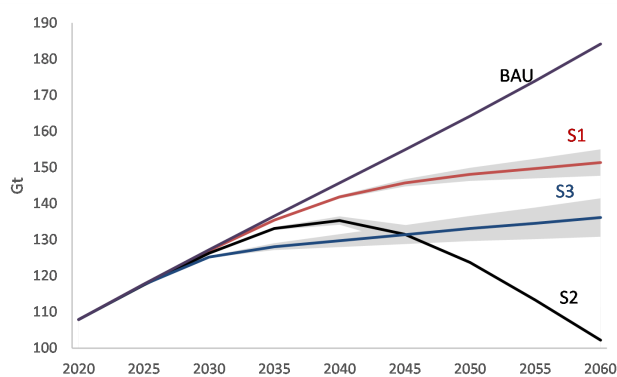


(d) Regional lost stocks

Figure 4.49: Global in-use, recovered and lost flows (a) and stocks (b) in the B2DS. The regional recovered stocks are displayed in the Figure (c) and the lost stocks in the Figure (d).



(a) Annual demand in the S1, S2 and S3 computed on 100% of the inflow (b) Annual demand in the S1, S2 and S3 computed on 50% of the inflow



(c) Lost stock in the S1, S2 and S3 computed on 100% of the inflow (d) Lost stock in the S1, S2 and S3 computed on 50% of the inflow

Figure 4.50: Global annual demand of RCA for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the B2DS, and lost stocks of concrete for replacement scenarios on 100% of the inflow (a) and 50% of the inflow (b) in the B2DS.

"Green concrete"

Green concrete	Production energy reduction	CO₂ emissions reduction
GC1	19%	26%
GC2	38%	51%
GC3	60%	60%
GC4		22%

Table 4.10: Energy demand and CO₂ emissions reductions in the scenarios in 2100 for a use of "green concretes" on 100% of the concrete inflow.

Materials production energy and CO₂ emissions

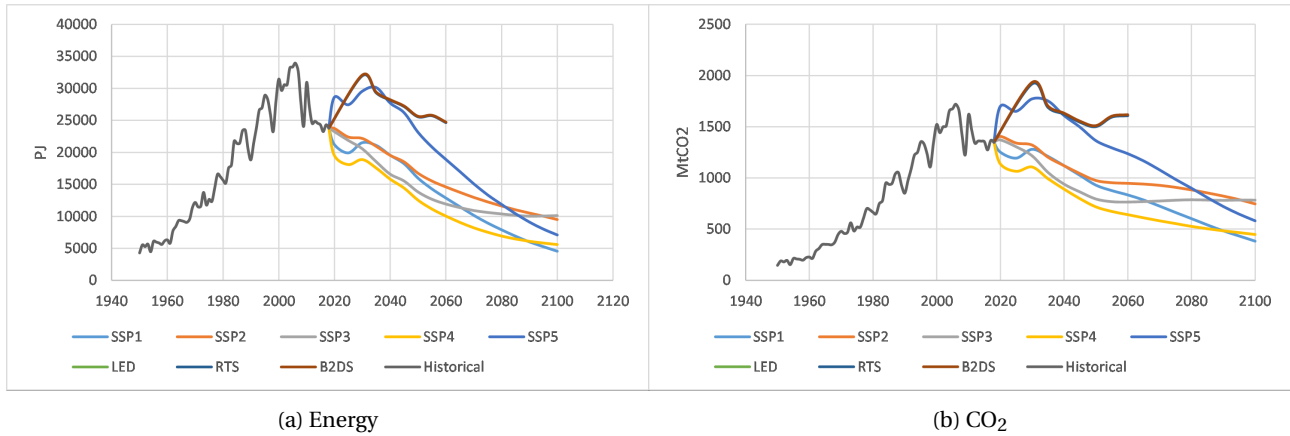


Figure 4.51: Global production energy and CO₂ emissions of the materials in the building sector for the selected scenarios. The residential and non-residential segments are aggregated.

4.2.4 Discussion

Comparison of materials results with other studies

References	Year	Area	Perimeter	Cement	Concrete	Steel	Copper	Aluminum
Stock (Gt)								
Marinova et al. (2020b)	2018	Global	Residential		240	12	0.2	1.2
Pauliuk et al. (2013)	2008	Global	Building and infrastructures			17		
Glöser et al. (2013)	2010	Global	Building and infrastructures				0.2	
Deetman et al. (2020)	2018	Global	Building		267	15	0.31	1.3
This study	2018	Global	Building		211	9	0.27	0.39
Deetman et al. (2020)	2050	Global	Building SSP2		406	27	0.56	1.8
This study	2050	Global	Building SSP2		355	16	0.54	0.8
Hu et al. (2010)	2010	China	Residential			0.7		
Dong et al. (2019)	2015	China	Building				0.03	
This study	2018	China	Building		66	3	0.03	0.14
Flow (Mt/yr)								
Gao et al. (2018)	2010	China	Building			210		
Hu et al. (2010)	2010	China	Residential			56		
Dong et al. (2019)	2015	China	Building				2.2	
Yin and Chen (2013)	2010	China	Building			190		
This study	2018	China	Building		2,200	87	4.9	1.6
Moynihan and Allwood (2012)	2006	Global	Building			290		
Glöser et al. (2013)	2010	Global	Building and infrastructures				7	
Deetman et al. (2020)	2018	Global	Building		8,900	600	12	44
This study	2018	Global	Building		8,100	330	16	10
Deetman et al. (2020)	2050	Global	Building SSP2		11,900	769	18	52
This study	2050	Global	Building SSP2		7,500	310	17	14
Annual demand	2018	Global	All sectors	4,050		1,800	25	29

Table 4.11: Results of stocks and flows of bulk materials in previous studies.

Chapter 5

A bottom-up modeling of the energy sector: raw materials, embodied energy and CO₂ impacts

Summary of the chapter

Objectives

- Modeling fossil fuel and renewable infrastructures from 1950 to 2050.
- Estimating embedded materials, energy and CO₂ emissions.
- Analyzing the role of the decommissioning of the fossil fuel supply chain from a material dimension.

Methodology

- Dynamic material flow analyses (MFA) are developed and applied.
- Baseline and low-carbon transition scenarios are considered.

Results

- The pace of the development and the short lifetimes of renewable technologies could create a substantial increase of the material demand.
- The material intensities of oil, gas and coal supply chains have stagnated for more than 30 years.
- Gas is the main driver of current and future material consumption.
- Recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll.
- To be ambitious, decommissioning strategies should enhance in-use steel recycling.

The ongoing energy transition is tackled from two angles: energy demand management and energy production decarbonation. The share of renewables in the global energy supply mix only reached 4.6% in 2018 and their share in the electricity mix amounted to 29% in 2020, mainly represented by hydro (IEA, 2020a,b). An acceleration of their penetration in the energy is required to achieve the political objectives—such as the EC proposal of a 40% target of renewable energy in the EU energy consumption in 2030¹. The increasing demand for low carbon technologies results in a constraints for both base and technological materials. Vast amounts of base materials are needed to produce decentralized facilities, in a context of growing energy demand and other material-intensive technologies development. Vidal et al. (2013) pointed out a shift from a energy materials dependency to a minerals and metals dependency. The quantification of the future materials demand emanating from renewables became a growing research field. Some studies focused on specific technological development such as photovoltaic panels (Shammugam et al., 2019; Kavlak et al., 2014) or wind turbines (Davidsson and Höök, 2017). The material requirements for an increasing share of low carbon technologies were estimated at a global level (Kleijn et al., 2011; Deetman et al., 2021b; Watari et al., 2019) and at national levels (Viebahn et al., 2015; Beylot et al., 2019), and studied with new angles (EROI in Capellán-Pérez et al. (2019) or substitution in Månberger and Stenqvist (2018)). In a first article included in the present chapter (Vidal et al., 2018), we propose a modeling of the base materials requirements for three low-carbon scenarios, and the associated embodied energy and CO₂ emissions.

The strong interest in renewable modeling conceals the domination of fossils fuels since the 19th century (Figure 5.1). Oil, coal and gas still represented more than 81% of primary energy supply in 2018 (IEA, 2020b). Their decreasing demand in energy transition scenarios brings out new matter about a future decommissioning of fossils supply infrastructures (OGUK, 2020; Ekins et al., 2006; Kaiser, 2018). No study was conducted on the materials embedded in those infrastructures. In a second article included in the Section 5.1, we aim at proposing a first estimation of the amount of base materials consumed in fossils fuels extraction and supply infrastructures, and the associated embodied energy and CO₂ emissions (Le Boulzec et al., 2022). The supplementary information is provided in Section 5.2.

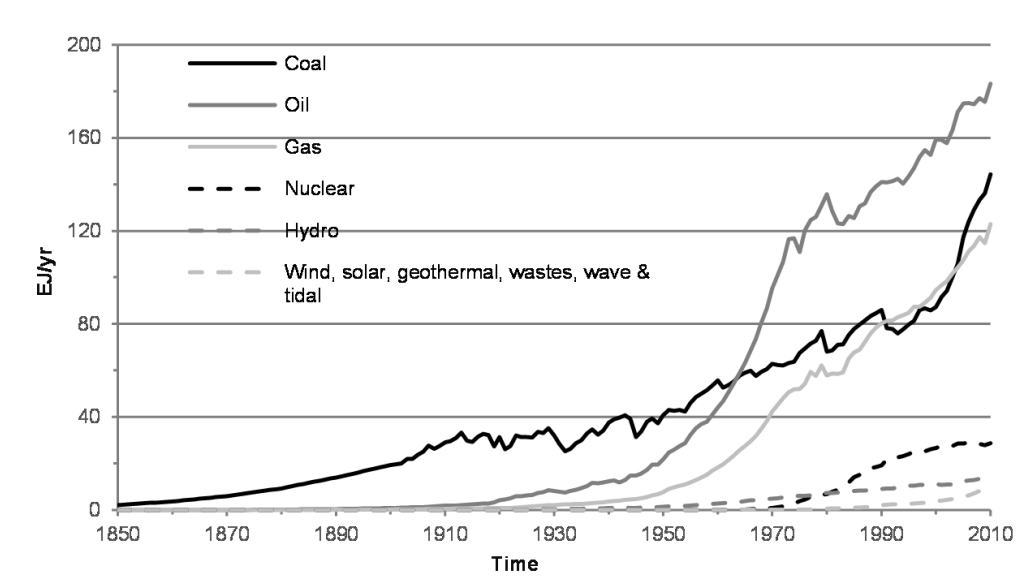


Figure 5.1: Global primary energy supply by sources from 1850 to 2014. Sources: Court (2016)

¹The 2021 amendment of the EC aims at raising the target from a previous 32% level in 2030 to 40%, and still considers a carbon neutrality by 2050.

Modelling the material and energy costs of the transition to low-carbon energy

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Summary. — The evolution from 2000 to 2050 of the needs in concrete, steel, aluminium and copper to build the infrastructure of electricity generation is modelled for the scenarios of García-Olivares *et al.* (2012), Ecofys-WWF (2012) and the blue map scenario of the IEA (2010). A simple dynamic model is used to estimate the primary production, recycling and lost flows as well as the cumulative stocks of material to be produced, to go into the infrastructure and to be lost. The energy of material production is also estimated. When compared with the expected evolution of global material and energy demands, the modelling results suggest that i) the transition to low-carbon energies implies a substantial increase of raw materials and energy consumption, ii) the shorter lifetime of wind and solar facilities and the loss of recycling implies that the total amount of metal to be produced during the deployment of the infrastructure of energy is significantly higher than their amount stocked in the infrastructure, and iii) the needs in materials and energy will occur in a period of expected increase of primary metal consumption at the world scale and limited potential of recycling.

Introduction

Meeting a growing demand for energy while reducing greenhouse gas emissions is a crucial challenge of the 21st century. The European Commission aims to reach a share of renewable energy of at least 27% of EU energy consumption by 2030 and the COP21 Paris agreement on climate change targets reaching the “carbon neutrality” worldwide

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by 2050. To achieve these objectives, it is necessary to transform within 40 years the existing fossil-fuels-based system of energy generation, transportation, storage, distribution and use. Large infrastructures of energy generation with a material intensity significantly larger than that of fossil fuels power plants are required to capture renewable but diluted energy [1-6]. The latest generations of > 5 MW off-shore wind turbines with their foundation contain about 1000 t of steel and they require wiring network and grounding systems that consume up to 9.6 tons of copper per MW [7]. This corresponds to steel intensities 2 to 6 times larger than fossil fuel power plants and copper intensities 4 to 13 times larger [4]. The same observation is made for many other mineral resources including cement, aggregates, aluminium, and a variety of rare metals and other “critical” raw materials like REE, platinum group metals, etc. [8]. The production of all these materials is not neutral and it requires high amounts of energy. At present, about 10% of the world energy demand is used for cement and steel productions alone. It appears thus that the transition to renewable energy will be a source of energy and material overconsumption during the next 40 years. An estimation of the needs must be made to evaluate the best deployment options in regard to the actual and forecasted global supply of material and energy for the next decades.

In the following, we propose a quite simple dynamic modelling of material flows and stocks and energy flows. It is used to estimate the needs in primary and recycled material for the future infrastructure of electricity generation for three contrasted energy scenarios. The results are then compared to the needs of matter and energy at the global scale. Our study focuses on the case of steel, cement, aluminium and copper, which are the major and non-substitutable materials carrying the most important part of embodied energy in the energy production facilities. Moreover, the historical consumption and production of these raw materials are well documented since several decades, and their future needs can be estimated in a relatively reliable way as it poorly depends on technological innovation (in contrast to rare metals used in high technologies metals).

1. – The considered scenarios of energy

Many scenarios of the future energy demand have been published during the last decades, which foresee contrasted evolutions in the shares of conventional and renewables capacities. In the following, the IEA blue map scenario (BM) from [9] was selected because it is rather conservative in anticipating that about 40% of the global electricity (36500 TWh/yr in 2050) will be produced from renewable sources. The Ecofys-WWF scenario (WWF) from [10] is more ambitious. It assumes a 100% renewable electricity production in 2050, produced with a mix of solar PV and concentrated solar power (CSP) technologies, wind turbines and hydropower (fig. 1). The WWF scenario is based on the sobriety of use and assumes a strong reduction of global energy consumption down to 260 EJ in 2050 (393 EJ in 2015; see [11]). Similarly, it assumes a limited increase of electricity consumption to 29000 TWh/yr in 2050 (36500 TWh/yr for BM). The last considered scenario (GO) proposed by García-Olivares *et al.* [2] assumes that the unique source of energy in 2030 is electricity produced by wind turbines, CSP and hydropower.

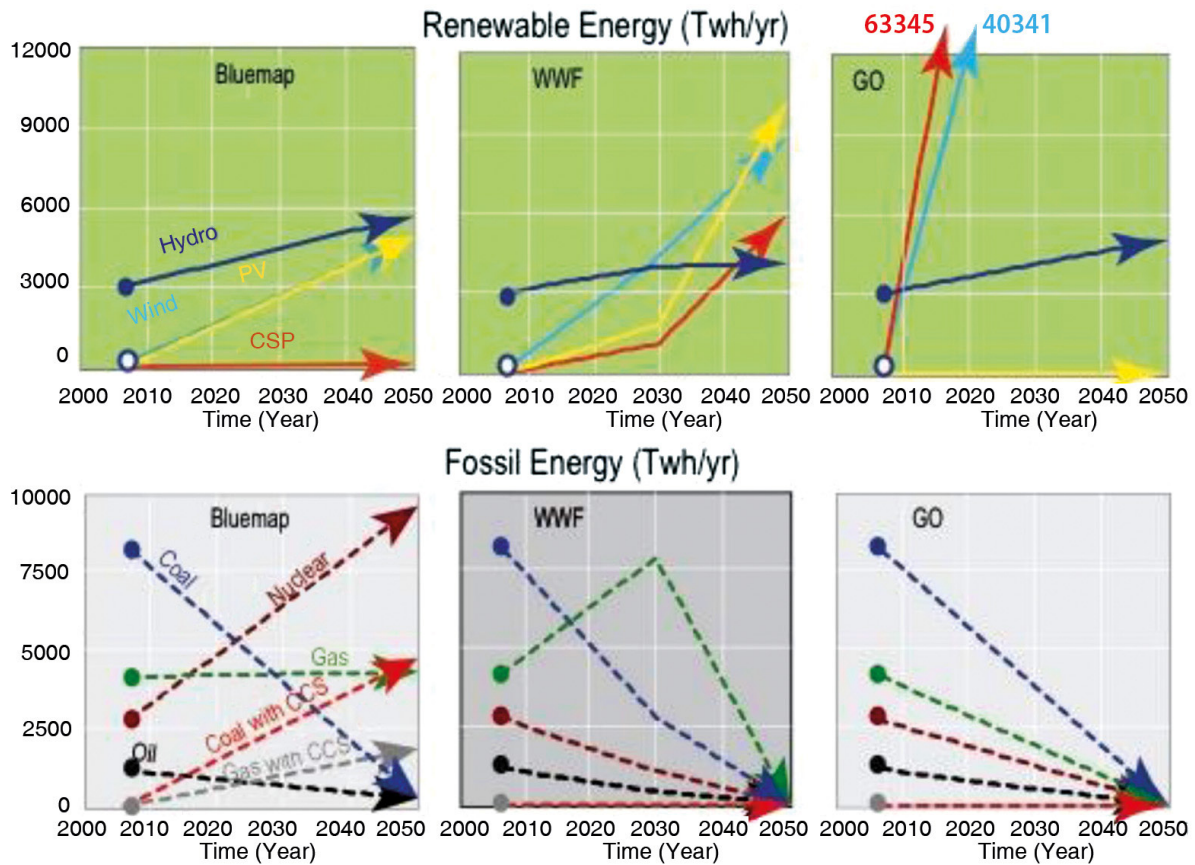


Fig. 1. – Evolution of the energy mix for the blue map [9], Ecofys-WWF [10] and García-Olivares *et al.* [2] (GO) scenarios.

The global demand in electricity will reach the enormous value of 108000 TWh/yr in 2030. Such an evolution is clearly unrealistic, but the GO scenario remains interesting because it provides an upper limit in raw materials demand for the transition to low-carbon energy. In order to be more realistic, we have considered that the scenario is achieved in 2050 instead of in 2030.

2. – The dynamic model

The value chain from primary extraction, use, end-of-life and recycling has been modelled as shown in fig. 2. Three types of power generation infrastructures have been considered on the basis of their lifetime. The lifetime of wind and solar power sources is assumed to be 20 years, 40 years for coal, gas and oil-fired power plants, and 60 years for nuclear power plants. For each type of installation, the stock in tons of “Primary raw material in the infrastructure” is supplied by the flow in tons/year of “primary production”, and the stock of “recycled metal in the infrastructure” is supplied by the “recycling” flow. The infrastructure manufactured at t_0 reaches its end of life in $t_0 + \Delta t$ where $\Delta t = \text{lifetime}$ (20, 40 or 60 years). The stock “primary raw material in the in-

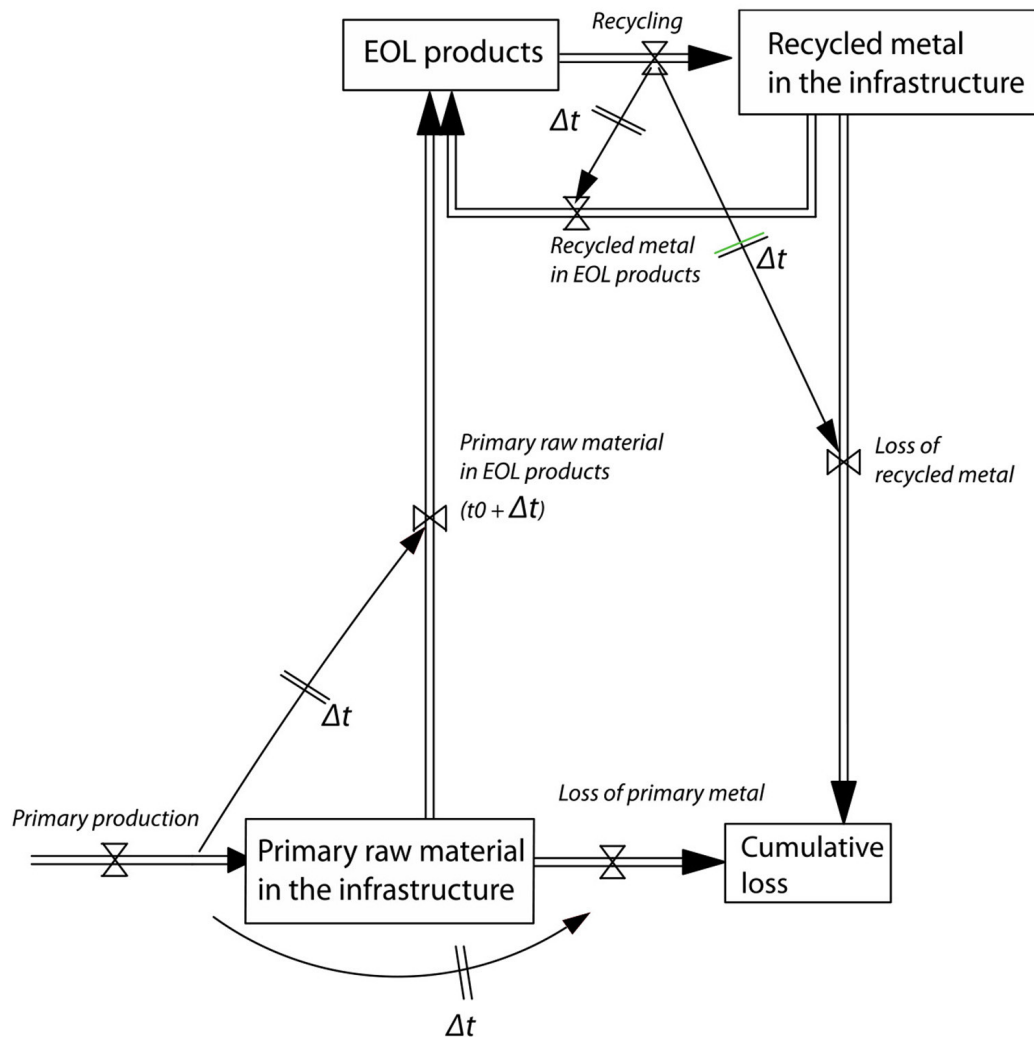


Fig. 2. – Schematic view of the model used to estimate the stocks and flows of matter during the construction and maintenance of the infrastructure of electricity generation [4].

“infrastructure” is then reduced by the outgoing flow of “primary raw material in EOL products”, which represents the flow of primary raw materials from the working infrastructure to the stock of end-of-life products (EOL). This $t_0 + \Delta t$ flow is equal to the “primary production” flow at t_0 multiplied by a collection rate (CR). The rest of the material is lost at $t_0 + \Delta t$ through the flow “loss of primary metal” = “primary production” $\times (1 - CR)$. The stock of “EOL products” is also supplied by the already-recycled metal flow entering a new recycling loop (“recycled metal in EOL products”). At $t_0 + \Delta t$, this “recycled metal in EOL products” flow is equal to the “recycling” flow at t_0 multiplied by CR. We have assumed that all the EOL products are immediately recycled, so that this stock is empty. This assumption implies that the collection rate (CR) used in the present study encompasses both the true collection and recycling rates of EOL products.

The model is run from 1900 to 2100, assuming that i) the installed capacities of

TABLE I. – Energy consumed for the production of concrete, steel, aluminium and copper [12], and collection rates (CR) of metals from the infrastructure of energy or for all goods at the global scale.

	2010	2030	2050	2050/2010
Primary energy of production (MWh/t)				
Concrete	0.3	0.2	0.2	0.84
Steel	6.11	5.1	4.2	0.68
Al	23.6	20.8	18.1	0.77
Cu	8.3	8.3	8.3	1.00
Recycling energy (MWh/t)				
Steel	1.9	1.5	1.1	0.57
Al	2.4	2.1	1.8	0.77
Cu	4.2	4.2	4.2	1.00
CR of metals in the infrastructure (%)				
Steel	0.70	0.70	0.70	1.00
Al	0.70	0.70	0.70	1.00
Cu	0.70	0.70	0.70	1.00
Global CR (%)				
Steel	0.65	0.67	0.68	0.73
Al	0.43	0.47	0.51	0.60
Cu	0.43	0.47	0.51	0.60

nuclear power stations increase linearly from 10 GW in 1950 to 609 GW in 2010, ii) the installed capacities of other fossil fuel power stations and hydropower plants increase exponentially at a constant rate of 3%/yr between 1900 and 2010, and iii) the installed capacities remain constant after 2050.

The amounts of material in the electricity-generation infrastructures are calculated using the material intensities in tons per MW installed capacity listed in table 5.1 of [4]. The energy required to produce the materials are calculated using the values in energy/mass from [12] for primary production and recycling, which are listed in MWh/t in table I. The collection rates (CR) of all metals from the electricity-generation infrastructure have been set at 70%.

3. – Concrete, steel, aluminium and copper requirements for the future electricity-generation infrastructure

For the three scenarios, the needs of copper for renewables represent more than 85% of the total needs (*i.e.* including the other sources of electricity generation). For the blue map scenario, the cumulative stock of primary copper in the infrastructure of electricity generation is about 39 Mt in 2050 (24 Mt primary and 15 Mt recycled, see the graph in the

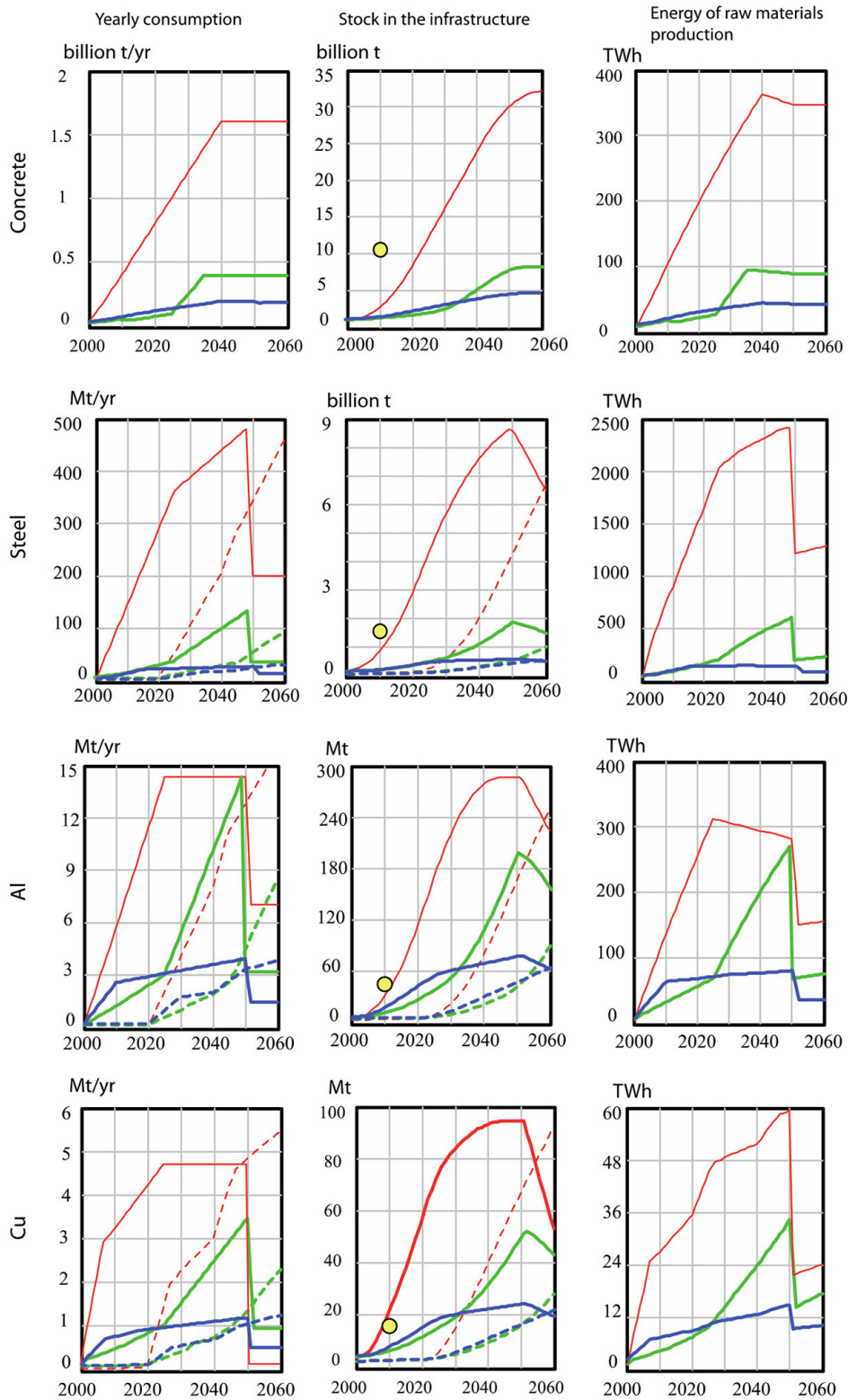


Fig. 3. – Annual consumption (first column) and cumulative requirements (second column) of primary materials (solid lines) and recycled materials (dotted lines) for the deployment of the infrastructure of electricity production. The third column shows the annual energy consumed for primary production and recycling. The red, green and blue lines show the GO, WWF and BM scenarios, respectively. Yellow dots: annual global production.

second column and last row of fig. 3). However, 30% of copper is lost during recycling, so that the true amount of copper to produce by 2050 is about 55 Mt. This estimated value is almost two times higher than that estimated by [5] for the same scenario (29 Mt). The cumulative amount of copper increases to 90 Mt for the WWF scenario (50 Mt primary, 22 Mt recycled and 18 Mt lost) and 205 Mt for the GO scenario (55 Mt primary, 90 Mt recycled and 60 Mt lost), in fair agreement with García-Olivares *et al.*'s [2] own estimates (183 Mt). Finally, the BM, WWF and GO scenarios need 2, 4 and 10 years of the present Cu global production, respectively, which will have to be allocated to the infrastructure of electricity until 2050. In the BM scenario, the annual production of copper assigned to the infrastructure of electricity generation peaks at 2.2 Mt/yr (1.2 Mt/yr of primary Cu) at the end of the deployment period. It drops to 1.6 Mt/yr (0.5 Mt/yr primary) after 2050, which is the flow of virgin Cu required to maintain the infrastructure and balance the loss of recycling. For the GO scenario, the yearly consumption reaches 9 Mt (4.5 Mt/yr primary) and it drops to 5 Mt/year (1 Mt/yr primary) after 2050.

Following our assumption that 70% of copper is recycled, from the infrastructure, primary copper consumption between 2030 and 2050 ranges from 1 to 4.5 Mt/yr for the three considered scenarios. This yearly consumption is equivalent to 5 to 20% of the present global production. García-Olivares *et al.* [2] estimated that the share of copper in the infrastructure of electricity generation represents 55% of the total amount required to achieve the full shift from fossil to renewable energy. The cumulative amount of primary copper to be produced until 2050 could be therefore as high as 270 Mt for the GO scenario and 145 Mt for the WWF scenario, which is equivalent to 7 to 13 times the present annual global production, and 20 to 40% of the known copper reserves. However, it is emphasized that a significant portion of the needed metals comes from recycling. The most exigent scenario (GO) requires 205 Mt copper, but if the infrastructure is recycled for the same use, "only" half of this amount is primary copper.

The cumulative production and consumption of steel and aluminium show trends similar to those of copper (fig. 3). About 500 Mt aluminium are necessary to achieve the GO scenario, 230 Mt for the WWF scenario and 120 Mt for the blue map scenario. These amounts represent 8, 4 and 2 years of the present global production, respectively. The yearly consumptions of primary Al and steel between 2030 and 2050 represent 5% (BM) to 25% (GO) of the present global productions. For the GO scenario, our estimated amounts of steel incorporated in the infrastructure (13000 Mt) are much larger than García-Olivares *et al.*'s own estimates (3800 Mt). The difference stems from the use of different steel contents per MW of installed CSP facilities and to a lesser extend from wind turbines. The steel content used in the present study for CSP technologies (563 t/MW) was estimated by [4] as an average of the literature data and it is similar to the average of the data reported by [5]. In contrast, García-Olivares *et al.* used data representative of Andasol 1 only (180 t/MW). Similarly, the steel content of wind turbines estimated by [4] (166 t/MW) considers a range of on-shore and off-shore installations, while García-Olivares *et al.* used the value of Vesta V-90 (3 MW) turbine only (132 t/MW). As for copper, a strong drop in primary metal consumption occurs after 2050, when the capacity of the installed infrastructure is assumed to remain constant.

The primary metal consumption after 2050 remains however significant (200 Mt/yr, see fig. 3), because the short lifetime of solar and wind infrastructures implies rapid renewal and high losses of material during collection and recycling of the end-of-life infrastructure. For the WWF and GO scenarios, the yearly recycling of metals from the infrastructure after 2050 oscillates around values equivalent to the present global recycling from all manufactured products. To achieve this goal, the present recycling capacities will have to be scaled up significantly.

4. – Generated and consumed energy

The consumed energy to produce the raw materials for the electricity generation infrastructure increases until 2050, it drops sharply after 2050 and remains almost constant until 2100 (fig. 3, last column). For the GO scenario, this energy rises from 63 TWh/yr in 2000 to 3050 TWh/yr in 2050, and it stabilizes at 1650 TWh/yr after 2050. The energy consumed to produce the materials of the infrastructure is thus multiplied by 50 in 50 years, and it is 25 times higher after 2050 than in 2000, even if the installed capacity remains constant. This is due to the fast replacement of wind and solar facilities, which are assumed to have a twenty-year lifetime. Nevertheless, the energy consumed to produce the materials represent only from 2 to 4.5% of the annual energy generated by the infrastructure between 2010 and 2050 and 1.5% after 2050. For the WWF scenario, the energy consumption increases from 63 to 950 TWh/yr between 2000 and 2050 (between 0.4% and 3% of the produced energy) and stabilizes at 400 TWh/yr after 2050. For the blue map scenario, the consumed energy increases to 250 TWh/yr in 2050 and remains below 1% of the produced energy. For the three scenarios, the energy used to produce the concrete, aluminium, copper and steel is less than 5% of the energy generated by the infrastructure. This fraction may appear small, but it omits the energy to produce other components than the generation system of the infrastructure, as well as the energy consumed by the numerous industrial processes that transform the raw materials into complex machines, the construction of the infrastructure, its maintenance and repair operations. Whatever the true amount of energy consumed to build the infrastructure of energy, our results show that greater amounts of energy are needed for the construction and maintenance of fully decarbonized electricity generation infrastructures than for an infrastructure maintaining a fraction of the electricity produced from fossil fuels. The shift to renewables will thus be a source of material and energy overconsumption. The WWF scenario assumes a significant reduction of global energy demand down to 260 EJ/yr (72000 TWh/yr) in 2050 from 393 EJ/yr in 2015 [11]. Is this reduction of final energy compatible with the increasing demand of energy at the global scale? This point is discussed below.

5. – Comparison with future global trends

The results presented above can be compared with the global production of concrete, steel, aluminium and copper as well as the global energy consumed for their supply. At

this end, the model shown in fig. 1 was used and run for each commodity assuming an average lifetime for all goods produced globally. This allowed us to infer the evolution of primary and secondary productions, as well as the energy of production at the global scale. The lifetime of iron (steel), copper and aluminium at the global scale were assumed to be 30 years. The CR of steel was estimated in order to reproduce the 1900 to 2015 production data of crude steel reported by the USGS and the share of primary iron (pig iron) and global scrap steel consumption reported by the AME group [13]. Between 2007 and 2050, the primary production and recycling of steel were assumed to increase from 1300 Mt and 400 Mt, respectively, to 2200 Mt and 1000 Mt, respectively. To reproduce these trends, the collection rate of steel should increase from 0.65 in 2000 and to 0.68 in 2100 (table I). The collection rate of copper was constrained to 0.43 for the period 1930 to 2015 in order to reproduce the yearly amount of copper produced from old scrap since 1960 [14] and the amount of primary copper produced since 1900 reported by the USGS [15]. It was more difficult to find reliable data for aluminium and we assumed a collection rate similar to that of copper. The future primary copper production was assumed to follow the trend estimated by [16] and the future production of steel until 2050 corresponds to the base case scenario of [13], which is consistent with the BM scenario. For aluminium, we assumed a constant growth rate of production that reaches 150 Mt/year in 2050, in agreement with the estimates of [9] ranging from 142 to 190 Mt/yr. The growth rate of concrete production was assumed to increase to 7 Gt/year in 2050, which is slightly higher than the IEA estimates ranging between 5 and 6 Gt/year [9].

For the BM scenario, the proportions of metals for the infrastructure of electricity are 0.8 to 3% of the global production for steel, 1.5 to 6% of aluminium production and 2 to 5% of copper production. These proportions are much higher for the WWF scenario (up to 9.5% for steel, 15% for aluminium and 10% for copper between 2040 and 2050), and become huge for the GO scenario (9% for aluminium and 25% for steel and copper between 2025 and 2050). In the case of copper, the maximum consumption of metals by the infrastructure of electricity is reached at the time of the primary production peak forecasted by [16] and [17]. If these copper peaks occur, the implementation of the WWF and GO scenarios might be compromised by the availability of primary copper. In any case, a significant proportion of the global copper production should be reserved for the generation and use of electricity, and/or substitutes to copper will have to be found. The same trends are observed for the recycled portion. Between 2025 and 2075, 20 to 30% of steel, 10 to 20% of aluminium and 30 to 50% of copper recycled every year should be used for the infrastructure of electricity according to the GO scenario. It must be emphasized that a significant increase of recycled metal is not possible, because the amount of recycled metal is primarily constrained by the flow of metals to the EOL products stock. This flow corresponds to the total production 30 years earlier multiplied by the collecting rate. About 850 Mt of crude steel has been produced in 2000, while the expected demand in 2030 will be about 2300 Mt. The share of recycled steel in total production will thus be less than 35% in 2030. Actually, the true share of recycled steel in total production is calculated to decrease down to 25% between 2000 and 2010 and to

remain stable until 2030. Steel recycling and the ratio recycled/total should then rapidly increase to reach 45% in 2050. Similar trends are observed for aluminium and copper. In the same time, the substantial increase of (recycled metal)/(total production) ratios after 2030 is accompanied by an equally significant decrease in raw materials energy consumption.

The huge needs in commodities for the GO scenario result from the enormous renewable production of electricity, which reaches 109000 TWh/yr in 2050. In comparison, electricity productions in the WWF and BM scenarios are 29000 TWh/yr and 36500 TWh/yr, respectively. The WWF scenario also assumes a decline in final global energy from 102000 TWh/yr in 2010 [11] to 72000 TWh/yr in 2050. For the energy efficiency improvements considered in table I, the energy consumed by the global production of cement, aluminium and steel is 10700 TWh/yr in 2010 and 17200 TWh/yr in 2050. It follows that the share of global final energy used to produce these commodities increases from 10% to 16% between 2010 and 2050 in the BM and GO scenario. It increases from 10% to 24% over the same period of time in the WWF scenario. If we assume that the industry worldwide will consume one third of the final energy in 2050 (as in 2015), 70% of the industrial consumption of energy should be assigned to the production of cement, steel and aluminium for the WWF scenario (fig. 4). This is quite unrealistic.

Apart from the raw materials availability, the WWF scenario thus raises the problem of available energy for the future global production of mineral commodities. To cope with the problem, the authors of the WWF scenarios assumed a 50 to 60% reduction of energy consumed for the production of cement, steel and aluminium. Part of this reduction can be achieved through an increase of the ratio recycling/primary production of metals, because recycling is much less energy demanding than primary production (see table I). However, as stated above, this ratio will remain unchanged until 2030, because the long lifetime of metals in finished goods implies that their available amounts for recycling are at best 50 to 80% of their primary production 30 to 50 years earlier. In a period of strong growth of metal consumption, the available amounts of old scraps are therefore much less than total production. Another way to reduce the energy of production is to significantly improve the energy efficiency. However, a 50 to 60% reduction of embodied energy of metals production in the next 40 years will be very difficult to achieve. In the past 40 years, the global average energy requirements for production of pig iron from ore and aluminium smelting have been lowered by 25 to 30% only, and steel and aluminium are already close to 60% efficiency relative to their thermodynamic limits [18]. Further energy savings are more and more difficult when approaching these thermodynamic limits. For the 16 to 32% energy improvement considered in the present study (table I), the global final energy must remain above 110000 TWh/yr in 2050 in order to keep a constant proportion of energy consumed by the production of concrete, steel and aluminium below 15%. This value is 40% higher than that envisaged in the WWF scenario, which is extraordinary low compared to the majority of published values, which range between 110000 and 250000 TWh/yr. The final energy consumption assumed by WWF is only one third of the value of the reference case proposed by the International Energy Outlook 2016 (815 PJ/yr = 238800 TWh/yr).

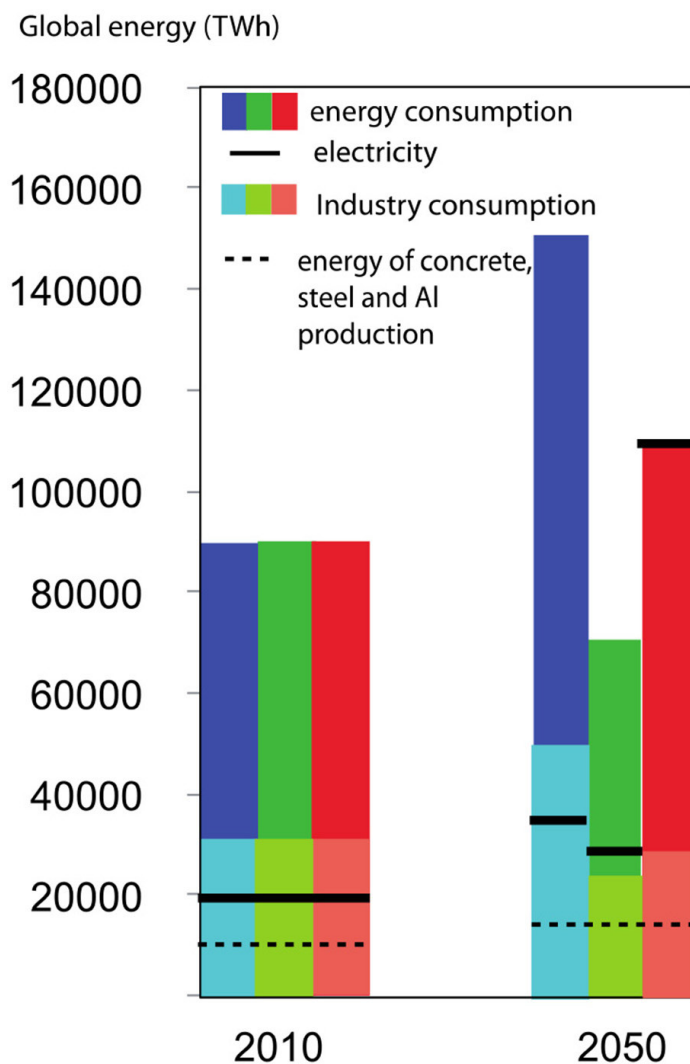


Fig. 4. – Global energy demand and electricity consumptions for the scenarios GO (red), WWF (green) and BM (blue). The industry consumption (black line) is estimated to be 30% of the global energy consumption. The energy consumed for the global production of concrete, steel and Al (dashed lines) is calculated from the relative proportions of primary and secondary production derived from dynamic modelling multiplied by the energies of production listed in table I.

Conclusion

Contrasting needs in raw materials and energy are estimated for the different energy scenarios used in the present study. This reflects the diversity of assumed energy mixes and installed capacities. The huge amount of raw materials required by the scenario GO makes it unrealistic to achieve in a short time. The WWF scenario is less exigent in terms of materials requirements, but the very low final energy production in 2050 is also unrealistic compared to the expected demand. Actually, the needs for the WWF scenario are similar to those of the GO scenario if the capacity to be installed is scaled up to the same value of the final energy. It must be emphasized that our estimates

are fraught with large uncertainties because the variability of metal contents reported in the literature for the different kinds of electricity generation is equally large. This was illustrated by the differences discussed above for the steel content of CSP facilities, but the same uncertainties exist for all technologies and commodities. It is also possible that the energy efficiency of mineral resources production increases more than we have assumed in this study. Having said that, at least three qualitative conclusions can be drawn from the results of dynamic modelling:

- 1) With the current technologies, the transition to low-carbon energies implies a substantial increase in base materials consumption such as concrete, steel, aluminium and copper. This result is in line with previous estimates [1-8] and studies focusing on critical metals [19, 20]. The consumed raw materials and energy are maximum during the building of the new infrastructure of energy, but they remain significant after this period to maintain and renew the wind and solar infrastructures of with a short lifetime.
- 2) The results of modelling show that i) the total amount of metal to produce during the deployment of the infrastructure of energy is significantly higher than the cumulative amount stocked in the infrastructure. This is due to the losses during recycling. Assuming a twenty-year lifetime for the renewables infrastructure and $CR = 0.7$, about 30% of the total copper production is lost by 2050, and 50% is lost by 2100, which will have to be balanced by primary extraction; ii) a significant portion of metals in the infrastructure is supplied by the recycling of the infrastructure. Therefore, the cumulative amount of metals in the infrastructure cannot be interpreted in terms of primary resources consumption. Dynamic modelling is necessary to estimate the true amount of primary metal and other resources required to build the infrastructure. Since the relative proportions of recycled-to-virgin metals as well as the energy mixes both change with time, dynamic modelling should be coupled with ACV analyses to correctly estimate the impacts of the energy transition.
- 3) The needs in materials and energy will occur in a period of expected increase of primary metal consumption at the world scale and limited potential of recycling. The supply of metals from recycling is expected to increase but it will not become higher than primary supply before the full shift to renewable energy.

More work is necessary to reach a comprehensive estimate covering the needs in mineral resources and energy from other sectors of energy such as the storage, distribution and use of electricity for applications that traditionally used fossil fuels, (transport, heating). Cement, steel, aluminium and copper are hardly substitutable and bear the most important part of the energy consumed for the production of mineral resources. The supply and impacts of supply of these basic raw materials that do not present any sign of scarcity yet it is an issue as important as the supply of the so-called “critical elements” produced in much lower quantities and whose use is likely to evolve fast with technical innovation.

* * *

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5.1 Dynamic modeling of global fossil fuel infrastructure and materials needs: overcoming the lack of available data

Dynamic modeling of global fossil fuel infrastructure and materials needs: overcoming a lack of available data

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Abstract

The low-carbon energy transition requires a widespread change in global energy infrastructures which in turn calls for important inputs of energy and materials. While the transport and electricity sectors have been thoroughly analyzed in this regard, that of the hydrocarbon industry has not received the same attention, maybe in part due to the difficulty of access to the necessary data. To fill this gap, we assemble public-domain data from a wide variety of sources to present a stock-flow dynamic model of the fossil fuels supply chain. It is conducted from 1950 to 2050 and along scenarios from the International Energy Agency. We estimate the concrete, steel, aluminum and copper requirements for each segment, as well as the embedded energy and CO₂ emissions through a dynamic material flow analysis (MFA) model. We find that (i) the material intensities of oil, gas and coal supply chains have stagnated for more than 30 years; (ii) gas is the main driver of current and future material consumption; and (iii) recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll. Furthermore, we highlight that regional decommissioning strategies significantly affect the potential of material recycling and reuse. In this context, ambitious decommissioning strategies could drive a symbolic move to build future renewable technologies from past fossil fuel structures.

1. Introduction

Human society and nature interactions have experienced a radical change over the 20th century, driven by the rapid industrialization of Western economies and that of several emerging countries in more recent years [1, 2, 3]. Economic expansion is largely attributable to the availability and affordability of fossil resources, whose high energy return on investment (EROI) have triggered productivity gains [4, 5]. The abusive use of energy has however unleashed unprecedented climate and ecological damages, jeopardizing the planet's life supporting functions [6].

As a tentative response, 196 countries gathered during the 2015 United Nations Climate Change Conference of Paris and agreed to hold the increase in the global average temperature to well below 2°C above pre-industrial levels. Such a target requires deep transformations of our society including, but not limited to, a shift away from fossil fuels to low-carbon energies, which calls for important quantities of energy and materials [7, 8, 9, 10, 11, 12]. While the transport and electricity sectors have been thoroughly analyzed, the hydrocarbons have not received the same attention, to the best of the authors' knowledge¹. This may in part be due to the fact that infrastructure data for the fossil fuel industries are relatively difficult to access, and are often commercially

sensitive. This makes the analysis of this sector particularly complicated for the scientific community not affiliated with fossil fuel producers or operators. To fill this gap, we present a stock-flow dynamic modeling of the infrastructures as a part of the fossil fuels supply chain, from 1950 to 2050 and along scenarios from the International Energy Agency (IEA). We estimate the concrete, steel, aluminum and copper requirements for each segment, as well as the embedded energy and CO₂ emissions through a dynamic material flow analysis (MFA). Finally, the potential of recycling steel from decommissioned fossil fuel infrastructures to build power technologies is further discussed.

This paper is structured as follows. Section 2 examines the existing literature. Section 3 describes the methodology and data used. Section 4 presents the results, section 5 discusses them, section 6 details the robustness and limitations of the study and section 7 concludes.

2. Literature review

2.1. An evolving field

Modeling the stocks and flows of metals or minerals that make the infrastructures has been a research topic for more than twenty years. Early publications focus on static global or regional MFA of the base materials used over the 20th century—such as copper and steel. The Stocks and Flows Project (STAF) launched in 2000 by the Center for Industrial Ecology is one example [13, 14, 15, 16]. These studies allow for top-down analysis, relying on material databases

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¹The relevant literature is reviewed in Section 2.

such as the International Copper Study Group [17] and the World Bureau of Metal Statistics [18]². The authors aim at providing insights in the material cycles within human society, and quantifying the losses-dissipation, landfills-and the potential of secondary use. Materials analysis has progressively evolved towards dynamic studies, and bottom-up approaches³ enable a better understanding of the technological drivers of raw materials demand over time. A significant number of these publications deal with the building sector because of waste generation and secondary resources aspects [19, 20, 21], stock drivers [22], the effect of lifetime [23] or materials demand in transition scenarios [24, 25]. More recently, several authors also analyze the material facet of the energy sector with growing consideration on the consequences of the ongoing energy transition.

2.2. The energy transition challenge

The transition requires vast amounts of minerals and metals [9, 26, 27] due to a significantly higher material intensities of renewables [28, 29, 8] and new technologies [30]. Vidal et al. [8] state that "a shift to renewable energy will replace one non-renewable resource (fossil fuels) with another (metals and minerals)", while Li et al. [31] point out the trend toward a "more metal-intensive energy future" as renewable energy are increasingly being developed. Recent dynamic MFA or simple flow analysis⁴ focus on quantifying the prospective demand in non-energetic materials for a low-carbon energy system in various institutional scenarios (e.g. IEA-450, IEA BlueMap, NDRC scenarios), non-governmental scenarios (e.g. Greenpeace, WWF-Ecofys) or academic scenarios (e.g. SSP). Researchers show that the most environmentally ambitious scenarios display the highest material constraints [34, 35], and identify two areas of concern: criticality, which is defined as the levels of importance in use and availability of a material [36], as well as environmental and energy impacts.

Among low-carbon technologies, the most significant material constraint could stem from solar PV and wind turbines along with power storage [37, 35] and the transmission and distribution networks [38]. A higher level of pressure for rare-earth elements (REE) than for base metals is emphasized, with potential constraint in REE for each PV solar technology [29, 39, 40], region-specific supply risk [41, 42, 43, 44, 45] which require future increase in numerous metal supplies [46, 47] with potential limitations in reserves which could hamper future projects [48]. The downscaling

²A top-down study is defined as a modeling relying on input output tables which assesses stocks from a flow analysis.

³Bottom-up modeling focuses on describing parts of the system in details and then conducting a part-whole modeling.

⁴Further modeling on the topic has been conducted through Life-Cycle Analyses. For example, Kleijn et al. [28] examine the metals demand and CO₂ emissions of low-carbon energies for the power sector, in regard to four different scenarios, while Koning et al. [32] estimate the required extraction of 11 metals until 2050 under technology-specific low-carbon scenarios, for the electricity and road transportation systems and Hertwich et al. [33] take on the issue by approaching the needs in steel, cement, copper and aluminum for power generation technologies in the IEA BLUE Map and Baseline scenarios.

of a global issue to a political scale also paves the way to the criticality literature, estimating potential supply risks for various situations [49, 50, 51, 52, 53, 54, 55]. Future constraint on raw materials also comes from the energy and environmental impact of their production. While the criticality research field focuses on technological materials, impact analyses are mainly conducted on base materials though the link between energy and materials.

2.3. Recycling and the energy-raw materials nexus

The energy-material nexus remains insufficiently addressed in energy transition scenarios, and several authors call for a better understanding of its impact [34, 35] and for a better understanding of the assessment of the emission costs and gains of the energy transition [31]. Elshkaki [39] further estimates that the global energy demand of material production for photovoltaic solar technologies could represent up to 12% of solar power generation in the IEA-450 scenario by 2050, and its CO₂ emissions could reach up to 2.2% of the global emissions. Several policy tools are incorporated in the publications, in order to discuss the upcoming challenges. First, recycling could diversify supply sources to reduce pressure on primary materials [35, 56] for geopolitical purposes [46], and environmental concerns as dilution of metals in deposits rises [57, 58]. However, the short-term objective of energy transition is equivalent to lifetimes of technologies, thus limiting the potential of recycling before 2050 [9, 59, 45]. Second, studies emphasize that material supply pressure could be mitigated by reducing the material content in power generation technologies [40, 34].

2.4. Toward more systematic analysis

The upcoming material challenge is also addressed in integrated assessment models (IAMs), as a necessary step to produce "biophysically more consistent descriptions of society's future metabolism" [60]. IAMs allow to quantify the material requirements in scenarios of low-carbon transitions from a system perspective. For instance, Hache et al. [61, 62] and Seck et al. [63] use a modified version of the TIMES model (TIAM-IPEN) to study the critical materials for the transportation sector electrification, the impact of the future power generation on cement demand and the copper availability up to 2050. Sverdrup et al. [64, 65] and Olafsdottir and Sverdrup [66] focus on nickel, helium, copper, zinc and lead using the WORLD7 model. Using on the MEDEAS integrated assessment model, Capellán-Pérez et al. [67] assess the material investments necessary for a transition to renewable energies, in a Green Growth narrative, concluding it to be unrealistic.

The literature on the metals and minerals supply pressure stemming from the energy transition has been recently booming. However, despite the large share of fossil fuels in the global primary energy consumption, researchers have to date and to the best of the authors' knowledge not explored in detail the material requirements of the industry on a global

scale and in a long-term perspective⁵. This study attempts to tackle this question and fill the relative literature gap that exists today. To do so, the following methodology is carried out.

3. Methods and data

3.1. The DyMEMDS model

The *DyMEMDS* (Dynamic Modelling of Energy and Matter Demand and Supply) model is developed to estimate the needs in primary and recycled materials, as well as the energy and CO₂ emissions resulting from the extraction of these materials, along global or national energy scenarios. The entire energy chain is covered from primary energy to final consumption with forty technologies of energy production, storage, transport, transformation along three sectors of energy use: transport, construction and industry [58]. A multi-sector analysis of material stocks and flows is prepared for further work. Only the fossil fuels supply chain module is described in this section⁶.

Historical infrastructures data and energy scenarios are used to model the hydrocarbon supply chain. When no data are found, we use Gompertz functions of Gross Domestic Product (GDP) and population or correlations with the energy supply. Technological material intensities, recycling rates, normal lifetime distributions and end-of-life recycling rate (EOL-RR) are used to estimate retrospective and prospective flows and stocks of materials. Indirect impacts of the materials demand are evaluated relying on state-of-the-art works on embodied energy and CO₂ emissions of materials. A local sensitivity analysis is finally conducted to assess the effects of the mean lifetime and materials intensities uncertainties. Figure 1 presents the methodology lying behind the *DyMEMDS* model.

The most important box, 'raw materials stocks and flows', can be extended for further clarification. The *primary production flow* in tons/year feeds an *in-use stock* in tons of materials immobilized in the infrastructure. At the end of the lifetime of the infrastructure considered, the *in-use stock* is reduced by the flow of materials to be recycled. Normal lifetime distributions are considered in this study. The *losses flow during the recycling process* thus feeds the *cumulative losses stock*, while the *end-of-life recycling flow* builds a *recycled stock*. The latter then allows for secondary production of a *recycled materials flow*, which is ultimately reused in the *in-use stock*. New infrastructures thus mobilize primary and secondary production. In the specific case of a reduction of the infrastructure stock, there is a dismantling before the end of the life span. An *unused flow* is then created, ultimately feeding an *unused stock*, which then follows a recycling path. This stock could eventually produce a *reused flow* for other infrastructures. The infrastructures embodied energy and CO₂ emissions are finally estimated through assumptions about the material production energies

⁵Only Wang et al. [68] proposed an estimation of the steel weight of the drilled wells and the transportation pipelines in China.

⁶A detailed description of the inputs is provided in the Supplementary Information.

and CO₂ emissions. Figure 2 details the key loop used in the *DyMEMDS* model to estimate the stocks and flows of materials during the construction and maintenance of the infrastructure.

3.1.1. Infrastructures

The infrastructures considered in this study are separated into three main segments according to the historical distinction made in the petroleum industry: upstream, midstream and downstream activities. It totals 11 technologies used in supply activities from exploration to distribution. The fossil fuels supply chain encompasses a larger number of infrastructures some are excluded due to a lack of data (oil tanks, national coal transport and processing), large disparities in the data obtained (drilling rigs)⁷, or difficulties to model future distribution in technologies related to decentralized demand (petrol stations and compressed natural gas services). Figure 3 displays the infrastructures typology used in *DyMEMDS*.

3.1.2. Dynamic evolution of infrastructures

A stock-driven approach is conducted in order to model the dynamic evolution of fossil fuels associated infrastructures. The evolution of technology stocks is assumed to be correlated with the fossil fuels production (eq 1)⁸. Infrastructures are then attributed to a fossil fuel, either fully (eg. oil tankers only carry petroleum products) or in a proportionate manner (eg. wells produce both oil and gas). In this case, the evolution of each infrastructure stock is correlated to its related share of fossil products in the supply chain using historical and prospective shares of oil, gas and coal traded from BP [71] and the IEA⁹ [72].

Substantial annual variations are observed in hydrocarbon production, but only wells experience significant upwards and downwards annual changes. An adapted function of each fossil fuel supply was established to prevent these variations. It is defined as a third-order exponential moving average¹⁰ (eq 2), which enables both to smooth out the short-term impact of price variations on production and to overweight the more recent values.

$$S_{t,i} = \alpha_i \cdot \text{EMA}_{3,P_i}(t) \quad (1)$$

$$\text{EMA}_{3,P_i}(t) = P_i(t) \cdot 0.5 + \text{EMA}_{3,P_i}(t-1) \cdot 0.5 \quad (2)$$

⁷Significant disparities were observed in both material intensities and rigs census. It is explained by both the recent and rapid development of floating structures and the wide range of structure sizes.

⁸Some researchers rely on logistic or Gompertz functions, see for instance the work of Gutiérrez et al. [69] for vehicle stocks and Huang et al. [70] for buildings stocks. The link between hydrocarbon technologies and energy prices, as well as political decisions (e.g. OPEC's influence on prices) hamper the application of this methodology here.

⁹A high share of traded oil is noticed, while coal and natural gas are mostly consumed locally.

¹⁰A moving average is defined as an average of a predefined number of past values in a dataset, which are weighted equally in its simple form. In its exponential form, the weight of the values decreases exponentially, which enables to overweight the more recent data.

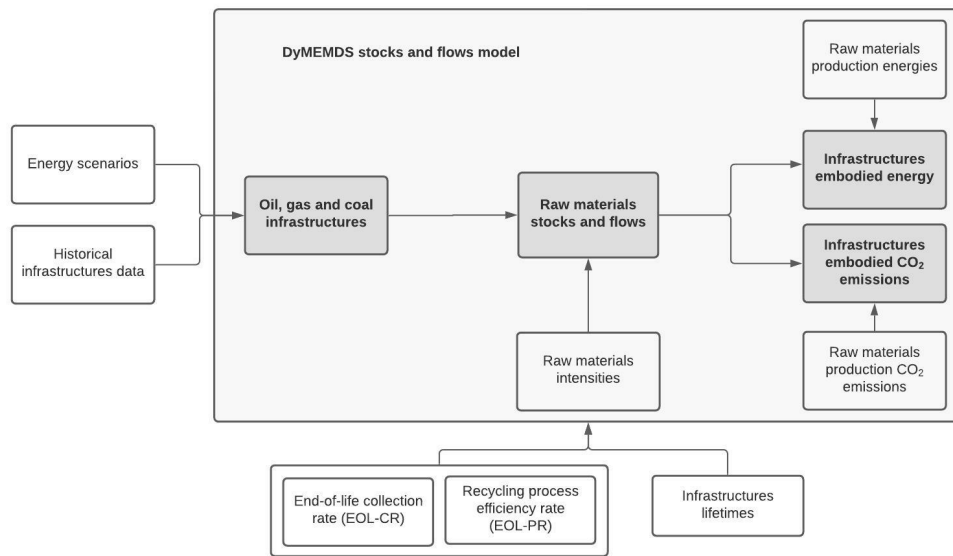


Figure 1: Simplified methodology lying behind the *DyMEMDS* model.

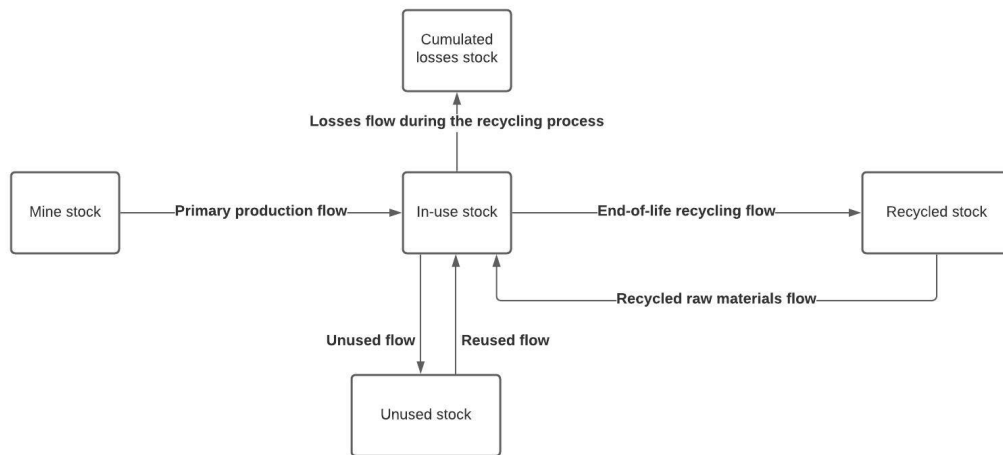


Figure 2: Key loop used in the *DyMEMDS* model to estimate the stocks and flows of materials during the construction and maintenance of the infrastructure.

With $S_{i,t}$ the stock of infrastructure i in the year t , α_i the correlation coefficient for the infrastructure i and $EMA_{3,P_i}(t)$ the third-order exponential moving average in year t of the hydrocarbon supply P_i related to the infrastructure i .

3.1.3. Material recycling

This study focuses on four bulk materials, namely aluminum, concrete, copper and steel, which represent a significant share of material consumption [73], energy demand and environmental impacts of material production [74]. No material substitution is assumed for the base materials, but some studies present contrasted views, e.g. Sverdrup et al. [75, 76] A dynamic end-of-life recycling rate (EOL-RR) is assumed for each material, encompassing both the recycling process efficiency rate (EOL-PR) and the old scrap collection rate

(EOL-CR), as defined by Glöser et al. [77] and Graedel et al. [78]. A global and multi-sectoral averaged EOL-CR is assumed in this study. Table 1 summarizes the considered rates.

	1950	2010	2030	2050
Concrete	0	0	0	0
Steel	0.6	0.7	0.74	0.84
Aluminum	0.39	0.45	0.48	0.54
Copper	0.34	0.4	0.42	0.48

Table 1
End-of-life recycling rates of the considered materials.

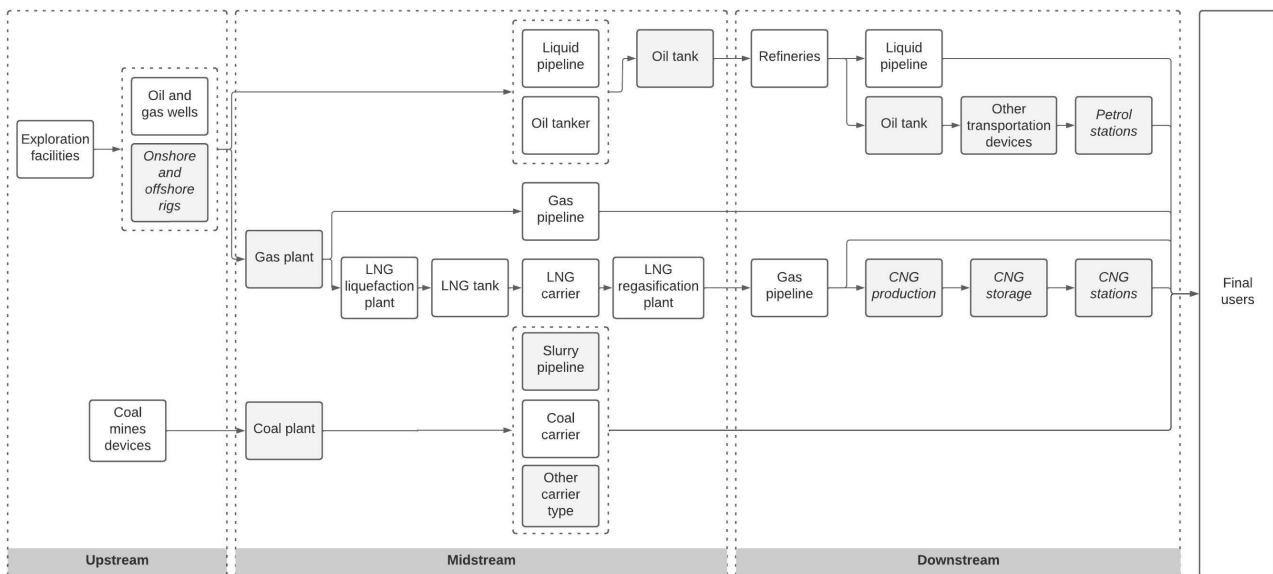


Figure 3: Oil, gas and coal infrastructures from production to final users supply. The infrastructures in grey and italic are not considered in this study.

3.2. Materials, energy and CO₂ intensities

The material requirements for the hydrocarbon production infrastructures are obtained from Monfort et al. [79]. The dataset extensively relies on the Ecoinvent database¹¹, which provides with useful data for a large panel of infrastructures. Remaining intensities are obtained from both academic publications and private firms reports. The material intensity data used in this study come mostly from sources dating from the 1960s to the 2000s. The correlation between infrastructure stock and hydrocarbon production justifies the temporal validity of these data for the study, since nearly 60% of historical oil production and 57% of historical gas production took place between 1960 and 2000 [80]. The embodied energies of primary and secondary materials are dynamic between 1900 and 2100, and their scope extends from cradle to gate. Primary metals embodied energies depend on both the ore grade of the mined material and the technological improvement of production technologies [81, 82, 83]. Data from Vidal [84] and Vidal et al. [85] are considered for copper, aluminum, and steel (assuming all steel alloys represent steel). The production energy of concrete is estimated from a multi-regional approach to cement production and clinker energy intensities. Energy of metal recycling is assumed to be consumed during secondary production as a fraction of the energy of primary production. An annual technological progress in production processes of 1% is estimated between 1900 and 2100, as well as a floor value equal that of the thermodynamic limit of the recycling processes. The minimum energy of recycling equals the melting energy of each metal plus the energy of collection and sorting. CO₂ intensities of materials production are also considered in the model:

¹¹The Ecoinvent database contains life-cycle inventory data for a wide range of technologies, with a thorough documentation on their hypothesis and validity (e.g. geographical and temporal).

they are dynamic and vary according to the CO₂ intensity of the energy consumed over time. We consider a decreasing intensity since 1900, and assume that 83g of CO₂ are emitted by MJ of consumed energy in 2015. This value is supposed constant from 2015 onward.

3.3. Scenarios

Two scenarios from the International Energy Agency (IEA) are selected: the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 (NZE) [86, 87].

- The STEPS considers government measures already in place or officially announced and envisions a quick return to pre-COVID-19 consumption levels. By 2050, the electricity mix is 55% renewable, coal consumption falls by 15% from 2020, oil consumption rises by 15% and gas consumption rises sharply by 50%. The effects of climate change are limited to an average global warming of 2.7°C in 2100 compared to pre-industrial levels (Fig. 4).
- The NZE scenario offers a more ambitious approach. Considered by the IEA as a deepening of the former Sustainable Development Scenario (SDS) [88], it assumes the achievement of a carbon neutrality of the energy sector by 2050, which allows to limit the average global warming to 1.5°C. Renewable energies play a predominant role, with solar and wind power accounting for nearly 70% of electricity production in 2050. Moreover, energy demand falls by 7% between 2020 and 2050, with a decline in coal consumption of 90%, 75% for oil and 55% for gas over the same period (Fig. 4). When some information is missing, data from the Sustainable Policies (SP) scenarios are used instead [72].

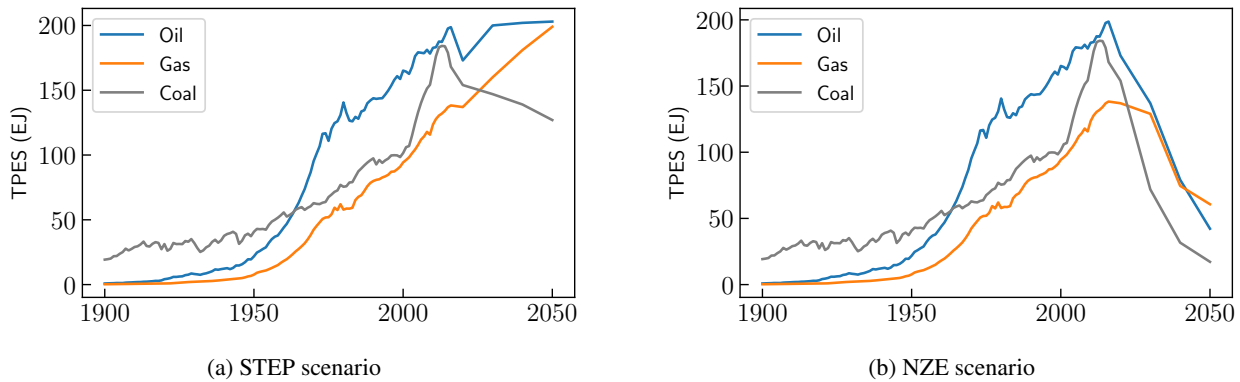


Figure 4: Historical and prospective global primary energy supply from fossil fuels in the STEPS and NZE scenarios.

3.4. Sensitivity analysis

A local sensitivity analysis was conducted to assess the impact of the input parameters uncertainties on outputs. Previous studies showed the significant share of lifetime uncertainty impacts in sensitivity analysis [23, 89], and further pointed out that the standard deviation and shape of lifetime distributions had little effects on the results compared to the mean value [90, 77, 91]. The sensitivity analysis therefore focuses on the mean lifetime value in the normal distribution, for which variations of $\pm 20\%$ were computed.

4. Results

4.1. Infrastructures

4.1.1. Gas

The gas infrastructures experience a significant increase in the STEPS and a drop after a peak in 2030 in the NZE scenario. The largest increase in infrastructure occurs for gas in the STEPS. The world fleet of LNG carriers reaches more than 1200 units in 2050 in the STEPS, the storage capacity exceeds 136 million cubic meters and the total capacity of liquefaction and regasification plants doubles to more than 3700 billion cubic meters between 2020 and 2050. Conversely, the carbon neutral NZE scenario involves 40% decrease in total LNG supply chain capacity between 2020 and 2050. The number of LNG carriers drops to 376, after peaking at 788 vessels in 2030. The global pipeline network displays a similar trend, raising to 15 million kilometers in 2050 in the STEPS, and dropping to less than 5 million kilometers in the NZE scenario (Fig. 5). The modeled values of the infrastructures stocks are available in the Supplementary Information.

4.1.2. Oil

Two trends of the infrastructure of the oil supply chain can be identified. After a slight increase between 2020 and 2030, the stock stabilizes in 2030 in the STEPS, while a slowdown is observed in the NZE scenario between 2020 and 2025 and followed by a substantial reduction. This unveils a significant constraint on the infrastructures mobilized in the oil supply stages. Pipelines, tankers and refineries experience a drop in their stock by nearly 75% between 2020

and 2050. The number of pipelines decreases to 242,000 km, and the tanker fleet to only 150 Million Dead Weight Tons (MDWT)¹². In the STEPS, the growth of the traded oil shares combined with the rise of the oil consumption induces a faster development of transport infrastructures than storage or refineries. The stock of petroleum products pipelines reaches 1.08 million kilometers in 2050, and the fleet of tankers 670 MDWT, while the global refining capacity increases to nearly 108 million barrels per day. Wells development depends the cumulative consumption. The number of wells thus slightly raises from 1.35 million to 1.4 million in 2050 in the STEPS and experiences a substantial decrease to 300,000 in the NZE scenario (Fig. 5).

4.1.3. Coal

The two global scenarios consider a drop in coal consumption between 2020 and 2050, albeit of varying magnitude. The bulk carrier fleet thus collapses over the period and finally reaches 150 MDWT and 21 MDWT in 2050, respectively, in the STEPS and NZE scenarios (Fig. 5).

4.2. Materials

Steel is the main source of materials requirements for fossil fuels. It represented nearly 70% of the sector materials demand between 1950 and 2020, and the remaining 30% is mainly concrete. In contrast, aluminum and copper consumption represent 0.04% and 0.06%, respectively. However, these proportions conceal major disparities in absolute annual consumption, depending on the evolution of the oil, gas and coal markets. A first peak in consumption can be observed in 1973, following the increase in hydrocarbon consumption since the early 1940s. The annual demand for concrete raised from 2.8 Mt/yr to 42 Mt/yr and steel consumption grown from 4.4 Mt/yr to 64 Mt/yr between 1940 and 1973. The succession of two oil peaks in 1973 and 1979 then reduced the demand for materials to almost zero for steel, concrete and copper, while the dependency of aluminum demand to oil products infrastructures drove its value to zero. The knowledge of historical material demand

¹²The DWT is a unit of the total carriage capacity of a vessel, including all types of goods and passengers.

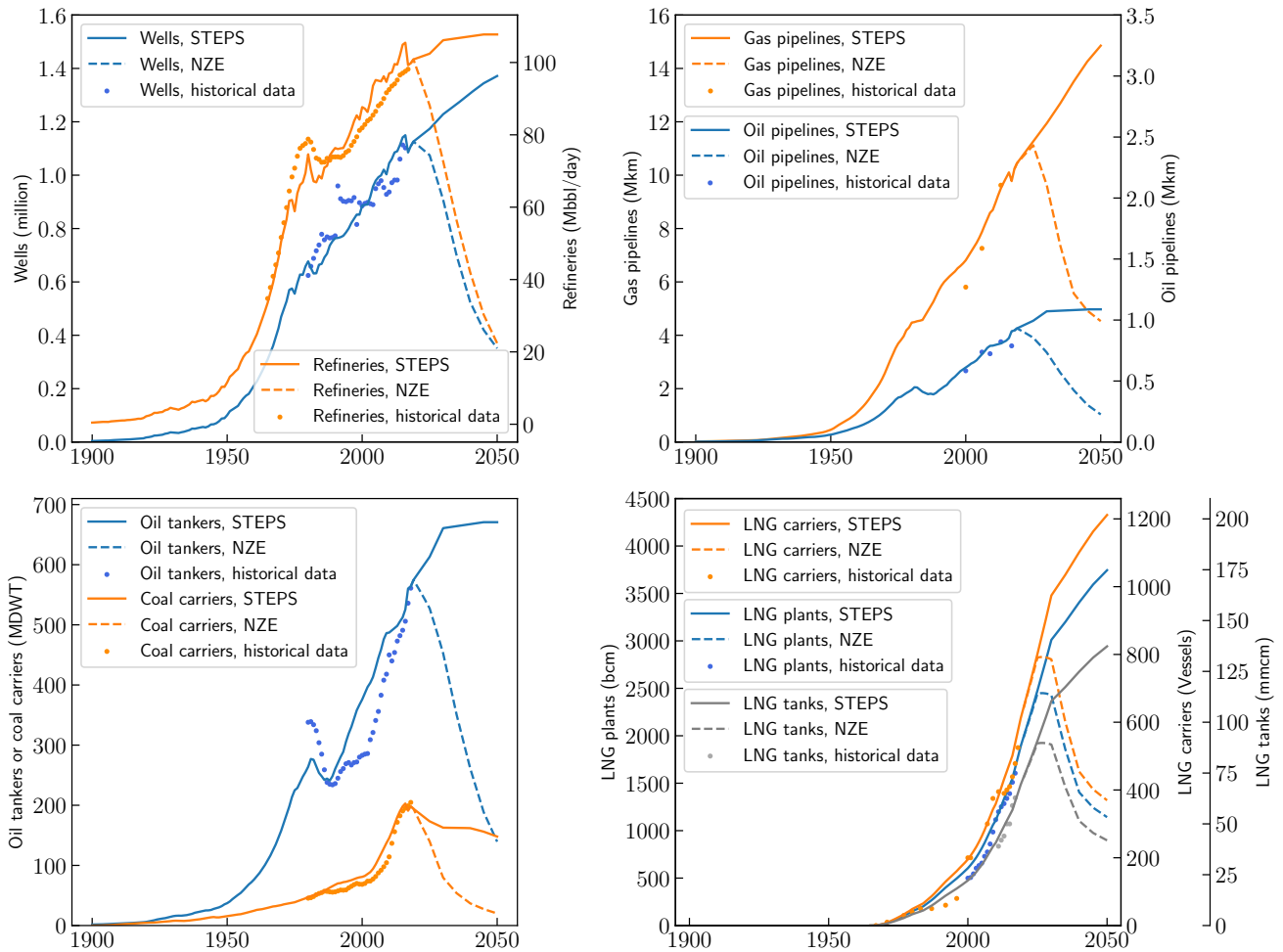


Figure 5: Historical and prospective stocks of key infrastructures in the STEPS and NZE scenarios, global scale.

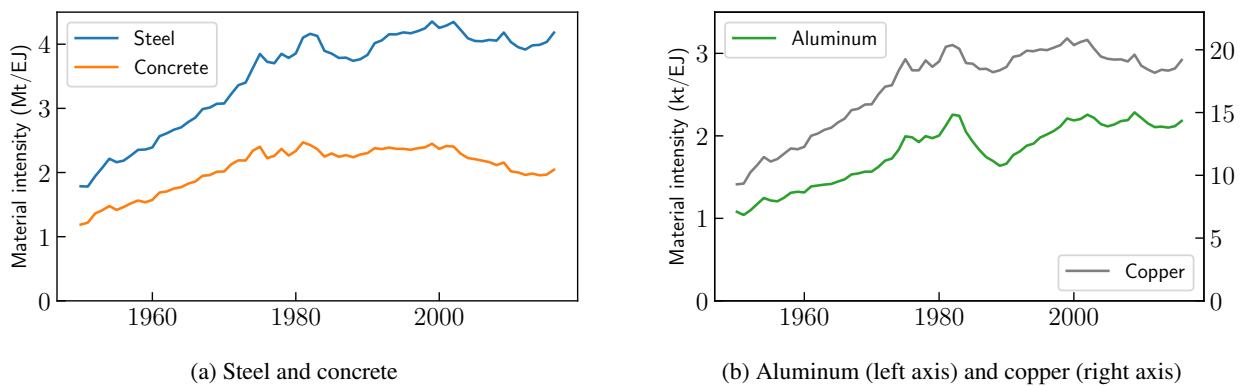


Figure 6: Historical material intensities in the fossils supply sector from 1950 to 2016.

allows to estimate historical materials intensities for the global fossils supply chain. Their values between 1950 and 2016 are displayed in Fig. 6. We observe a stabilization of their level since the 1970s, despite a significant drop in the sector’s aluminum intensities in the 1990s.

4.2.1. Material consumption in the scenarios

The historical distribution pattern of the cumulative consumption among the four structural materials remains similar in the scenarios. Steel accounts for 70% of the cumulative sectoral material demand between 2020 and 2050 for the STEPS and over 77% in the NZE scenario. The share of concrete in the total consumption experiences a decrease in

the scenarios considered and aluminum and copper shares remain low. The increase of the hydrocarbons demand until 2025 induces higher peak material requirements than those observed historically. The steel, aluminum and copper demands respectively reach 96 Mt, 80 kt and 0.44 Mt in 2025. In the STEPS, the cumulative flow of steel needed between 2020 and 2050 is 2.4 Gt and that of concrete exceeds 1 Gt. This represents 1.4 years of total global production at 2020 levels for steel, and a small amount compared to an estimated total global production of 20 to 24 Gt in 2020 for concrete [92, 93]. The NZE scenario requirements reach 0.34 Gt for steel and 0.1 Gt for concrete. An identical trend is observed for copper and aluminum. The cumulative demand for copper reaches 11 Mt in the STEPS, compared to a total global production of 20 Mt in 2020, and cumulative demand drops to only 1.5 Mt in the NZE scenario. The total aluminum requirements amount to 0.86 Mt for the STEPS and 51 kt for the NZE, which respectively represents 1.3% and 0.08% of 2020 total global production. The combination of this lower consumption and the identical historical stock allows the NZE scenario to rely more heavily on recycled materials. The proportion of recycled metals reaches more than 80% in the NZE scenario, and 29% to 42% in the STEPS scenario. The stock of concrete reaches more than 1.2 billion tons in 2050, while a substantial drop to 0.35 billion tons is observed in NZE scenario. This trend is similar for the three structural metals, and steel stock amounts to 2.9 billion tons in the STEPS and 0.82 billion tons in the NZE scenario in 2050 (Fig. 7). The peaks and drops observed in the stock evolution in 2017 are explained by the differences between the historical and prospective data.

4.2.2. *Material consumption per fossil fuels and segments*

The oil and gas infrastructures represent most of the raw materials, which is explained by the complexity and decentralization of the supply infrastructures. The aluminum is entirely consumed by the oil product pipelines for all scenarios—due to underlying data—and the midstream segment therefore dominates aluminum consumption. Conversely, the split between oil and gas remains more equal for concrete, steel and copper, although there is a clear trend towards an increase in the share of gas in materials demand over time. The share of gas in concrete consumption evolves from 30% to nearly 60% between 1950 and 2050 and from 45% to nearly 70% over the same period for steel. The distribution between the segments also shows important differences. The upstream segment represents most of the concrete demand between 1950 and 2050—in the production of wells—while a more equal distribution is observed for steel and copper.

4.2.3. *Material consumption per infrastructures*

The bulk materials demands show high level of domination of some infrastructures. Wells represented about 80% of concrete consumption until 1970 and their share declined with the progressive development of gas pipelines,

which share reaches about 25% in 2050 in the STEPS. A slight increase of the oil pipeline share was noticed, finally reaching 5% in 2050. The gas network also carries most of the sectoral steel demand. Its share experienced a rise from 45% of the consumption between 1950 and 1970 to almost 60% in 2050 in the STEPS. The wells have an opposite profile and the oil pipelines represent 20% of steel demand over the period. Copper is mostly consumed in steel alloys in the hydrocarbon supply chains. It therefore displays a distribution profile similar to steel. Finally, nearly all aluminum is consumed in oil pipelines—due to the underlying data.

4.2.4. *Opportunity and uncertainties in the future amount of recycled materials*

The share of recycled materials in the hydrocarbon supply chain increased over time. It evolved from 3% in 1950 to nearly 20% in 2020, with disparities depending on the metals considered. A future stabilization or drop in the fossil fuels demand could further induce a substantial rise of the recycled share of metals inflow in 2050, as pointed out in the STEPS and NZE scenarios. The combination of this trend with a lower production energy of recycled metals results in an overall decline of the embodied energy and CO₂ emissions in the oil, gas and coal infrastructures. A high recycling content of material depends on the EOL-RR of the hydrocarbon supply industry, which could be hampered by the evolution of the EOL-CR of the fossil fuels supply sector. The future of the unused infrastructures is a growing research field (e.g. OGUK [94] in the United Kingdom and Kaiser [95] in the Gulf of Mexico), and regional political decommissioning strategies will have significant impacts on the EOL-CR. Simulation of several decommissioning strategies by declines of 20% and 50% of the EOL-CR on the obsolete stock of steel are displayed in Figure 8. An estimated 0.8 billion tons of steel alloys are estimated to be accumulated in landfills or leave in-situ by 2050 in the STEPS. A decrease by half of the EOL-CR could lead to a substantial rise of this amount to almost 2 Gt by 2050. Similar results are observed in the NZE scenario, which is explained by the time-delay impact of the lifespan on end-of-life flows. The decommissioning scenarios will therefore have significant effects on the possibilities of recycling.

4.3. *Associated energy and CO₂ emissions*

The energy consumed to produce the materials increased significantly between 1950 and 2019. A domination of steel is observed in the historical and future results. It raised from 0.5 EJ to more than 1 EJ between 1950 and 2019, which represents about 0.15% of the world's primary energy demand in 2019. The energy requirements experience a slight drop to 0.96 EJ in 2050 in the STEPS and to only 0.08 EJ in the NZE scenario in 2050 (Fig. 9). This represents 0.1% of global final energy consumption in 2050 in the STEPS scenario and 0.02% in the NZE. A substantial rise is observed in the CO₂ emissions of sectoral materials production between 1950 and 2019. It evolves from 50 MtCO₂ to more than 130 MtCO₂, i.e. 0.4% of global emissions in 2019. They first peaked at more than 200 MtCO₂ in 1973, before decreasing sharply in

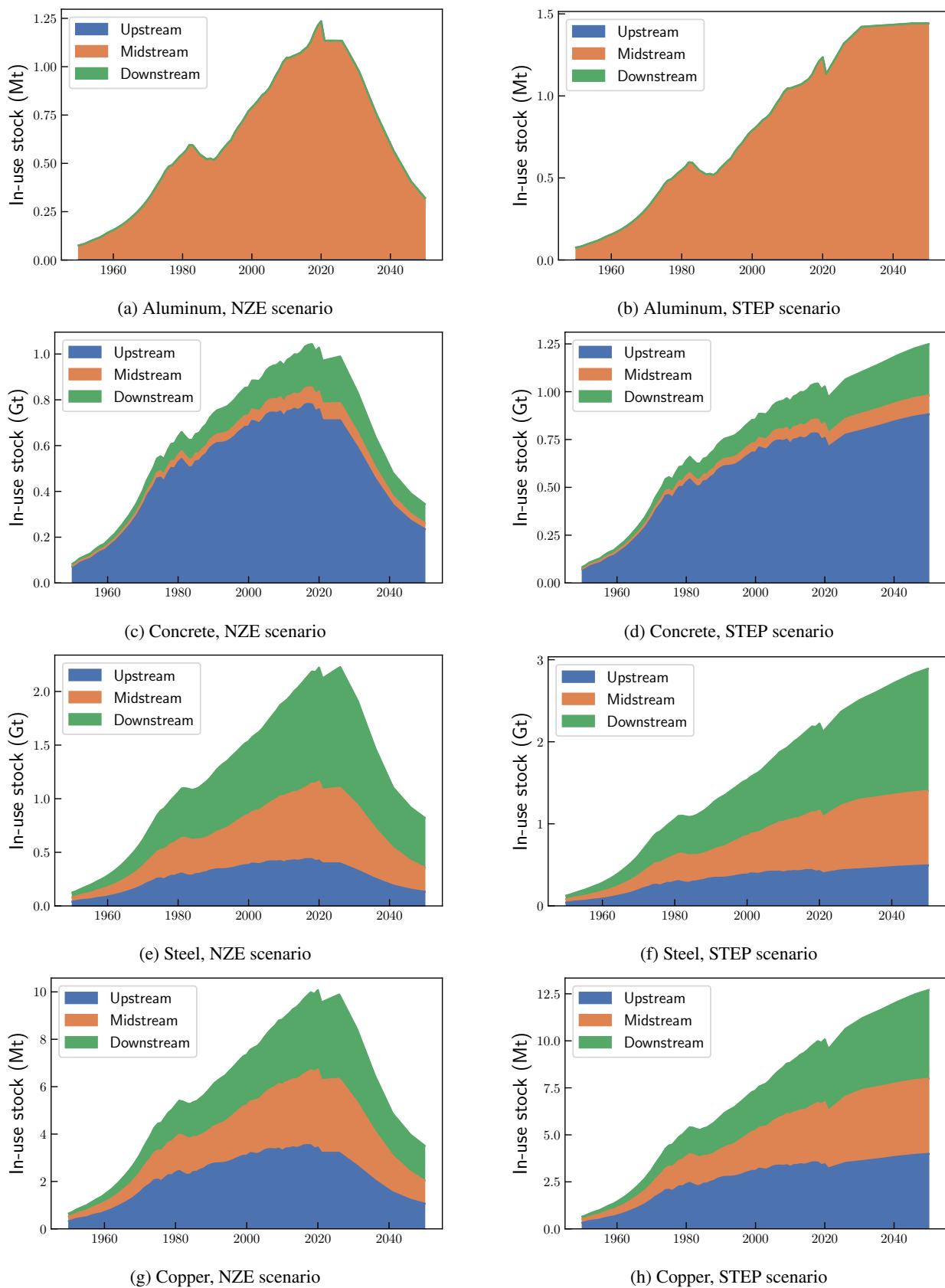


Figure 7: Historical and prospective stocks of structural materials in the NZE (left column) and STEPS (right column) scenarios.

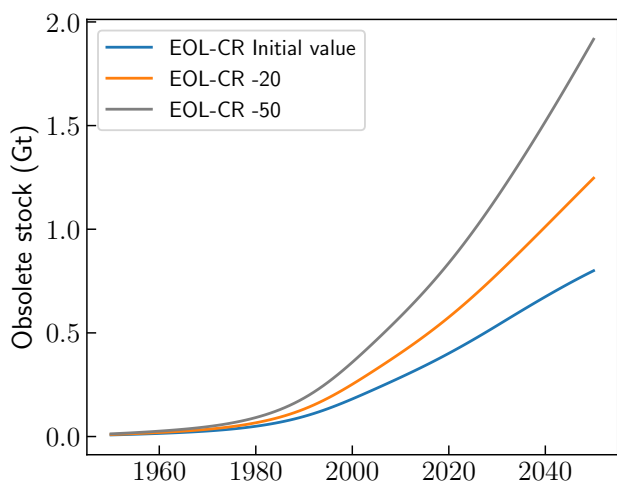


Figure 8: Obsolete steel stock in the hydrocarbon supply chain from 1950 to 2050 in the STEPS.

the 1980s. The trajectories observed in the scenarios allow for a slow decrease to 86 MtCO₂ in 2050 in the STEPS scenario and a significant drop to 25 MtCO₂ in the NZE scenario (composed only of recycling-related emissions, Fig. 9).

4.4. Sensitivity analysis

The local sensitivity analysis focuses on the mean lifetime value, for which variations of $\pm 20\%$ were computed. The results show that the materials inflows vary between -11% and $+14\%$, and the outflows changes range from -14% to $+19\%$. Higher impacts are observed in the outflows than on the inflows, as well as in the STEPS than in the NZE scenario.

5. Discussion

5.1. Drivers of demand and materials intensities in the fossils supply sector

The bulk materials computed in this study display different drivers. It was found that the midstream and downstream segments are the main drivers of steel, copper and aluminum demand. Conversely, the upstream segment constitutes the main consumer of concrete, ahead of the midstream activities. Those global findings can be extrapolated to national oil, gas, and coal industries. Indeed, a segmentation of countries depending on their profile (producer and/or consumer, oil, gas and/or coal) allows to estimate their materials demand pattern. A mainly consumer country is assumed to have a developed upstream segment on its domestic territory and thus a more significant share of concrete in the material demand than the global share depicted in this study. However, detailed sector data are required to accurately assess national materials demands. Sector materials intensities for the global fossils supply chain were estimated in this study (Fig. 6), and further intensities by segments were assessed (Figures S9 to S12 in the Supplementary Information). It allows for a first order evaluation of the materials consumed

per EJ of fossils produced and can be useful in future top-down materials modeling studies.

5.2. What potential for fossil fuels structures to provide materials for the energy transition?

The estimated amount of materials consumed in the hydrocarbon supply chain remains low compared to the global demand—with about 5% of the steel consumption, 1.7% of the copper and smaller share for aluminum and concrete—and to others sectors. A comparison of material intensities, annual demand, cumulative demand and in-use stock with previous studies is provided in Table 2 for both the power infrastructures and the fossil fuels supply chain. The renewable and fossil primary energy supply in scenarios considered in the studies are summarized in Table 3. The current steel demand and in-use stock estimated in this study are higher than in the power infrastructures computed by Deetman et al. [38], while concrete, copper and aluminum needs remain well below. A similar trend is observed for the in-use stocks, and an estimation of the base materials need for the fossil fuels infrastructures in SSP2 BL and SSP2 450 are provided in Table 2 for comparison basis with the results for renewable energies, grid and storage in Deetman et al. [38]. Conversely to copper, aluminum and concrete, the steel in-use stock in the fossil fuels supply chain remains twofold the amount in the renewables and power infrastructures in 2050.

Only the recycling of steel from end-of-life or decommissioned fossil fuels structures could potentially provide a significant contribution to the construction of low-carbon infrastructures. However, it will depend on both future fossil fuel and renewable supply. Relying on data scenarios and sectoral material intensities (Table 2), an estimation of the available recycled steel is provided in Table 3 and hereafter compared with the cumulative demand for the renewable technologies. An EOL-RR of 0.8 was assumed, and the actual available amounts will ultimately depend on the evolution of the collection rate, as depicted in Section 4.2.4. We observe that the increase of fossil fuels demand in the STEPS, SSP2 BL and 450 hinders any secondary steel use in the construction of low-carbon infrastructures. Conversely, moderate reduction of fossil consumption in the BlueMap, 2D and B2D scenarios could allow to partially supply the cumulative steel need of the power technologies¹³. Finally, significant amounts of steel could be recycled in the WWF-Ecofys, NZE and GO scenarios, which would potentially meet the cumulative steel demand of the renewable and power storage infrastructures in the WWF-Ecofys scenario. It would only represent about 17% of the need in the GO scenario, which considers a 100% renewable energy mix. Through intensive recycling of decommissioned infrastructures, the accumulated steel stock in the fossil fuels supply chain could therefore represent an achievable means to reduce the energy and environmental toll of material use for the energy transition.

¹³Careful attention must be paid to the technological scope of each study.

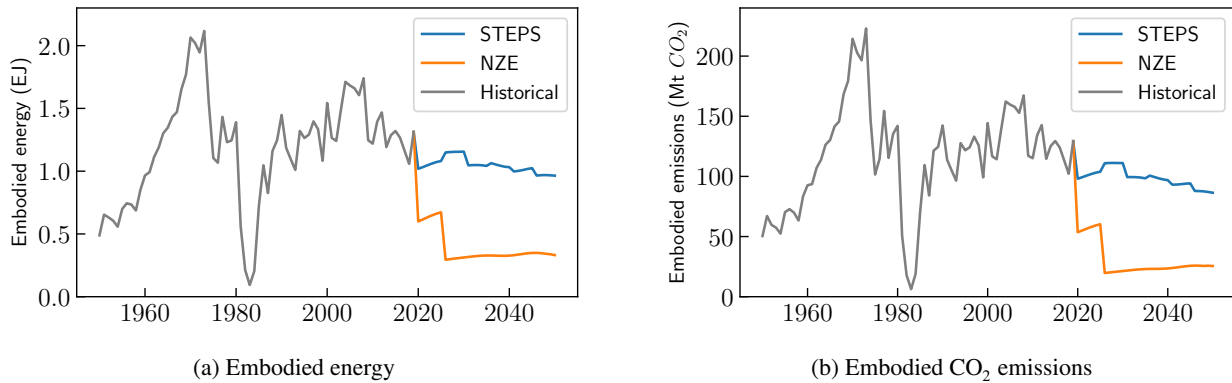


Figure 9: Embodied energy and CO₂ emissions of materials supply in the STEPS and NZE scenario.

References	Steel (iron)	Concrete	Copper	Aluminum	Years	Technologies	Scenarios
Sectoral material intensities (Mt/EJ)							
Deetman et al. [38]	5.9	54	0.4	1.5	2015	PG+G+S	Historical
This study	4	2	0.02	0.002	2015	HU+HM+HD	Historical
This study	3.8	2.5	0.023	0.006	2015	Oil	Historical
This study	9.7	3.8	0.038	0	2015	Gas	Historical
Demand (Mt/yr)							
Deetman et al. [38]	29	184	2.1	7	2015	PG+G+S	Historical
This study	79	30	0.4	0.04	2015	HU+HM+HD	Historical
Deetman et al. [38]	58	108	4.2	14	2050	PG+G+S	SSP2 BL
Deetman et al. [38]	75	227	4.9	16	2050	PG+G+S	SSP2 450
Vidal [9]	50	200	1.7	5.5	2060	R	Bluemap
Vidal [9]	600	1600	5.5	23	2060	R	GO
This study	2.3	0.2	0.01	0.005	2050	HU+HM+HD	NZE
This study	86	34	0.37	0.05	2050	HU+HM+HD	STEPS
Cumulative demand (Mt)							
Vidal et al. [57]	1,000	N/A	40	160	2000-2050	R	Bluemap
Vidal et al. [57]	12,000	N/A	200	300	2000-2050	R	GO
Månberger and Stenqvist [96]	N/A	N/A	40-170	N/A	2010-2050	R+T	B2D
Moreau et al. [59]	840	N/A	57	94	2010-2050	R+S	WWF
Moreau et al. [59]	1,500	N/A	32	46	2010-2050	R+S	2D
Moreau et al. [59]	900	N/A	78	130	2010-2050	R+S	IRENA REMAP
This study	1,000	390	4.6	0.6	2010-2050	HU+HM+HD	NZE
This study	3,200	1,300	14	1.9	2010-2050	HU+HM+HD	STEPS
In-use stock (Mt)							
Deetman et al. [38]	521	4,772	38	132	2015	PG+G+S	Historical
This study	2,000	1,000	9.3	1.1	2015	HU+HM+HD	Historical
Deetman et al. [38]	1,456	9,199	98	365	2050	PG+G+S	SSP2 BL
This study	2,880	1,390	12.6	0.77	2050	HU+HM+HD	SSP2 BL
Deetman et al. [38]	1,413	8,386	91	319	2050	PG+G+S	SSP2 450
This study	2,700	1,340	12	0.86	2050	HU+HM+HD	SSP2 450
Vidal [9]	5,000	1,200	40	120	2060	R	Bluemap
Vidal [9]	32,000	13,200	140	480	2060	R	GO
This study	820	350	3.5	0.3	2050	HU+HM+HD	NZE
This study	2,900	1,250	12.7	1.4	2050	HU+HM+HD	STEPS

Table 2

Summary of the materials intensities, demand, cumulative demand and in-use stock consumed in the power generation, storage and grid infrastructures and comparison with the hydrocarbon supply chain. PG = power generation, R = renewables, G = power grid, S = power storage, T = electric transportation, HU = hydrocarbons upstream, HM = hydrocarbons midstream, HD = hydrocarbons downstream, GO = scenario by García-Olivares et al. [97]. Value do not sum due to rounding.

Scenario	Year	Renewable supply (EJ)	Fossil supply (EJ)	Total TPES (EJ)	Estimated available recycled steel (Mt)	Reference
Historical	2015	23	370	474	N/A	IEA [98]
SSP2 BL	2050	84	694	842	0	Riahi et al. [99]
SSP2 450	2050	98	590	771	0	Riahi et al. [99]
Bluemap	2050	125	297	674	510	IEA [100]
WWF-Ecofys	2050	144	13	262	1,500	Singer et al. [101]
2D	2050	152	269	633	470	IEA [102]
B2D	2050	172	192	581	830	IEA [102]
STEP	2050	193	490	742	0	IEA [98]
IRENA REMAP	2050	222	166	494	N/A	IRENA [103]
NZE	2050	258	110	550	1,000	IEA [87]
GO	2050	389	0	389	2,000	García-Olivares et al. [97]

Table 3

Primary renewable, fossil and total energy supply in 2050 in energy transition scenarios. Bioenergy is not accounted for in the renewable supply. The available recycled steel is estimated from the steel in-use stock in 2015 and the scenarios fossil supply in 2050, assuming a 0.8 EOL-RR. GO = scenario by García-Olivares et al. [97].

5.3. The need to conduct ambitious decommissioning strategies

The significant potential of recycling materials-and especially steel-in end-of-life fossil fuels structures was identified in section 5.2. We estimated that the current in-use stock of steel could provide large amount of secondary materials to build the future renewable technologies, but that the future EOL-RR could substantially impact recycled materials availability. Two main elements could affect the EOL-RR. First, most of the copper of the fossil fuels supply chain is consumed in steel alloys (e.g. stainless steel, 7% nickel steel and 36% nickel steel in LNG infrastructures), for which down-cycling¹⁴ is frequently observed. Hayatama et al. [104] and Ciacci et al.[105] outlined the losses of copper in alloys recycling and changes in functionality of complex recycled steel alloys. Second, partial or total phasing-out of fossil fuels will require decommissioning policies. Many strategies can be adopted depending on the technology (e.g. removal, partial removal, left in place, reefing or left in place and repurposed) and will impact the EOL-RR. The removal process of the infrastructures could generate substantial energy consumption and environmental impacts [106], which-if recycled-could be compared to the savings from avoiding the extraction of primary materials at a global scale in future studies.

Decommissioning remains decisive to avoid both indirect environmental impacts (e.g. preventing primary material production) and direct environmental impacts¹⁵ (e.g.

¹⁴Down-cycling is defined as the recycling resulting in a lower quality of materials, and therefore a loss of functionalities.

¹⁵The materials and environmental opportunities of decommissioning have been emphasized [107, 108].

GHG emissions of abandoned wells [109, 110, 111]¹⁶). Ambitious decommissioning policies could allow to enhance material recycling and reuse¹⁷. However, some processes will require material demand (e.g. cement plugs of oil and gas wells), a part of the estimated in-use stock will inevitably be left in place (e.g. the materials embedded in the wellbore [113]) and prohibitive collection price could hamper material recovery¹⁸. The EOL-CR will ultimately be impacted by the primary material prices and the local decommissioning policies. At a global scale, decommissioning remains at its early stage, and while some countries pave the way for ambitious policies [95, 115], other display nascent strategies [116]. However, the climate emergency urges to take rapid action to reduce the environmental toll of human activities, and ambitious decommissioning strategies could provide an additional way to increase materials recycling and reuse.

6. Robustness and limitations

6.1. Robustness criteria and local sensitivity analysis

The dynamic modeling of the hydrocarbon production and supply infrastructure stock proposed in this study represents a simple global approach to the sector, focusing on the main infrastructures. This model needs to be robust and transparent, and several robustness criteria have been identified. First, the stock modeling results are satisfactory

¹⁶Significant methane emissions have also been identified during the operational phase [112]. The study shows that large methane emissions during maintenance or failures of oil and gas equipments could represent between 8% and 12% of the sector global methane emissions.

¹⁷Davies and Hastings [111] estimated that a 16,000 tons steel jacket left in place and repurposed could retain 55,040 tCO₂eq in GHG emissions.

¹⁸Raimi et al. [114] estimated median prices for wells plugging and surface reclamation to \$76,000 in the US, with significant disparities.

for nine of the eleven infrastructure types modeled from energy production. A first category of modeled infrastructure stocks displays averaged errors of less than 10% (wells, gas and oil product pipelines, LNG liquefaction and re-gasification plants, LNG storage facilities and refineries) and a higher value are observed for coal carriers (11%), oil tankers (12%) and LNG carriers (16%). Second, the global approach developed in this study allows to assess the evolution of hydrocarbon supply chain from a minimal panel of characteristics of the hydrocarbon production and supply sector. This approach, although minimal, does allow for the analysis of the evolution of infrastructure stocks according to assumptions such as the progression of LNG or non-conventional hydrocarbons.

The sensitivity analysis conducted in this study shows moderate effects of lifetime changes. However, as previously described by Dong et al. [117] and Yin et al. [118], the time delay induced by the lifetime carries growing effects over time. A better knowledge of technological and regional values of lifetime over time is needed to prevent substantial variations in prospective dynamic modeling. It can also be noticed linear impacts of the material intensities on stocks and flows of the model. Global homogeneous data were assumed in this analysis, and a better understanding of the regional dynamics could increase the accuracy of the results. Finally, local sensitivity analysis only describes variations in a given point in space. This methodology therefore carries limitations [119], and further studies should develop global sensitivity analysis on more parameters and their possible interactions [120].

6.2. Methodology-related limitations

The hydrocarbon production and supply sector are computed independently of the other sectors, and the materials recycled are consumed in the same sector. This approach does not represent the actual recycling industry, and only a multi-sector study considering recycling as a sector would estimate accurate flows of recycled metals between the consumer sectors. In addition, the materials consumed for well closure is not considered [113], as well as the numerous decommissioning strategies (Section 5.3). The choice of a physical approach to the flows and stocks of materials also carries limitations on the effectiveness of the model in terms of operational reality of the sector. For example, an increase in concrete demand is observed in the late 2040s in the NZE scenario, despite a context of significant slowdown in hydrocarbons production. It is explained by end-of-life renewal of some infrastructures. Assumptions of life extension, well closure for profitability considerations and other sectoral and financial realities could be considered in further studies.

6.3. Data-related limitations

Most of current infrastructures data on the fossil fuels supply chain are difficult to access. To overcome this problem, the sector's players call on the services of economic intelligence companies (IHS Markit, Rystad Energy, Wood Mackenzie, etc.) which collect confidential information (obtained in an undisclosed manner) and provide data, tools

and analyses in return of a high price. Conversely, this study relies on free and online available dataset describing the evolution of the global fossil fuels supply chain over time. They require extensive sources research, remain scarce and suffer from a lack of sources comparison and from numerous gaps, which hamper any extrapolation over time. For instance, access to reliable data over time and consistent over the geographical perimeter remains a limitation to this study. The selected data were qualified according to their geographical scope, technological scope and year of the study. The data collected do not allow a complete understanding of the complexity of the hydrocarbon production sector, due to the great variety of systems used from exploration to distribution¹⁹. Detailed data on all these technologies and their associated material intensities are not yet available, and sub-segment scale data were therefore considered²⁰. Thus, the results displayed in the study are likely an underestimate of the actual material demand. In addition, most of the data are based on European or North American devices, which could create high uncertainties in the results. This is explained by the difference in both the global hydrocarbons production and consumption patterns²¹.

Furthermore, our analysis relies on oil production scenarios which can be thrown into question. Indeed, the International Energy Agency tends to assume parameters which proved to result in too optimistic projections in the past [123, 124]. It consequently neglects the possibility to suffer from a production crunch in the coming years [125] or to experience a peak in the production of all oil liquids in the mid 2030s now envisioned by an important number of actors [126]. While the issue of credible long-term oil scenarios is critical at times of the resurgence of the 'peak oil' debate [127], it seems not to be taken into account by the IEA. We acknowledge the fact that projecting oil demand and supply is an intricate and complex task. Yet, we feel that the projections we used carry great uncertainty, and that they should be treated with a grain of salt.

7. Conclusions

This study models the evolution of the world's fossil fuel infrastructures and estimates dynamic embedded materials, energy, and CO₂ emissions from 1950 to 2050. To do so, it firstly collects and centralizes free data from a large number of sources and thus avoids using expensive datasets from energy intelligence firms (McKenzie, IHS Markit, Rystad Energy, etc.). Without claiming to provide the same quality

¹⁹A detailed list of equipment used in the offshore production of hydrocarbons is provided by Rosneft.

²⁰For example in the exploration sub-segment, see Supplementary Information.

²¹Oil and gas drilling technologies are different from country to country, with conventional hydrocarbons requiring fewer wells drilled than unconventional hydrocarbons for an equivalent level of production. There is therefore a lack of correlation between the amount of oil produced and the number of wells drilled at the regional level, with OPEC, for example, accounting for nearly 32% of global oil production and 15% of natural gas production between 1980 and 2019 for only 2.8% of wells completed over the same period [121, 122].

and disaggregation of data, our comprehensive dataset can be used by other researchers to understand the role of hydrocarbon infrastructures in the energy transition. Secondly, it develops and applies a dynamic material flow analysis (MFA).

We find that (i) the material intensities of oil, gas and coal have stagnated for more than 30 years; (ii) gas is the main driver of current and future material consumption and (iii) recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll.

We furthermore highlight that the regional decommissioning strategies will significantly affect the potential of material recycling and reuse. In this context, ambitious decommissioning strategies could drive a symbolic move to build future renewable technologies from past fossil fuel structures.

CRediT authorship contribution statement

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

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

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5.2 Supplementary information: *Dynamic modeling of global fossil fuel infrastructure and materials needs: overcoming the lack of available data*

5.2.1 Global historical data of the hydrocarbons supply infrastructures

The **upstream** segment is common for oil and gas, and is composed of exploration and production devices for which recent data is available. This segment includes exploration infrastructures-including devices used in seismic, magnetic and gravity methods-wells and onshore and offshore drilling rigs. At the global level, the Organization of the Petroleum Exporting Countries (OPEC) provided a census of the number of wells between 1980 and 2016 with more than 1.1 million wells in 2016 and 5,123 well pads in 2013 (OPEC, 2018). The organization also listed drilling platforms between 1982 and 2013, without distinguishing between onshore and offshore structures. However, those drilling devices are not considered in the study, because of the high level of uncertainty on the data collected. Indeed, the census of rigs remains difficult at the global level, notably due to the lack of detail in the perimeter considered in the majority of sources, and the diversity of offshore infrastructures. Baker Hughes provided a monthly report on onshore and offshore rotary rig counts worldwide, with a value of 758 rigs in June 2021². A value of more than 6,000 offshore oil and gas platforms are announced globally by Bull and Love (2019) and Schroeder and Love (2004), compared to 3,000 fixed offshore platforms by the IEA (2018b) and more than 12,000 offshore devices by Ars and Rios (2017). However, IEA (2018b) stated that the recent increase in offshore production has been partly provided by floating facilities, the number of which more than doubled between 2000 and 2016, making any accurate assessment of offshore production devices difficult. Adding to this difficulty of identification is a trend toward larger platforms, greatly complicating modeling from fossil fuel generation. IEA (2018b) stated that the size of platforms increases over time, allowing production to be maintained while decreasing their number. Conversely, no census of the equipment used in exploration methods has been obtained, but a study listing the quantities of raw materials consumed has been produced by the American Petroleum Institute (Steiniger, 1962). Finally, the coal mines have been separated into two underground and opencast categories. It is estimated that 40% of coal production comes from surface mines and 60% from underground mines (World Coal Institute, 2009), with various extraction equipment.

In contrast to upstream, the activities of the **midstream** segment are different for oil and gas, especially for processing. While oil does not require processing, several steps are required before eventual gas transportation and then distribution. Schori (2012) further stated that the extent of processing depends on the quality of the gas produced. The processed gas and oil are then transported to consumption centers. Four methods of transportation exist: road, rail, sea, and pipeline. Only the last two are modeled here. Only 20% of gas is traded on international markets and not consumed regionally. Similarly, in 2015, 61% of the transportation of petroleum products was by sea lanes (EIA, 2017). For natural gas, pipeline transportation and marine transportation in liquefied form were therefore considered in this study. It includes the liquefaction of natural gas, its transport in the form of liquefied natural gas (LNG) in LNG tankers, and its regasification. The market share of LNG has strongly increased over the recent decades, with global liquefaction capacity growing from 165 bcm in 2000 to more than 467 bcm in 2017, while regasification capacity has evolved from 334 bcm to more than 1,138 bcm in the same period (ENI, 2018). Similarly, the evolution of the number of LNG carriers since the late 1960s - the years of construction of the first ships - follows a strong growth, linked to the rapid development of LNG globally. IGU (2018) detailed a growth to about 200 ships in 2000, eventually progressing to 525 units in 2018. The liquefaction of gas allows storage. Over the past decades, LNG global storage capacity have increased from 39 mmcm to 62.8 mmcm between 2011 and 2018³ (IGU, 2018). Gas pipelines represent the second main way of transportation of natural gas. The network of natural gas transmission and distribution pipelines has grown considerably over the last two decades. Its length was estimated at more than 844,000 kilometers in 2000, finally evolving to 3.04 million kilometers in 2017 (CIA, 2019). However, these data do not agree with the estimates of CEER (2018), announcing more than 1.9 million kilometers for the European network, compared to only 224,000 km for CIA (2019). We can also identify a strong difference for the French case, with 195,000 km of gas pipeline network announced by the French Ministry of Ecological Transition (2022), against about 15,000 km for CIA (2019), as well as

²Baker Hughes proposes a [monthly inventory](#) of the global active rigs.

³The storage capacity is measured in).

for Canada, with more than 450,000 km of gas pipelines [NRCAN \(2020\)](#) against 110,000 km for [CIA \(2019\)](#), and finally the United States, with 1.9 million kilometers announced by [CIA \(2019\)](#), lower than the 2.3 million kilometers identified by [PHMSA \(2022\)](#). These differences stem from the scope of the studies considered. Pipelines can be separated into three broad categories: transmission pipelines, carrying hydrocarbons over long distances from production centers, distribution pipelines, serving end-users over short distances, and gathering pipelines, used between the field and the transmission system ([Moureau and Brace, 1993](#)). However, the latter network remains a minority, accounting for only 0.7% of the U.S. gas network in 2018 ([PHMSA, 2022](#)). Using data for the European, US, and Canadian gas networks, we estimated a distribution pipeline share of 85% of the pipeline network. The rate was applied to the data on the gas transmission pipeline network provided by [CIA \(2019\)](#), allowing us to obtain the historical evolution of the global network between 2000 and 2017. In this study, the transportation network evolved from 840,000 km to more than 1.36 million km between 2000 and 2018. For petroleum products, the midstream segment includes both tankers, transport and distribution pipelines, and storage infrastructure. Globally, tanker transport grew strongly between 1980 and 2018, from 388 million Dead Weight Tons (MDWT) to 561 MDWT, for about 12,000 units ([UNCTAD, 2018](#); [GIIGNL, 2019](#)). Tanker transport can be considered "dynamic" storage, but is not considered as such here to avoid double counting. Geological storage was also excluded, due to lack of raw material data. Finally, only man-made "static" storage tanks have been considered here. These are estimated at 8 billion barrels, more than half of which are in OECD countries, including both commercial and strategic stocks ([Magazine, 2016](#); [IEA, 2018b](#); [OPEC, 2018](#)). Finally, in contrast to the natural gas pipeline network, the petroleum product pipeline network has seen little growth between 2000 and 2018, with the length increasing from 584,000 km to 788,000 km ([CIA, 2019](#)). The data considered do not suffer from the same drawback, as the global network is predominantly a transportation network, not a distribution network, unlike the gas network. For coal, the midstream segment remains simpler. After extraction, coal can be processed before being transported, in order to meet customers' requirements. This is accomplished by crushing it, separating it by size, and then purifying it of mineral matter ([Miller, 2017](#)).

The final segment of the hydrocarbon supply chain is the **downstream**, which gathers refining and distribution activities. Refining capacity has increased significantly between 1965 and 2017, from 34.8 to more than 98 million barrels per day with more than 600 refineries worldwide ([BP, 2021](#); [OGJ, 2014, 2009](#)). In the absence of data on the share of transmission and distribution networks, the entire petroleum product network was considered a transmission network. The gas network is 86% a distribution network, and its length has increased from 4.4 to over 10 million kilometers between 2000 and 2018 ([CEER, 2018](#); [CIA, 2019](#); [NRCAN, 2020](#); [PHMSA, 2022](#)).

5.2.2 Recent evolution of the oil, gas and coal sectoral production structure

Several developments in the oil and gas sector have been taken into account in this study. As mentioned above, an increase in the share of gas transported in the form of Liquefied Natural Gas (LNG) has been considered, as well as the share of unconventional oil and gas. Unconventional production has been separated into two main categories with different characteristics: oil sands and shale oil on the one hand, shale gas and tight gas on the other. Since oil sands exploitation does not require drilling, only the second category was considered. In order to model the impact of the increase in production of unconventional hydrocarbons, three factors were considered: a decrease in the lifespan of the wells, a decrease in their depth, and an increase in their number.

For the same level of production, more unconventional wells are needed, which is explained from the production profile of unconventional drilling, measured by the production decline rate. It is defined as the annual rate of reduction in oil or gas production from an oil field, and is calculated for each well and at the aggregate level. It differs according to the age of the well, but also between conventional and unconventional hydrocarbons, for which its value is higher ([Kleinberg et al., 2018](#)). The average value of the production reduction rate is about 2% to 8% for conventional hydrocarbons ([IEA, 2019b](#); [Michaux, 2019](#); [Höök et al., 2009](#)). The rate fluctuates depending on the size of the oil field, its geographical location and its physical situation-offshore or onshore ([Höök et al., 2009](#); [IEA, 2013](#)). The values observed for fields producing unconventional hydrocarbons are considerably higher. In the Bakken field, located in the United States, this rate reached nearly 60% in the first year of production, and then 25% in the second year ([IHS, 2013](#)),

while the Barnett field experienced a rate of 39% after 2 years, eventually reaching 95% over 10 years (Stevens, 2010), and the Eagle Ford field experienced a reduction of 74%, 47%, and 19%, respectively for the first, second, and third year of production (Wachtmeister et al., 2017). This hyperbolic pattern of production reduction therefore explains the need to increase drilling in order to maintain a high level of production. The density of wells per square kilometer, however, varies considerably by reservoir, by hydrocarbon type, and by data source. Komduur (2010) announced a density of 12 wells per km² in the Barnett oil field in the United States, compared to 2 wells per km² according to the EIA (2013). At the national level, the EIA (2013) provided the density of wells in the large unconventional American fields, ranging from 0.4 to 6 wells per km² with an average value of 2.8 wells per km², which is still higher than the largest conventional fields in the world for which the values vary between 0.07 and 8.9 wells per km². Because of this large disparity, no difference in well density was retained in this study.

In addition to a change in well density, a decrease in well life is observed. Indeed, the production reduction rates allow us to estimate a lifetime of unconventional hydrocarbon wells between 8 and 12 years, compared to 30 to 40 years for conventional hydrocarbon production (Stevens, 2010). Finally, the increase in the share of unconventional hydrocarbons and deepwater drilling changes the average depth of drilling. The horizontal drilling technique increases the total length of the wells, composed of a vertical part and then a horizontal part. The first part of the drilling consists of the vertical part of the well, in the same way as conventional hydrocarbons. Newell et al. (2016) announced an average vertical depth between 1,200 and 3,900 meters, while Zendehboudi and Bahadori (2017) between 1,000 and 3,000 meters. This value reaches an average of 1828 meters in the Marcellus Basin (Fractrack, 2022). Once the reservoir depth is reached, horizontal drilling begins. On the Marcellus Basin, located in the United States, the average length of this second portion was 1150 meters between 2006 and 2016, and an increase in the length of the horizontal portion of drilling over time (Doak et al., 2019). The average horizontal drilling distance in the Marcellus Basin increased from 690 meters in 2003 to 1,200 meters in 2013, and to 3,000 meters in 2018. Nationally, this distance has evolved from 1547 meters in 2012 to 2,221 meters in 2018 (Hughes, 2019), for a total drilling length of approximately 4,000 meters in unconventional wells in the United States. This evolution can be seen in the distribution profile of drilling in Canada and the United States, with a sharp increase in the proportion of drilling to a depth of around 2,000 meters, and the appearance of drilling to a depth of over 5,000 meters. The average depth of drilling in the United States has increased from 1,100 meters in 1950 to more than 1,700 meters in 2008. Finally, the characteristics retained are an average drilling length of 1,500 meters and a life span of 40 years for conventional deposits and 4,000 meters and 12 years for non-conventional deposits.

5.2.3 Embodied energy and CO₂ emissions

The embodied energies of primary and secondary materials considered in this study are dynamic between 1900 and 2100, and their scope extends from cradle to gate. Primary metals embodied energies depend on both the ore grade of the mined material and the technological improvement of production technologies (Norgate et al., 2007; Birat et al., 2013; Gutowski et al., 2013; Vidal, 2021). Data from Vidal (2021) are considered for copper, aluminum, and steel. The values considered for steel are used for all steel alloys in this study. Cement and concrete production is decentralized, so material intensities depend on the efficiency of regional production facilities. Numerous cement and concrete material intensities are proposed in the literature, both globally (Van den Heede and De Belie, 2012; Birat et al., 2013) and by region (Marinković et al., 2017; Goggins et al., 2010; Praseeda et al., 2015)⁴. Because of this decentralization, a multi-regional approach is adopted to estimate a global cement material intensity. In this study, we have assumed an identical intensity for clinker and cement, theoretically composed of 95% cement (Taylor et al., 2006). In order to simplify the calculations, only the main producing areas have been considered. China, India, Europe, the United States and Japan represent nearly 70% of the world cement production between 1956 and 2016 (USGS, 2021a), so regional energy intensities were determined for these regions using historical data and a logistic approach. For this purpose, a theoretical energy intensity limit for cement was set at 1.76 MJ/kg (Worrell et al., 2001; Taylor et al., 2006)

⁴Many other studies provide regional cement and concrete intensities. A non exhaustive list of them include : Alcorn and Wood (1998); Hammond and Jones (2008); Baird (1997); Kofoworola and Gheewala (2009); Dias and Pooliyadda (2004); Scheuer et al. (2003); Debnath et al. (1995); Wan Omar et al. (2014); Dixit (2017); Worrell et al. (2001, 1994); Praseeda et al. (2017); Li et al. (2015); Gervasio et al. (2018); Lu et al. (2009); Mack (2015); Taylor et al. (2006)

and a maximum intensity of 20 MJ/kg. This value remains uncertain but has little impact on the study since 96.7% of cement produced since 1900 was manufactured after 1950, and nearly 90% after 1970 (USGS, 2021a). Regional energy intensities are then weighted by regional cement production, yielding a global cement/clinker intensity. Historical data for regional shares of global production are obtained between 1956 and 2016 (USGS, 2021a). The observed 1956 distribution is assumed constant since 1950, and the 2016 distribution is assumed constant through 2100. Cement/clinker energy intensity varies annually between 1900 and 2100 according to the combined change in regional energy intensities and regional market shares in world production.

Recycling reduces the energy required for the production of materials, due to the lower number of stages in the production of secondary metals than in primary metals. Indeed, primary production involves steps such as mining and mineral processing (for copper, nickel, zinc, lead...) or crushing and screening for steel (Norgate et al., 2007; Chen et al., 2019), which are not mobilized during secondary production. Secondary production primarily involves scrap smelting and refining, as well as several steps of collection, recovery sorting and shredding (Norgate, 2013). Schäfer and Schmidt (2019) and Johnson et al. (2007) pointed out that the origin of the metals collected influences the energy required for their recycling, and report embodied energy of secondary copper sometimes of the same order of magnitude as that of primary copper. The scope of secondary metals production thus includes processes from collection to refining. In this study, the embodied energy of secondary metals is assessed from a literature review of the energy typically consumed in secondary processes, either in absolute terms or in terms of the energy consumption of primary processes. However, this proportion of primary production consumption varies considerably over time as the ore grade changes (Norgate and Jahanshahi, 2006). The proportion estimated in this study is therefore valid only for the current period. This makes it possible to estimate a world average consumption of secondary metals, varying then according to an annual rate of technological improvement of 1% between 1900 and 2100. Only steel, aluminum and copper are considered in the secondary production. Nearly 70% of steel is currently produced by the Blast Furnace/Basic Oxygen Furnace (BF/BOF) process and 30% via Electric Arc Furnace (EAF), with large regional disparities (Yellishetty et al., 2010). EAF route steel represents most of the secondary steel production, explaining this heterogeneity. This route allows secondary steel to consume between 1.3 and 6 GJ/t currently (Harvey, 2021), 2.6 MJ/kg according to Norgate (2013), 4.5 MJ/kg in Europe according to Birat et al. (2013) and decreasing from 8.8 MJ/kg in 2010 for the United Kingdom (Hammond and Jones, 2008) and 7 MJ/kg at the end of the 1990s for the most energy efficient processes (de Beer et al., 1998). Secondary steel thus consumes between 8 and 37% of the primary production energy depending on the source. A current value of 20% is chosen, in agreement with the most recent sources, i.e. 3.5 MJ/kg for the metallurgical processes. After adding the energy needed for collection, recovery, sorting and shredding, the final value of embodied energy of 3.9 MJ/kg is finally considered⁵.

Aluminum has a more drastic decrease of the energy consumption necessary for its production thanks to recycling⁶. It reaches between 5 MJ/kg and 8.9 MJ/kg (Kear et al., 2000; Quinkertz et al., 2001; Schifo and Radia, 2004; Green, 2007; Birat et al., 2013; Norgate, 2013; Milford et al., 2011), which represents a proportion of the primary production energy mostly between 5% and 10%, and reaching up to 13%. A current proportion of 7% was selected based on a weighting according to the age of the sources, allowing to estimate an average embodied energy value of secondary aluminum of 5.1 MJ/kg for metallurgy, and a final value of 5.6 MJ/kg. Secondary copper production is achieved depending on the origin of the copper scrap, either through the pyrometallurgical process or the hydrometallurgical process, especially for printed circuit boards (Xu et al., 2016). No works studying the embodied energy of secondary copper at the global level have been found. At the Chinese level, Chen et al. (2019) proposed a quantification of each stage of primary and secondary production, and arrive at a proportion of 21% of secondary copper embodied energy to primary. A similar proportion is estimated by Gaines (1980), with 20% on the US perimeter. Presenting differences according to the ore concentration rate, Norgate and Jahanshahi (2006) reported a share of smelting and refining of only 9% for copper mined with a concentration of 0.5%, reaching 40% for 3% Cu. A world average value of 15% is finally retained, i.e. 11.6 MJ/kg for the metallurgical process, and 12.8 MJ/kg for the final embodied energy value of secondary copper.

⁵This value depends on the distance traveled for between the collection site and the recycling site (Norgate, 2013). A distance of 150 km was considered in this study. The strong impact of transport on recycling was also considered by Barba-Gutiérrez et al. (2008)

⁶Salonitis et al. (2019) provided a breakdown of energy consumption by primary production stage.

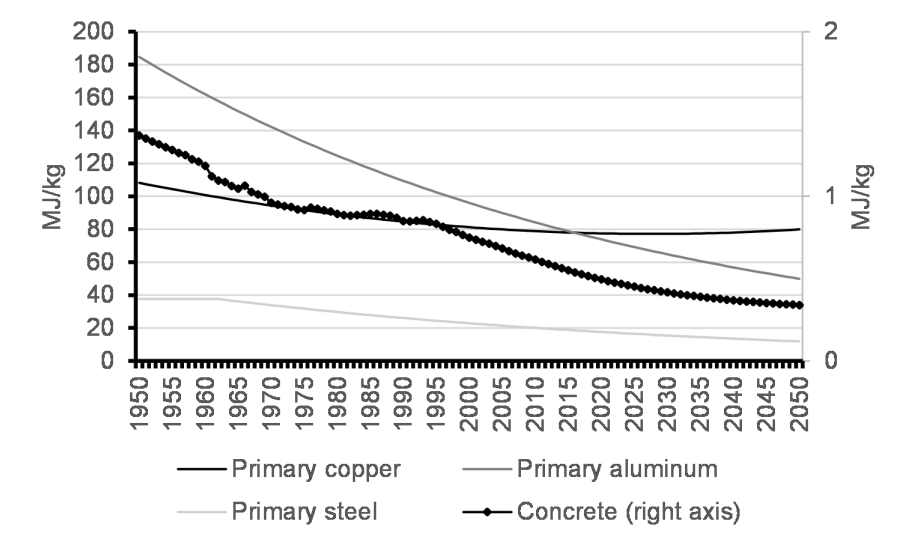


Figure 5.2: Embodied energy of the primary materials production.

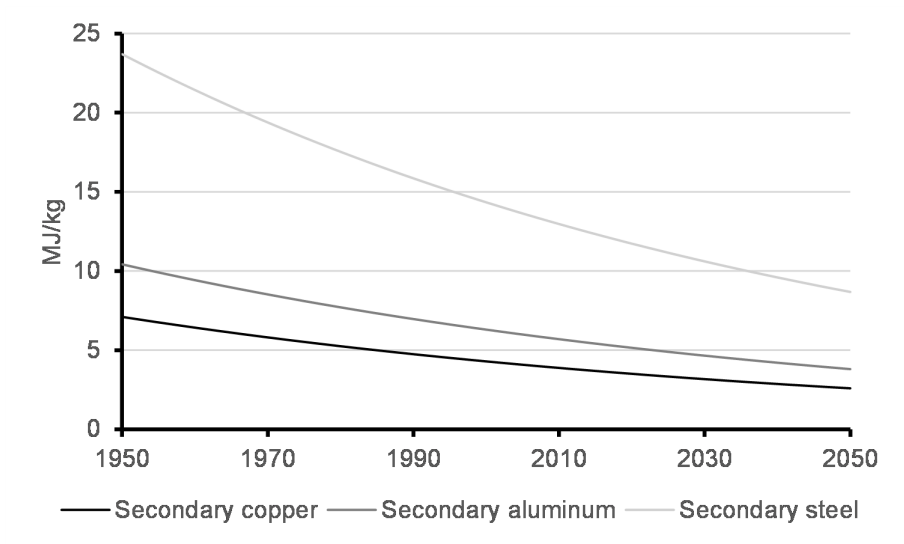
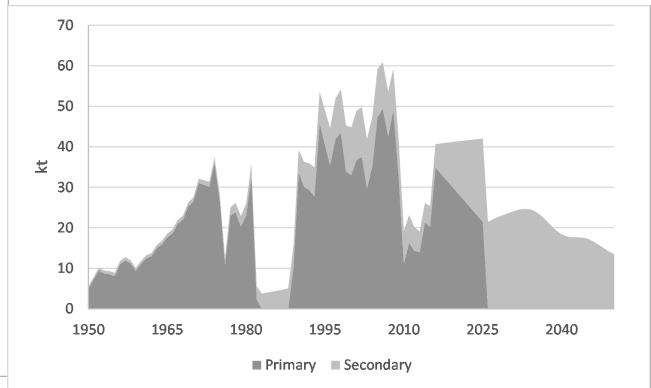
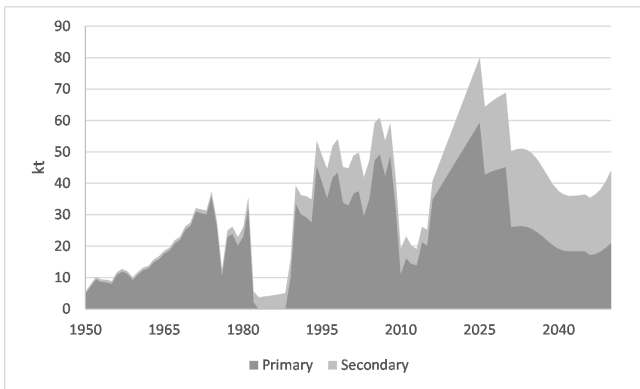


Figure 5.3: Embodied energy of the secondary materials production.

5.2.4 Materials, energy and CO₂ : further results

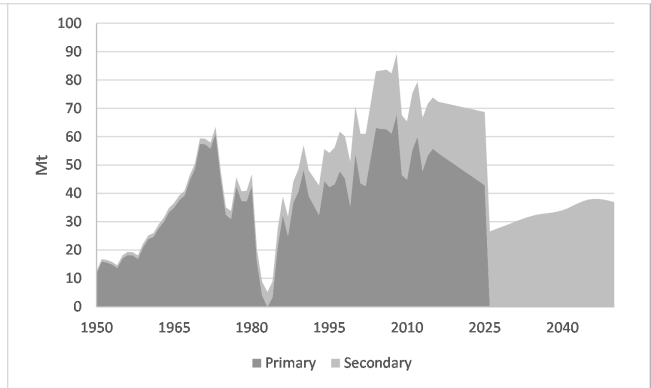
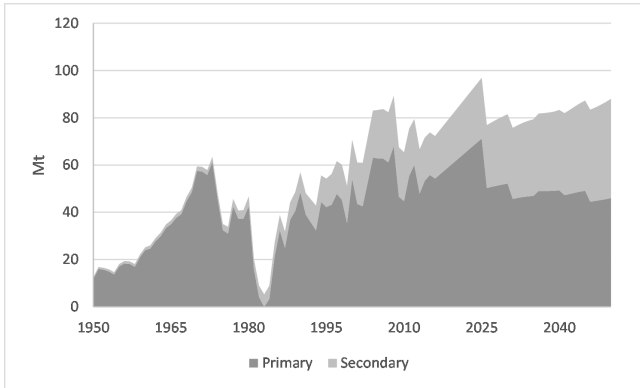
Bulk materials primary and secondary flows in the STEP and NZE scenarios

The bulk materials primary and secondary flows are presented in this section for the two considered scenarios.



(a) Aluminum primary and secondary flows in the STEPS scenario.

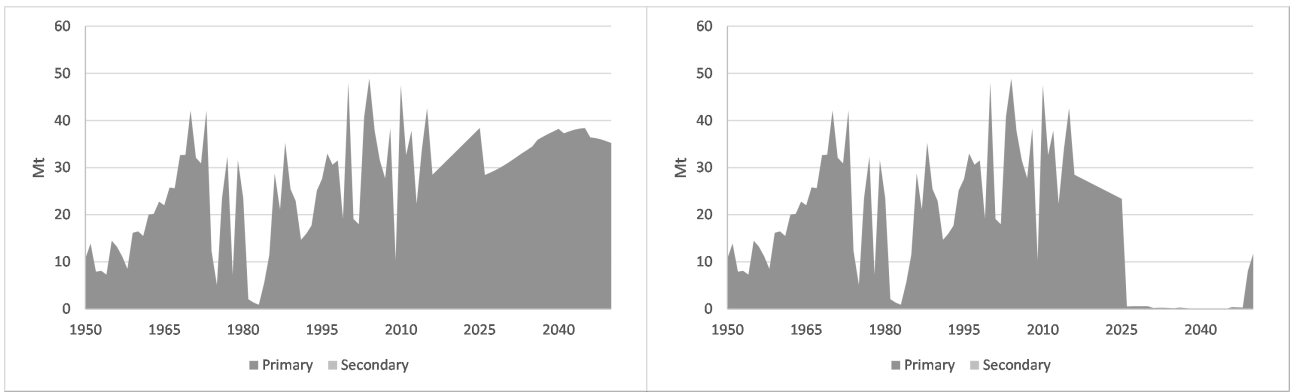
(b) Aluminum primary and secondary flows in the NZE scenario.



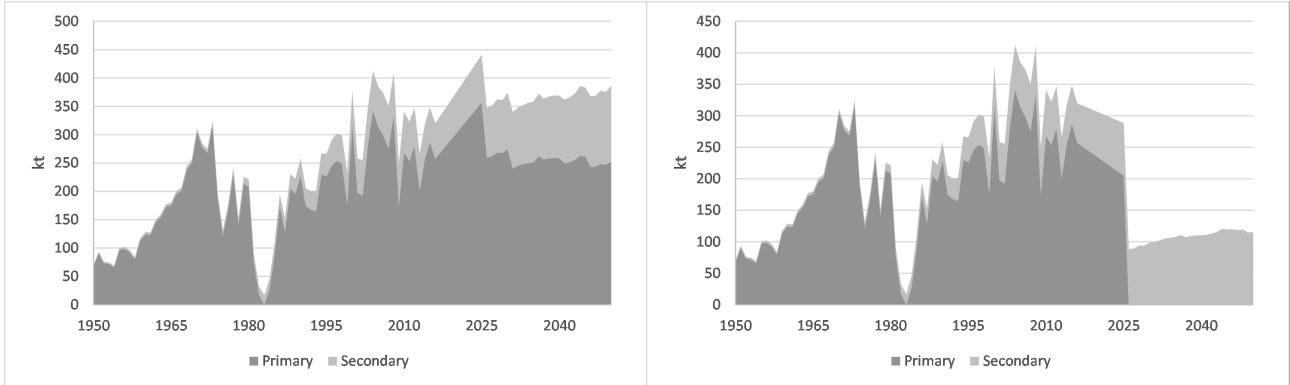
(c) Steel primary and secondary flows in the STEPS scenario.

(d) Steel primary and secondary flows in the NZE scenario.

Figure 5.4: Aluminum and steel primary and secondary flows in the fossil fuels supply sector for the NZE and STEPS scenarios.

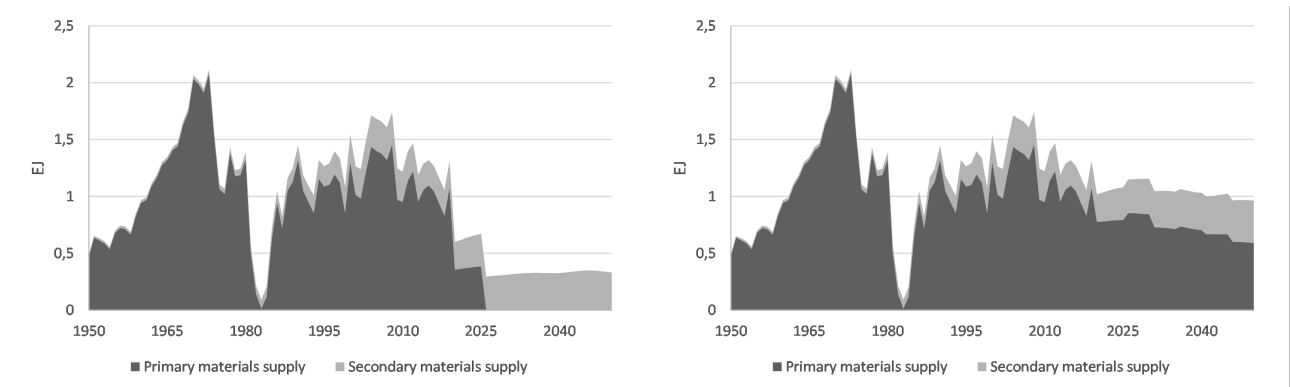


(a) Concrete primary and secondary flows in the STEPS scenario. (b) Concrete primary and secondary flows in the NZE scenario.

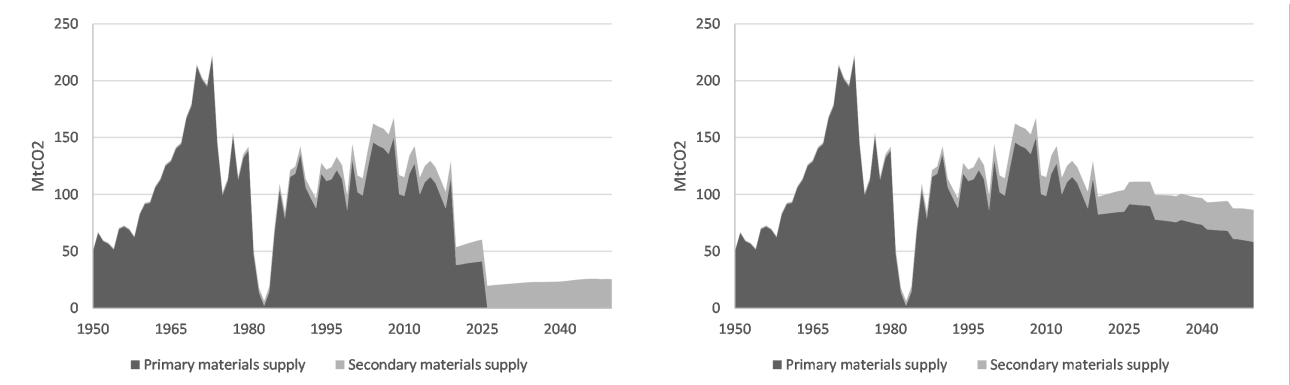


(c) Copper primary and secondary flows in the STEPS scenario. (d) Copper primary and secondary flows in the NZE scenario.

Figure 5.5: Concrete and copper primary and secondary flows in the fossil fuels supply sector for the NZE and STEPS scenarios.



(a) Embodied energy of materials supply in the NZE scenario. (b) Embodied energy of materials supply in the STEPS scenario.



(c) Embodied CO₂ of materials supply in the NZE scenario. (d) Embodied CO₂ of materials supply in the STEPS scenario.

Figure 5.7: Embodied energy and CO₂ of materials supply by segments in the STEP and NZE scenarios.

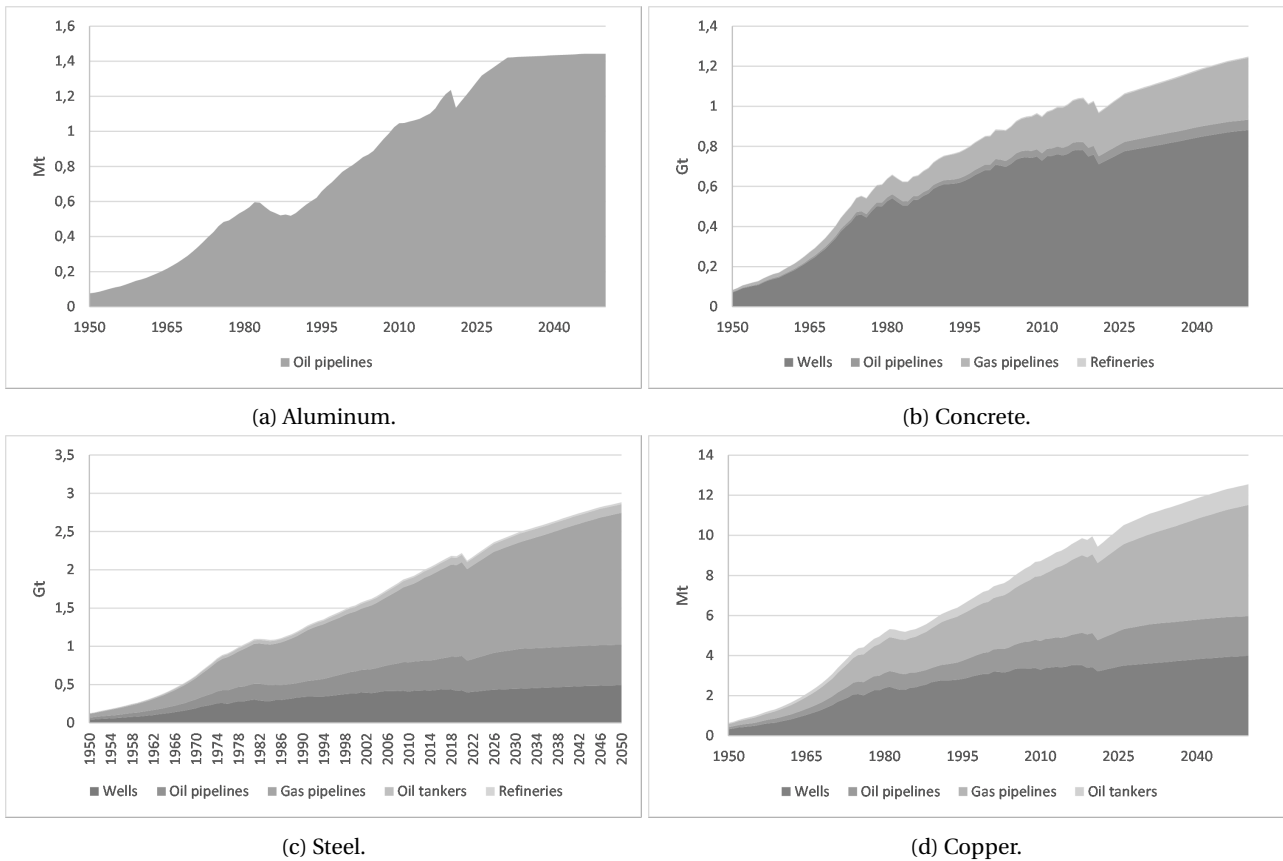


Figure 5.6: Structural materials stocks by main consuming infrastructures in the STEPS scenario.

Historical sectoral materials intensities in the fossils supply sector

References	Steel (iron)	Concrete	Copper	Aluminum	Years	Technologies	Scenarios
Sectoral material intensities (Mt/EJ)							
Deetman et al. (2021a)	5.9	54	0.4	1.5	2015	PG+G+S	Historical
Deetman et al. (2021a)	3.9	50	0.3	0	2015	PG	Historical
Deetman et al. (2021a)	2	4	0.1	1.5	2015	G	Historical
This study	4	2	0.02	0.002	2015	HU+HM+HD	Historical
This study	0.8	1.5	0.007	0	2015	HU	Historical
This study	1.3	0.1	0.006	0.002	2015	HM	Historical
This study	1.9	0.4	0.006	0	2015	HD	Historical

Table 5.1: Summary of the materials intensities in the power generation, storage and grid infrastructures and comparison with the hydrocarbons supply chain. PG = power generation, R = renewables, G = power grid, S = power storage, T = electric transportation, HU = hydrocarbons upstream, HM = hydrocarbons midstream, HD = hydrocarbons downstream. Value do not sum due to rounding.

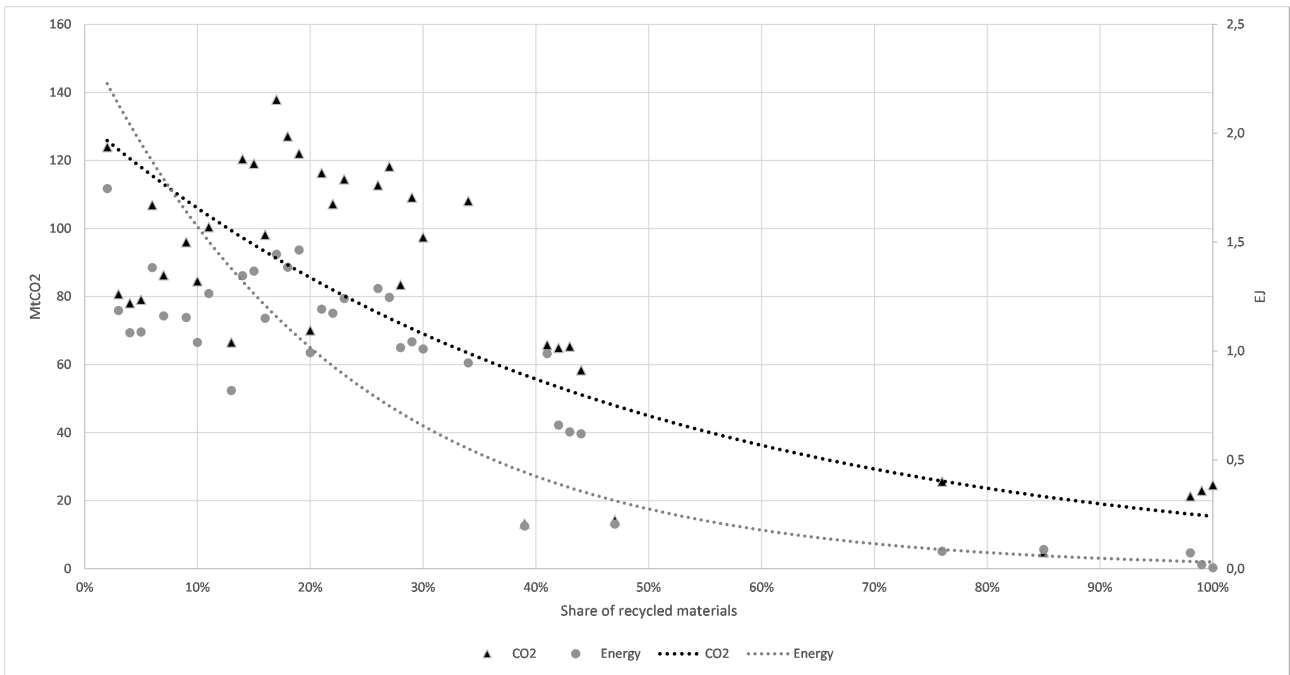
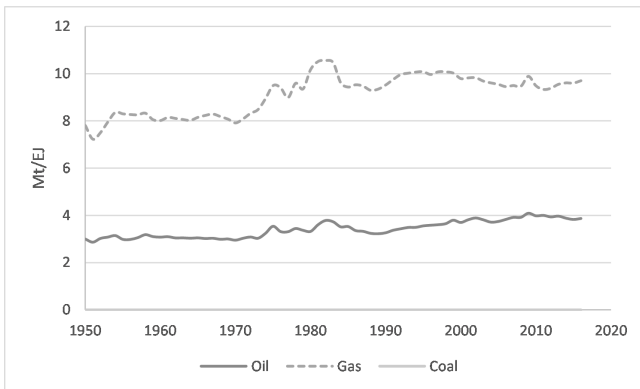
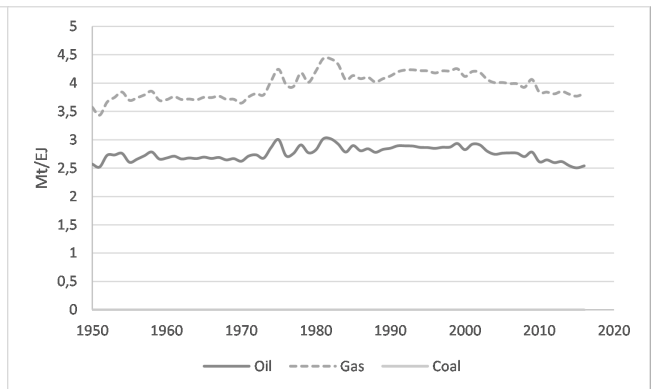


Figure 5.8: Evolution of embodied CO₂ emissions and embodied energy consumption depending on the share of recycled materials in the demand.

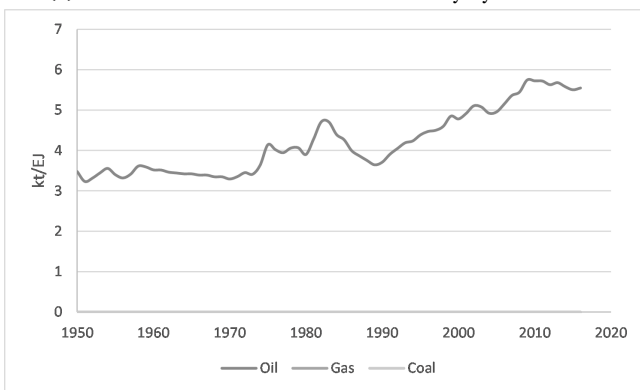
Historical sectoral materials intensities by hydrocarbons in the fossils supply sector



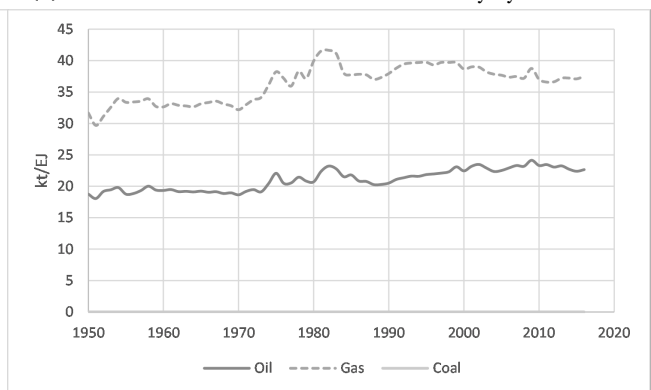
(a) Historical steel materials intensities by hydrocarbon.



(b) Historical concrete materials intensities by hydrocarbon.



(c) Historical aluminum materials intensities by hydrocarbon.



(d) Historical copper materials intensities by hydrocarbon.

Historical sectoral materials intensities by segment in the fossils supply sector

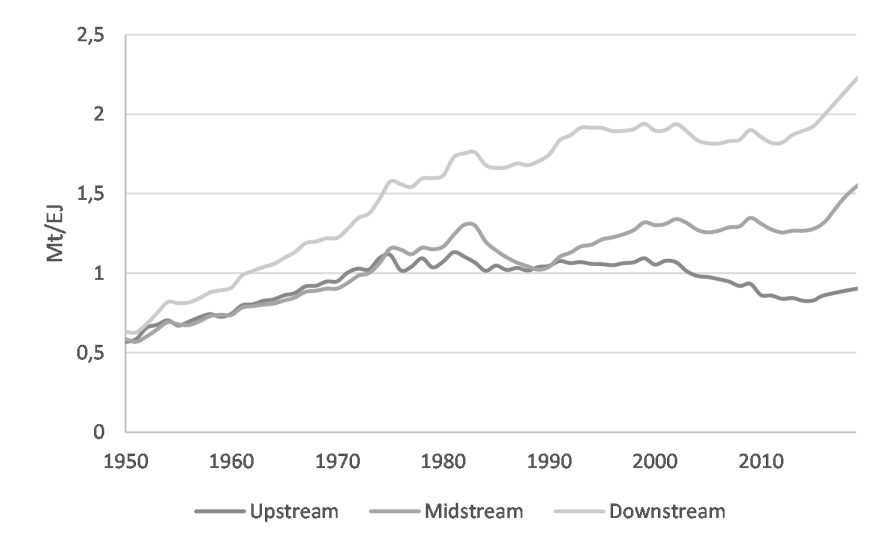


Figure 5.10: Historical steel materials intensities by segment.

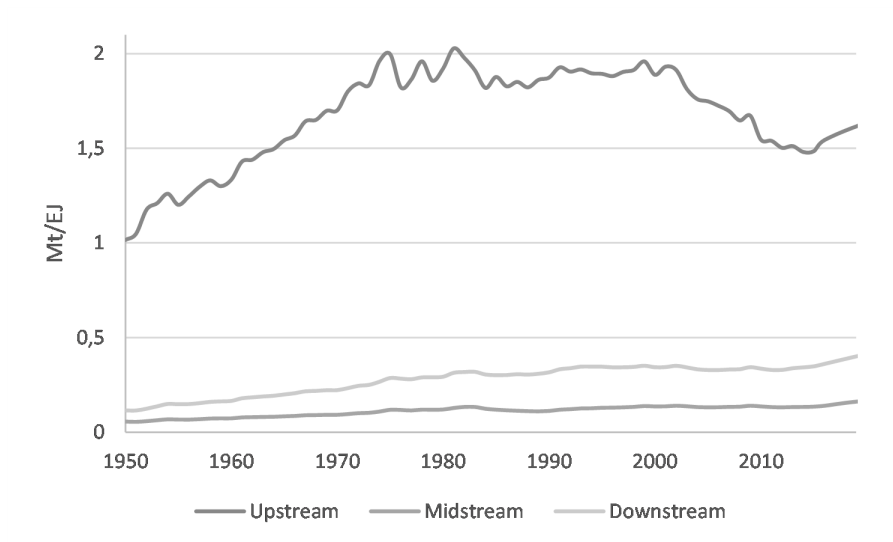


Figure 5.11: Historical concrete materials intensities by segment.

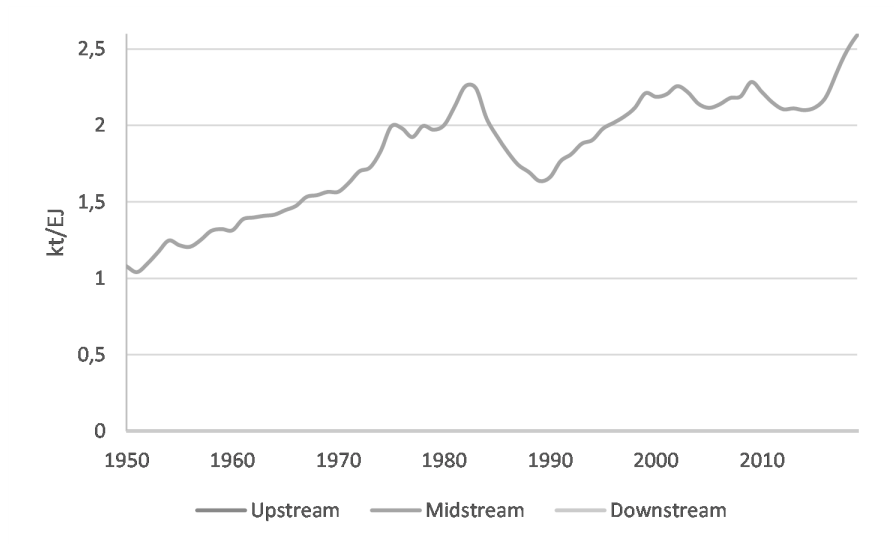


Figure 5.12: Historical aluminum materials intensities by segment.

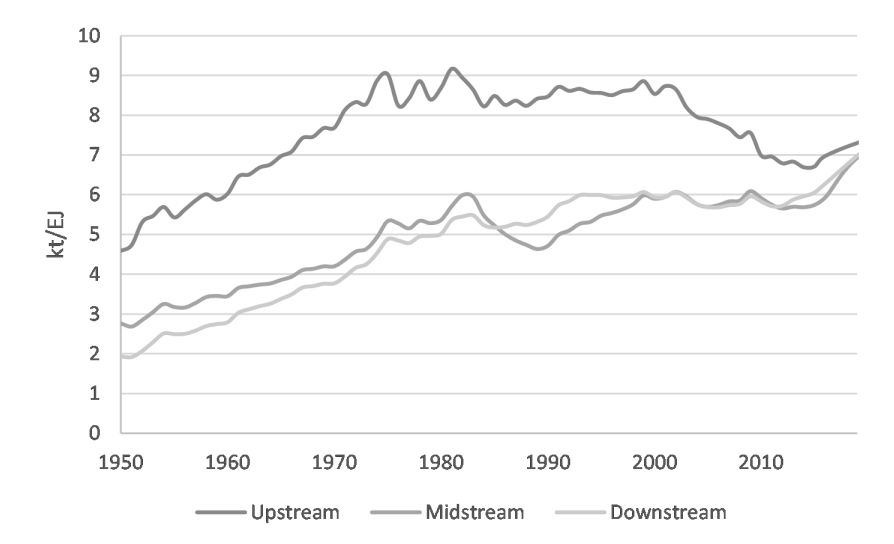


Figure 5.13: Historical copper materials intensities by segment.

Chapter 6

General conclusion

Human interaction with its environment has drastically evolved over the past centuries. The socio-metabolic regime initially changed from a hunter-gatherer society to an agrarian society, and humanity currently faces an industrial transitory phase to a new unknown regime (Fischer-Kowalski, 2011; Pauliuk and Hertwich, 2015). Given the global impacts on the Earth system and the development of inequality, a more sustainable use of resources would be fundamental to reach a new stable socio-metabolic regime (Pauliuk and Hertwich, 2015). The observed transition relies heavily on Earth resources. The global material extraction of biomass, excavated materials, fossil fuels, metal ores and non-metallic minerals increased from 92 Gt to 290 Gt between 1970 and 2019. Among the resources, metals and minerals are the backbone of the industrial development, which led Graedel et al. (2015) to state of a "materials basis of modern society". Their growing and versatile use has enabled complex technologies to emerge on large scales, substantially enhancing the lifestyle of some societies. This materials use carries significant environmental impacts, and resources consumption represent the major source of GHG emissions. Moreover, the exponential use of materials remains extensively coupled to economic growth, and the current and dominant growth paradigm compels a steady increase in resources use. Reaching a circular and sustainable state requires questioning our relationship to growth as well as an adaptation of both our production system (e.g. through the energy transition) and consumption habits (e.g. through sobriety). Estimations of materials flows and stocks are essential to understand the demand pattern and the current accumulated stocks, which could provide secondary materials to build future infrastructures. The metals and minerals demand has been widely assessed within the industrial ecology field, and a growing focus has been observed on the material weight of the low carbon transition. It carries changes for all sectors, and a potential shift from an energy materials dependency to a minerals and metals dependency. The material basis of our society has been addressed with various methodologies and scopes over the past decades. A critical literature review has allowed to identify the main insights and gaps in a panel of publications displaying material flow analysis of base materials between 2000 and 2021. This work aimed at providing further insights on four specific gaps: (1) a lack of prospective studies in a low-carbon context, (2) a lack of analysis of the energy-material nexus, (3) a lack of modeling of some sectors and (4) a limited number of solution-oriented and political-oriented studies.

This thesis is included in a larger project of multi-sector material modeling: the Dynamic Modeling of Energy, Materials Demand and Supply (DyMEMDS) model, which presents a wide scope and very ambitious objectives. I want to emphasize the significant role of data in the feasibility of developing such a model. It represents a data collection and cleaning challenge, especially for dynamic data at a multi-regional level, which can substantially hampers the result. The increasing development of open databases (Heeren et al., 2019 ; Gontia et al., 2018) could allow to better grasp local data and their evolution over time. The DyMEMDS model is part of this open-data approach (for many parameters and sectors).

Using the model, colleagues and I analyzed the base material requirements of the energy supply chain and the building sector, with an extensive focus on the energy transition consequences. In this regard, several conclusions can be drawn:

1. A low impact of thermal renovation on base material in the building sector is observed and the socioeconomic assumptions remain the main driver.
2. We could observe a supply challenge of the energy infrastructures for base material requirements for renewable technologies.
3. We estimate that the steel use in the fossil fuel supply chain is not lower than for renewables when the transportation and distribution activities are considered.

Then, the energy demand and environmental impact of base material production were estimated, and the significant role of recycling was highlighted, however with regional disparities. This showed the role of lifetime and age of stock is a decisive aspect of evaluating the recycling potential, as previously highlighted in many previous studies. From a recycling perspective, we also emphasized two key aspects :

1. The fossil fuel supply chain could represent a potential collect and management challenge in the coming decades. Only the recycling option was considered to display an extreme case, but many other options are available and should be properly studied.
2. By-products could play a significant role to decrease the impact of concrete production. Only CFA and BFS were considered, but many other options are available.

This demonstrates the need to increasingly consider integrated approaches of both the end-of-life of infrastructures and recycling, which requires:

1. Developing multi-sector models ;
2. Enabling multi-options approaches for the end-of-life, for instance consisting in a top to bottom approach of recycling. Such an approach could compute the decommissioning process from a technological unit level (e.g. full reuse option) to a sub-unit level (e.g. repowering or wind farms on rigs) to a resource level (e.g. recycling).
3. Enhancing our knowledge of by-products uses to replace primary materials.

Finally, in the three studies, we outlined that the combination of energy transition and surging population and GDP per capita could have a significant impact on base material demand in the energy supply and building sectors. Both primary and recycled materials production could satisfy the growing demand. We showed that a larger use of recycled materials would minimize energy demand and environmental impacts, while preventing soaring lost stocks in landfills. However, we identified that technology lifetimes and decommissioning strategies could hamper the availability of end-of-life materials, which could result in a substantial increase of primary production. It would lead to a growth of associated energy demand and environmental impacts. Ambitious policies are required to rapidly implement better collection strategies and develop recycling capacities. The large amount of outcomes produced by the academic community could benefit from enhancing the political message to reach a better and wider audience. The sector studies displayed in my thesis are included in a larger project of multi-sector material modeling. The Dynamic Modeling of Energy, Materials Demand and Supply (DyMEMDS) model aims at computing the materials stocks and flows from the energy supply to end-use sectors (building, transport and industry). Sector and multisector studies is provided in further work. The DyMEMDS model could progressively provide researchers or policy-makers with a valuable open-data and open-source tool to expand the understanding of the material challenge and enable transdisciplinary collaborations to tackle the upcoming material conundrum from a wide range of research fields.

Appendix A

Appendix to Chapter 2: *Dynamic base materials modeling: a critical review*

A.1 Review of the reviews

The challenges of quantifying resources stocks and flows in the anthroposphere, their energy and environmental impacts, and their link to development have produced a rich literature in recent decades. Eight literature reviews published over the last 10 years are analyzed in the following, which were selected because they report either a:

- Quantification of mineral or metallic raw materials stocks and flows;
- Quantification of the energy and environmental impacts of mineral or metallic raw materials;
- Quantification of the energy and environmental impacts of the production processes of one or more mineral or metallic raw materials;
- Linkage of mineral or metallic raw materials with economic development or growth issues;
- Study of mineral or metallic raw materials from a conceptual angle (criticality, dematerialization, governance, dissipation, etc.).

In the following, the eight literature reviews are explained, their methodologies are studied, and an analysis of the evolution of the literature according to their conclusions is conducted.

Scope of this review

The publication period of the selected literature reviews is from 2012 to 2020. Five of them address the topic of quantifying stocks and flows of mineral and metallic raw materials, using different approaches. [Chen and Graedel \(2012\)](#) provide an initial critical review of 48 papers addressing the issue of anthropogenic cycles for 75 selected elements, including 59 metals, 10 nonmetals and 6 metalloids. Both stocks and flows are considered, and only 59 elements are finally analyzed in the selected literature. Different modeling methodologies are covered in this study, including SFA and MFA. [Müller et al. \(2014\)](#) focus on dynamic materials flows analysis (MFA) used in the objective of modeling metal stocks and flows in the anthroposphere between 1999 and 2013. Unlike the study by [Chen and Graedel \(2012\)](#) that consider both static and dynamic studies, only papers proposing a dynamic analysis of the quantification are selected. Sixty academic papers are analyzed using a methodology adapted from the Overview, Design concepts, Details (ODD) protocol ([Grimm et al., 2006](#)). This dual stock and flow approach is also considered by [Augiseau and Barles \(2017\)](#), with the specificity of focusing on building materials. The sectors analyzed in the 31 selected studies thus include building, energy, rail, road, telecommunication networks and public infrastructure (ports, airports). The selected items encompass construction materials (concrete, cement, bricks, wood, steel, copper or aluminum) and the stocks and flows are modeled by MFA or stock analysis. [Wu et al. \(2014b\)](#) propose a literature review focusing on the construction

sector, but with the specificity of studying construction and demolition waste flows. Fifty-seven papers are reviewed, with a material scope identical to [Augiseau and Barles \(2017\)](#) and the following modeling methodologies: site visit, generation rate calculation, lifetime analysis, classification system accumulation and variables modeling. In addition, [Göswein et al. \(2019\)](#) analyze the construction sector, using a stock approach, but differentiating themselves by adding papers addressing the issue of embodied energy or emissions from construction materials. Twenty-eight studies are selected in this critical literature review, using LCA, MFA and spatial modeling methodologies, using GIS. In addition, the authors analyze the literature based on an adaptation of the IPAT equation¹ for building stock research. [Van den Heede and De Belie \(2012\)](#) also examine the quantification of environmental impacts in the literature, however with a restrained scope on the concrete production process, the objective being to compare the impacts of traditional and "green" concretes. A census of the impacts, environmental, mechanical and service life characteristics as well as an LCA is carried out, based on the results of 104 papers. Only one systematic literature review studies the issue of decoupling between GDP, resources and CO2 emissions. It is published in 2 parts: [Wiedenhofer et al. \(2020\)](#) firstly address the bibliometric approach and conceptual mapping, and [Haberl et al. \(2020\)](#) synthesize the insights. The main objective is to identify evidence—or lack thereof—of absolute or relative decoupling in a system that considers economic growth as a primary goal. 835 papers are analyzed in [Wiedenhofer et al. \(2020\)](#) and [Haberl et al. \(2020\)](#), 98 of which deal with the decoupling of growth and material consumption. The methodologies developed in this literature are cross-sectional analysis, descriptive trend analysis, decomposition and regression analysis, econometric time series analysis and econometric causality tests. Finally, [Jin et al. \(2016\)](#) propose a first systematic literature review on the topic of materials criticality². 48 studies are listed, analyzing Rare Earths Elements (REE), platinum group metals, 40 other metals, 12 non-metals and 27 other materials. This study aims at proposing a census of the definitions of this recent concept, of the methods to analyze the criticality of a material and of the gaps of the existing literature.

Search, selection and analysis methodologies

The methodology used in the selected research literature can be separated into two processes: the search and selection of papers, and the criteria for analysis. As the first phase of methodology is not systematically carried out, or presents different qualities of detail between the different studies, three levels were identified. A first level "not detailed" consisting of the absence of a description of a search and selection methodology, observed in [Müller et al. \(2014\)](#) and [Van den Heede and De Belie \(2012\)](#). A second "detailed selection" level within which studies present the methodology for selecting papers according to a list of criteria ([Augiseau and Barles, 2017](#); [Chen and Graedel, 2012](#)), separated into two categories:

- General criteria such as the language of writing or the year of publication;
- Criteria specific to the subject of the study. Some usually examined are the materials considered, the analysis of stocks and/or flows, energy, emissions or the spatial scope of the study.

[Wiedenhofer et al. \(2020\)](#); [Haberl et al. \(2020\)](#); [Jin et al. \(2016\)](#); [Göswein et al. \(2019\)](#) and [Wu et al. \(2014b\)](#) propose a third level of description "detailed search and selection" addressing both the search and selection methodology. The search part has different sub-levels of detail. A first one explains a quick explanation of the keywords and the diversity of databases mobilized in order to cover a broad spectrum or to prevent the Matthew effect³ ([Merton, 1968](#); [Göswein et al., 2019](#)). A second sub-level has been defined when a description of the selection process is established with sometimes a quantification of the number of studies selected by stages ([Wu et al., 2014b](#); [Wiedenhofer et al., 2020](#)). These differences in search and selection methodology may stem from the type of literature review. Four of the five studies developing a systematic approach present a "detailed search and selection" methodology. The wide range of studies available in the early stages of the search required a large number of steps to verify their relevance. The highest quality level in the description of the search and selection methodology is observed in [Wiedenhofer et al.](#)

¹The IPAT equation aims at describing the dynamics of impacts on the environment. The three letters refers to the terms of the equation : *Impact = Population · Affluence · Technology* ([Ehrlich and Holdren, 1972](#))

²The concept of criticality was first defined by the [National Research Council \(2008\)](#) as the levels of importance in use and availability of a materials.

³The Matthew effect can be defined as success attracting success ([Merton, 1968](#)). When adapted to scientific publication, it refers to increasing visibility effect of journal on already acknowledge researchers' publications ([Drivas and Kremmydas, 2020](#); [Larivière and Gingras, 2009](#)).

(2020), presenting over 11,500 studies initially obtained.

The development of analysis criteria constitutes the second part of the methodology observed in the literature reviews. A criteria-based approach is commonly used, depending on the scope chosen in the study. Only Müller et al. (2014) propose a standardization of analysis criteria for any MFA. It is based on the standardized ODD (Overview, Design concepts, Details) protocol developed by Grimm et al. (2006) to describe individual-based models (IBM) or agent-based models (ABM)⁴. The ODD protocol emerged from the difficult reproductibility of ABM/IBM models, explained by the combination of the lack of a common framework for description and the complexity of these models. The ODD sequence consists of three main blocks segmented into seven secondary blocks, allowing for a quick understanding of the general structure and purpose of the model (Grimm et al., 2006). The protocol is presented in Table A.1.

Main blocks	Secondary blocks
Overview	Purpose
	State variables and scales
	Process overview and scheduling
Design concepts	Design concepts
Details	Initialization
	Input
	Submodels

Table A.1: ODD protocol and its descriptive blocksGrimm et al. (2006).

The complexity of ABM or IBM models remains higher than that of MFA models, explaining their proposal of a simplified approach to the ODD protocol for the analysis of the latter (Müller et al., 2014). The ODD structure (Overview, Design concepts, Details) has thus been retained, and segmented - in a more detailed way than the original protocol - into 15 sub-blocks. The Overview presents the objective of the model, its general structure and its scope in terms of materials, processes and time scale considered. The Design concepts then describes the general principles of the selected modeling approach, including for example spatial distribution, uncertainty or static or dynamic, retrospective or prospective aspects. The Details presents the specifics for replicating the study in the last block (Müller et al., 2014). The protocol is presented in Table A.2.

Main blocks	Secondary blocks
Overview	Purpose
	Materials (goods, substances)
	Processes
	Spatial and temporal scale and extent
	System overview
Design concepts	Basic principles
	Static or dynamic modeling approaches
	Dissipation
	Spatial dimension
Details	Uncertainty
	Initial condition
	Model input data
	Model output data
	Evaluation
	Detailed model description

Table A.2: ODD protocol adaptation by Müller et al. (2014) for dynamics MFA studies.

Summary of the findings of the literature reviews

⁴These models are a population and community modeling approach that allows for a high degree of complexity of individuals and of interactions among individuals (DeAngelis and Grimm, 2014).

The selected literature reviews provide an analysis of the research field on mineral and metallic raw materials, covering a wide scope of approaches, methodologies and materials. In addition, they allow us to capture the main trends in terms of study perimeters, modeling, data limitations, and inclusion of work with a policy-making objective. These four aspects are developed in the following section.

Scope of studies

The scope is defined in terms of geography and materials. Of the 350 studies of anthropogenic cycles analyzed by [Chen and Graedel \(2012\)](#), a majority focus on the national scale. There is an initial domination of studies on the USA and Europe, and a progressive appearance of the Chinese perimeter. Base materials such as iron, copper, aluminum and zinc are the most represented ([Chen and Graedel, 2012](#); [Müller et al., 2014](#)). [Müller et al.](#) state that few studies focus on REE—until 2013—despite strong recycling constraints and dissipation and low concentration issues. Those are gradually becoming part of the concept of criticality, which appeared in 2008 ([National Research Council, 2008](#)). In the literature review conducted by [Jin et al. \(2016\)](#), 28 of the 48 selected studies were published in 2013 and 2014, demonstrating a growing interest in this research field.

Modeling methodologies : towards conceptual frameworks

Two modeling trends are observed by the above-mentioned authors of the reviews. First, a multiplicity of models is noted, in relation to the objectives of each study. Four types of objectives were identified: quantification of stocks and flows, estimation of environmental impacts of both production and consumption, waste quantification, and coupling with economic growth. In each case, different approaches and inputs data are involved:

- Stocks and flows are considered either separately and jointly, depending on urban mining, scenario analysis or recycling objectives [Chen and Graedel \(2012\)](#). Flows are sensitive to short-term variations, such as economic crises and technological choices, while stocks are a more robust approach for forecast purposes [Müller et al. \(2014\)](#).
- Bottom-up and top-down accounting. Whereas topdown approach refers to input-output tables and modeling stocks from a flow analysis, bottom-up modeling focuses on describing parts of the system in details and then conducting a part-whole modeling. Most of studies consider a top-down approach, with only 10% of papers in [Müller et al. Müller et al. \(2014\)](#). The authors then assess that topdown modeling is relevant on large geographical scales, for bulk materials. On the other hand, they point out that the bottomup approach allows a more accurate modeling, and is of great interest for a study of consumption habits and the consequences on technical, sectoral and socio-cultural specificities. However, bottom-up modeling appears to be intrinsically more complicated to conduct because of the higher data requirement. [Augiseau and Barles Augiseau and Barles \(2017\)](#) identified the complexity of hypothesis for this approach, often considering homogeneity between buildings types, urban zones at a national level, average lifetime and material intensities based on experts' convictions.
- Retrospective and prospective approaches, studying past stocks and flows for the former and extrapolating those results for projection purposes for the latter.
- Static and dynamic accounting modeling. Static approach consists in an evaluation of stocks and flows at a precise moment, whereas dynamic approach presents an evolution in time. Of the 1074 anthropogenic cycles reviewed by [Chen and Graedel Chen and Graedel \(2012\)](#), 989 are static and 85 are dynamic, demonstrating a domination of static models. A rise of dynamic studies has, however, been observed over the past years, and several reviews have been provided [Müller et al. \(2014\)](#); [Göswein et al. \(2019\)](#).

The conjunction of a multiplicity of methodological tools and objectives leads to a need for standardization towards a conceptual framework. The relevance of the use of existing methods and approaches is first analyzed. [Göswein et al. Göswein et al. \(2019\)](#) concluded on the application of LCA for environmental impacts at all scales, of MFA and GIS for dynamic materials flows in space while [Chen and Graedel Chen and Graedel \(2012\)](#) noted the interest of input-

output tools. However, the authors point out the difficulties identified in the literature, such as the inequality of data intensity and data quality, and the differences in perimeters (Augiseau and Barles (2017)). From the perspective of long-term foresight models, Müller et al. (2014) express the importance of dynamic parameters and the coupling of bottom-up and top-down approaches in time-variant MFA modeling.

Data quality and intensity

The data issue can be separated into two points, data quality⁵ and data intensity⁶ (Göswein et al., 2019). The uncertainty and quality of the data depends on the considered time series or geographical scope and the reliability of data from experts' opinions is hardly evaluable (Augiseau and Barles (2017)). This has a direct impact on the reliability of the outcomes of studies. Some parameters such as lifetime of infrastructures are poorly documented, while they have a very strong impact on the magnitude of raw material flows and stocks with time (Müller et al., 2014). There is therefore a need for further development of uncertainty and sensitivity analyses. Beside their quality, the number of available data also constrains the further modeling approach. A bottom-up study requires a minimum amount of input data (Göswein et al., 2019) which are not available for infrastructures such as ports, airports, and networks in the literature, despite their consequent share in the flows and stocks of construction materials (Augiseau and Barles, 2017; Wu et al., 2014b). Despite the increase of the number of available data, Jin et al. (2016) express their reservation about its evolution. The authors describe the difficulty of quantification inherent in the conjunction of dissipative uses and the integration of an increasing number of materials in technological products.

Policy-making and interdisciplinarity

A last weakness of raw materials modeling lies in the lack of integration into an environmental policy-making approach. Most studies acknowledge the possible importance of the issue of material stocks and flows at the economic and environmental levels (Chen and Graedel, 2012; Müller et al., 2014). However, the nature of direct recommendations given in the papers must be adapted to the target audience. Göswein et al. (2019) add that a better documentation of dynamic settings is necessary in this perspective, while Chen and Graedel (2012) emphasize the standardization and combination of methods. This would allow for more efficient anthropogenic cycle studies, comparisons, and thus better policy impact. A better effectiveness of recommendations and development of industrial ecology policies requires exploration of new fields of action, and integration of stocks and flows analyses into an interdisciplinary framework including social, economic, political and technical dimensions. This is the condition to a better understanding of social metabolism (Augiseau and Barles, 2017).

An example: building literature

A significant share of these studies focus on the construction sector and urban areas, and capture the evolving dynamics of research on the topic. Energy consumption has been identified as the main contributor to the environmental impacts of construction (Abd Rashid and Yusoff (2015)), most of it occurring during the operational phase (Lotteau et al. (2015)). The operational and embodied dimensions of energy have thus been widely studied, and industrial ecology is increasingly focused on an analysis of the link between resources and environmental impacts. Two fields of study have thus seen recent development in the construction sector, LCA and materials stock and flows analysis (Göswein et al. (2019)). LCA assess the environmental impacts of sectors or products on their life cycle, and a growing number of reviews focus on building LCA⁷. Material stocks and flows analysis aims at quantifying elements used in the sectors of construction. Göswein et al. (2019) add the embodied energy and emissions of materials, and the dynamics of their use. This allows one to define a methodological framework for stocks and flows analysis (Augiseau and Barles, 2017) as well as understanding the dynamics of cycles of elements (Müller et al., 2014). The combination of these

⁵Data quality is related to uncertainties and gaps in datasets.

⁶Data intensity is depicted as the amount of data available on the sectoral, temporal and geographical scope of a study.

⁷This studying field has been rapidly growing over the past years (Abd Rashid and Yusoff, 2015; Nwodo and Anumba, 2019; Lotteau et al., 2015; Minunno et al., 2021; Dong et al., 2021; Roberts et al., 2020; Mastrucci et al., 2017; Bahramian and Yetilmezsoy, 2020; Yilmaz and Seyis, 2021). Dong et al. (2021) provide a short review of the literature reviews about LCA of buildings.

two dimensions was achieved by studying the input dynamics with the IPAT equation⁸, initially defined by [Ehrlich and Holdren \(1972\)](#). [Göswein et al. \(2019\)](#) study each terms of the IPAT equation to account for temporal and spatial cohort dynamics. They find that the population and the affluence (GDP/cap) variables are often dynamic, whereas material intensity and emission intensity are mostly dynamic. This might be explained by the challenge to forecast future technological innovation [Göswein et al. \(2019\)](#). In parallel with these demand-side studies, the research field of embodied impacts related to materials is also studied from a supply approach. [Van den Heede and De Belie \(2012\)](#) conduct a literature review on the environmental impacts of traditional and “green” concretes, and the replacing possibilities. The authors insist on the importance of the definition of the functional unit – in terms of strength, durability and lifetime – which influences the final concrete choices.

A.2 Methodology : further details

Three types of methodologies are commonly observed in the reviews. The research methodology aims at embracing the largest panel of studies in order to have a broad outlook of the previous works. It is crucial to use a multi-source approach to prevent any Matthew effect, as stated by [Göswein et al. \(2019\)](#). The selection methodology intends to narrowing the outputs of the research by setting up a relevance and/or quality review, and sometimes a duplicate removal [Wiedenhofer et al. \(2020\)](#). Finally, the analysis methodology pursues an in-deep study of the selected literature through a contextual framework. The research phase of this review was first carried out through a keyword approach on Web of Science and a research Connected Papers. The queries used were "Material flow analysis OR substance flow analysis OR MFA OR SFA OR material flow OR material stock OR input-output OR IO" AND "Concrete OR cement OR steel OR iron OR copper OR aluminum" AND "Dynamic OR time series".

A.3 Further results

Bibliometric analysis

A bibliometric analysis was conducted on the 129 selected articles. The software [VOSviewer](#) was used to describe the network and temporal aspects of keywords and journals. The annual number of publications grew from 5 or less between 2000 and 2007 to more than 21 in 2019. A substantial decrease was observed in 2020, which could be link to the Covid-19 virus (Figure A.1). 52 journals were identified, and the most represented are displayed in Figure A.2. In this visualization, each node represents a journal, the line length depicts their references connections, and the size of a node describes a higher or lower number of publications ([van Eck and Waltman, 2014](#)). Resources, Conservation and Recycling is the most represented journal, with most of it occurrences in the last years. It is ahead of Journal of Industrial Ecology and Environmental Science & Technology, and a growing number of recent articles were published in the Journal of Cleaner Production (Figure A.2).

⁸The IPAT equation aims at linking the impact to its causes. It is defined as: Impact = Population * Affluence * Technology.

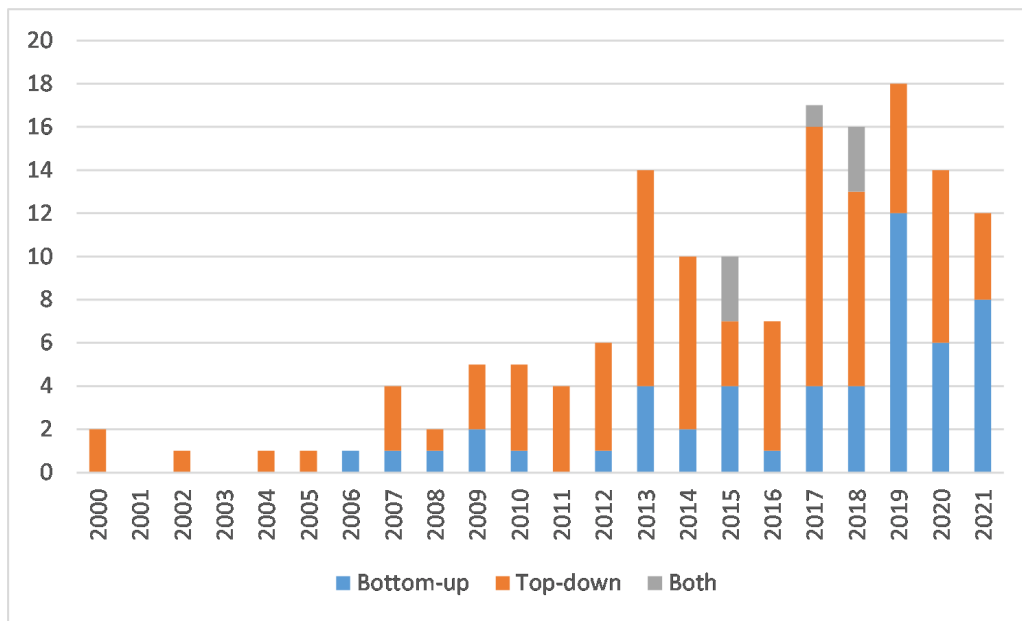


Figure A.1: Annual number of publications by approaches from 2000 to 2021.

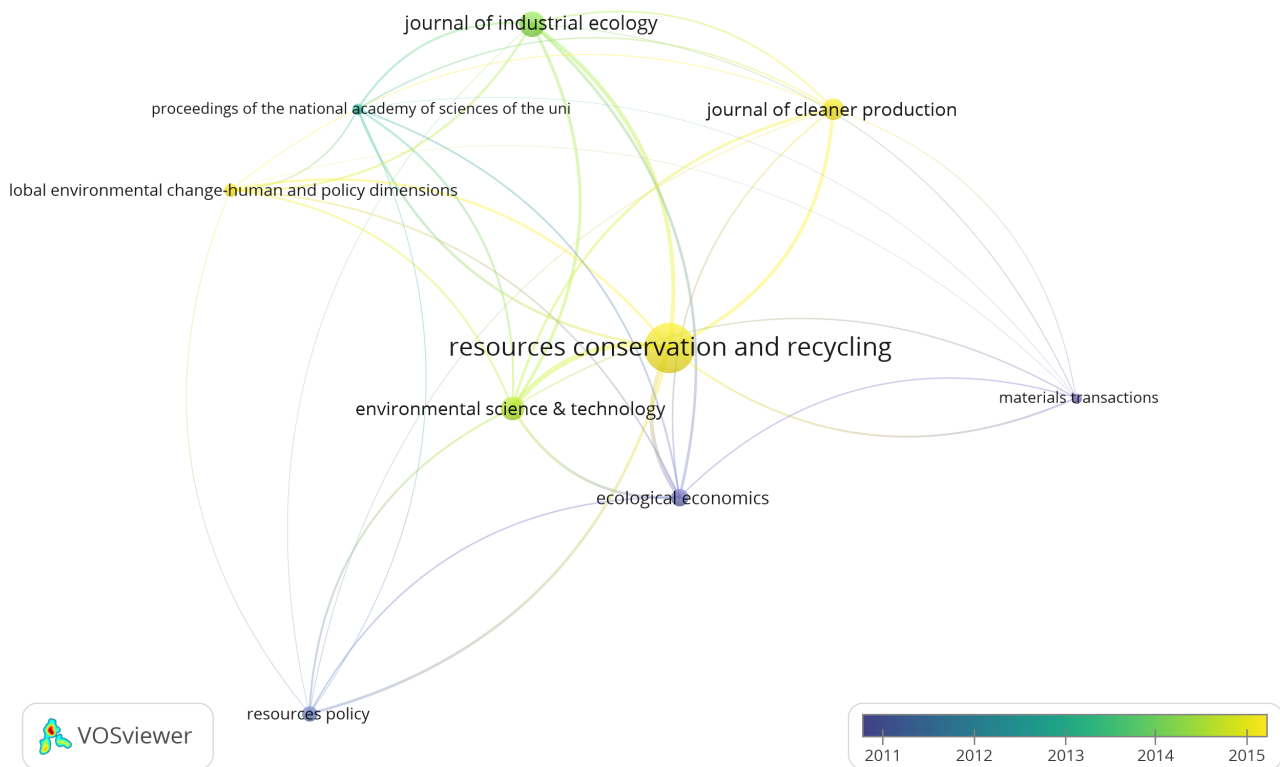


Figure A.2: Temporal visualization of the main publishing journals of the selected articles. The graph was generated using [VOSviewer](#) and a minimum number of documents of 5.

The keywords network visualization with a minimum occurrence of 5 allows to highlight 27 items segmented in four clusters. As for journal, each node represents a keyword, the line length shows the co-occurrences, and the intensity of occurrences is proportional to the nodes. Each cluster has a different color, and a node exclusively belongs to a cluster ([van Eck and Waltman, 2014](#)). They are displayed in Figure A.3 and some trends can be identified. The material flow analysis tool and industrial ecology show most occurrences ahead of recycling and copper. Three main clusters are pictured in Figure A.3, each gathering four main types of information :

- Materials (iron and steel, cement and copper)
- Modeling tools (MFA, dynamic MFA, SFA, LCA)
- Stocks and flows (overall, in-use stock, urban mining)
- General concepts (decoupling, social metabolism, efficiency, recycling, waste management, circular economy, sustainable resource management)

These categories interact in different manners. The cluster represented in red gathers iron, steel and cement with four concepts (material efficiency, resource efficiency, decoupling), the material flow analysis methodology and the industry ecology field name. It thus shows the strong integration of MFA within the field of industry ecology in the considered studies, and its preference for iron, steel and cement modeling. It also unveils the greater link between those two materials and efficiency or decoupling aspects compared to an "in-use stock" approach. The cluster displayed in red informs about the strong relation between recycling and waste management with buildings and construction through dynamic MFA. Moreover, it shows the central aspect of material intensities in buildings and waste management studies. The blue cluster is centered around copper. In the selected documents, this material is strongly related to scenario analysis about China using both MFA and SFA tools, and is more connected with circular economy than other materials. The last cluster gathers only aluminum and international trade, and shows weak links with the other clusters. It depicts the dynamic of international trade material with copper and aluminum in the Chinese area. The temporal dynamic of the keyword was also studied in [VOSviewer](#) (Figure A.4). Older modeling occurrences can be observed for iron, steel and aluminum than for copper and cement. The stock analysis dynamic evolves toward in-use stocks and urban mining, with recent links between in-use stocks and more conceptual approaches. It also shows the trend from modeling tools to more concepts in the analysis, and the recent consideration of scenario analysis. Given the growing complexity of studies, the keywords however have a limited capacity of description. It is illustrated by studies focusing on several materials, which do not appear in the keywords (2.2.1).

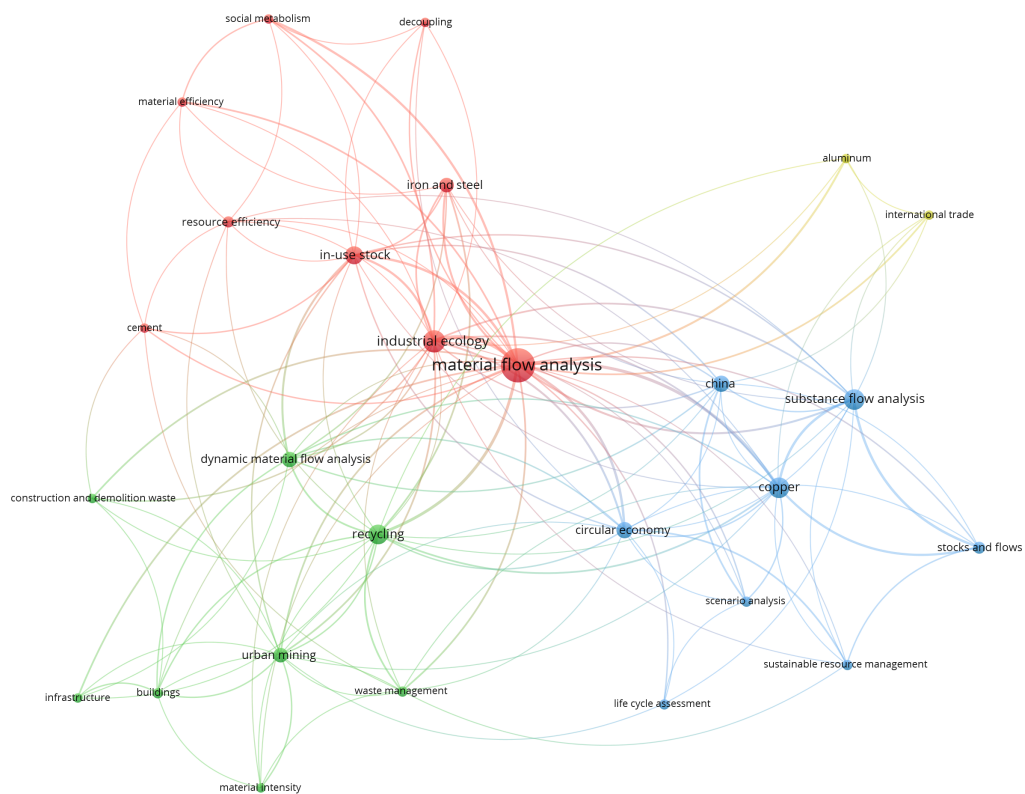


Figure A.3: Network visualization of the main keywords of the selected articles with a minimum occurrence of 5. Five clusters are depicted. The graph was generated using [VOSviewer](#).

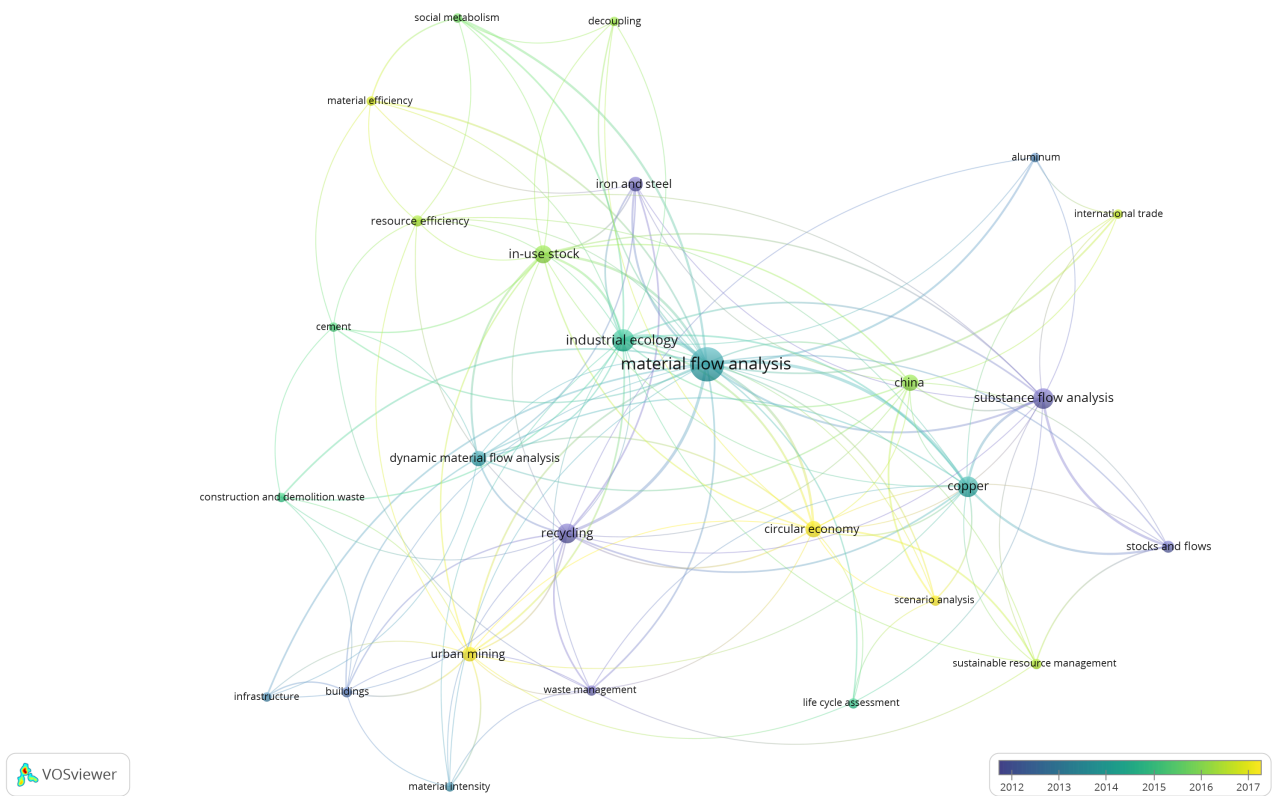


Figure A.4: Temporal visualization of the main keywords of the selected articles. The graph was generated using [VOSviewer](#).

Modeling characteristics, modeling tools and inputs

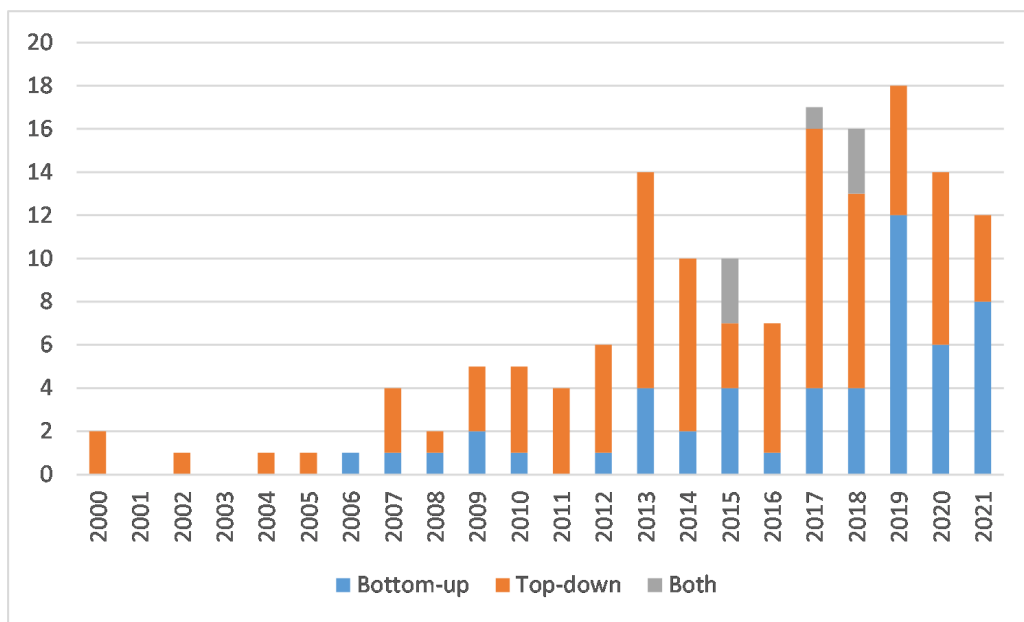


Figure A.5: Number of top-down, bottom-up and joint approaches publications between 2000 and 2021

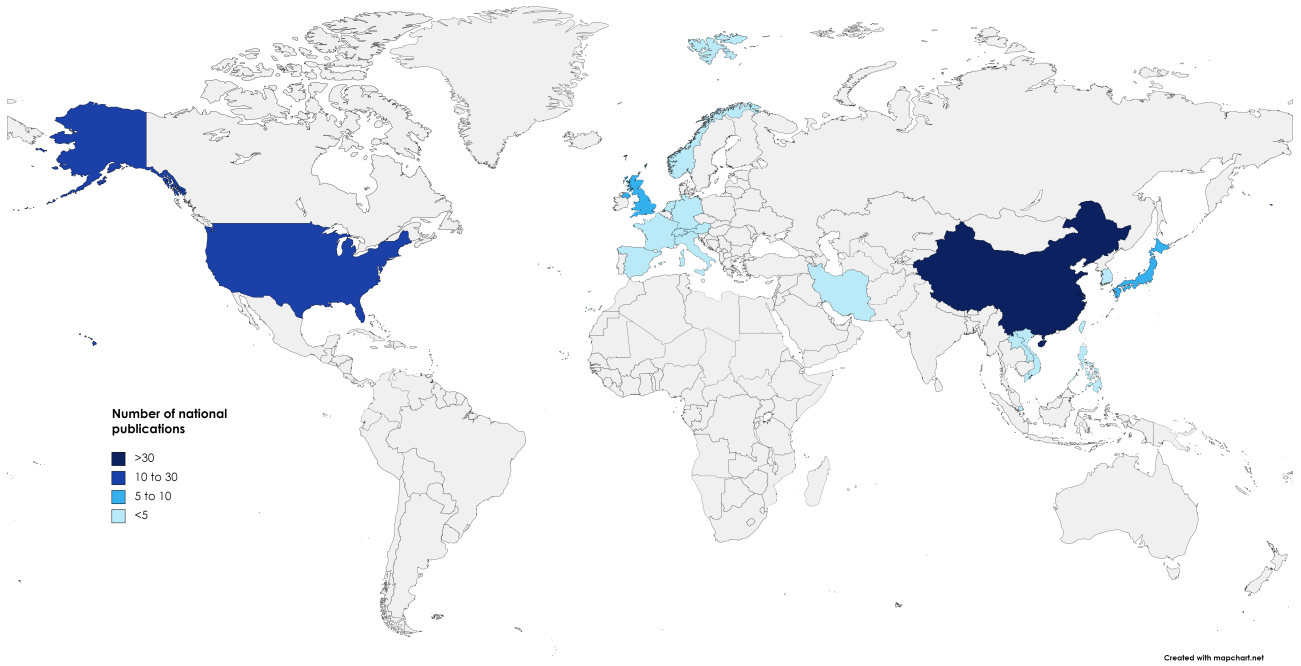


Figure A.6: Number of top-down and bottom-up national studies by country. The map was generated using [Mapchart](#).

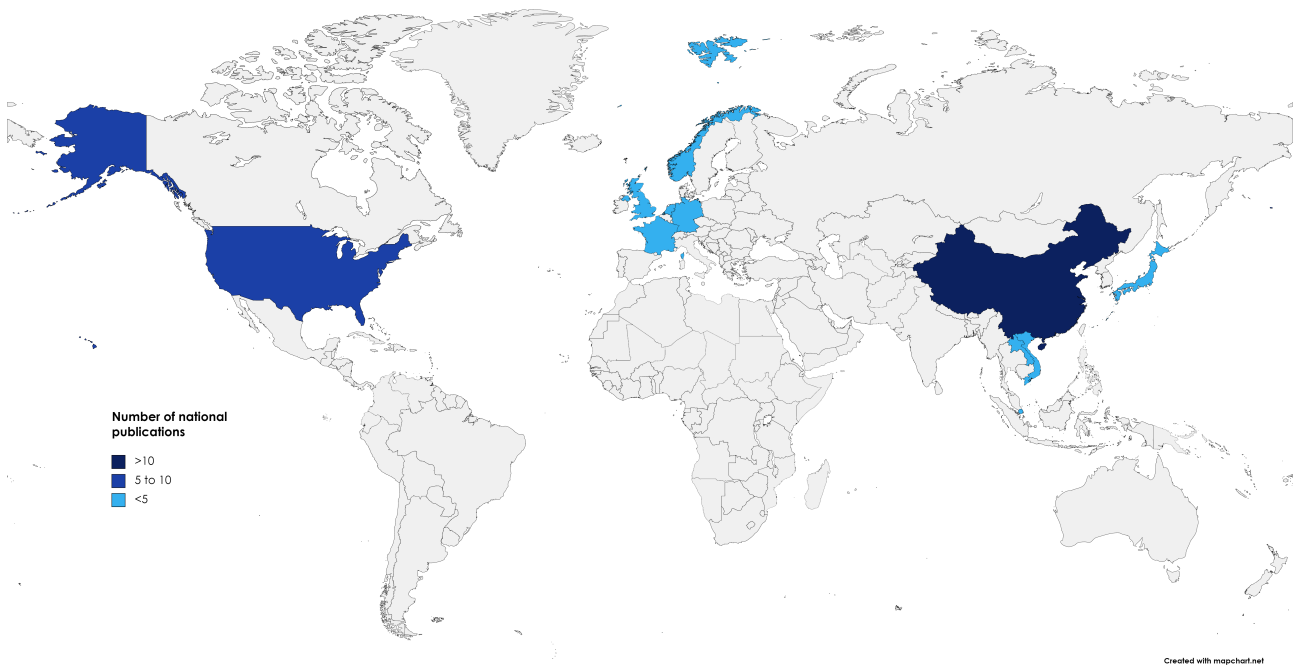


Figure A.7: Number of bottom-up national studies by country. The map was generated using [Mapchart](#).

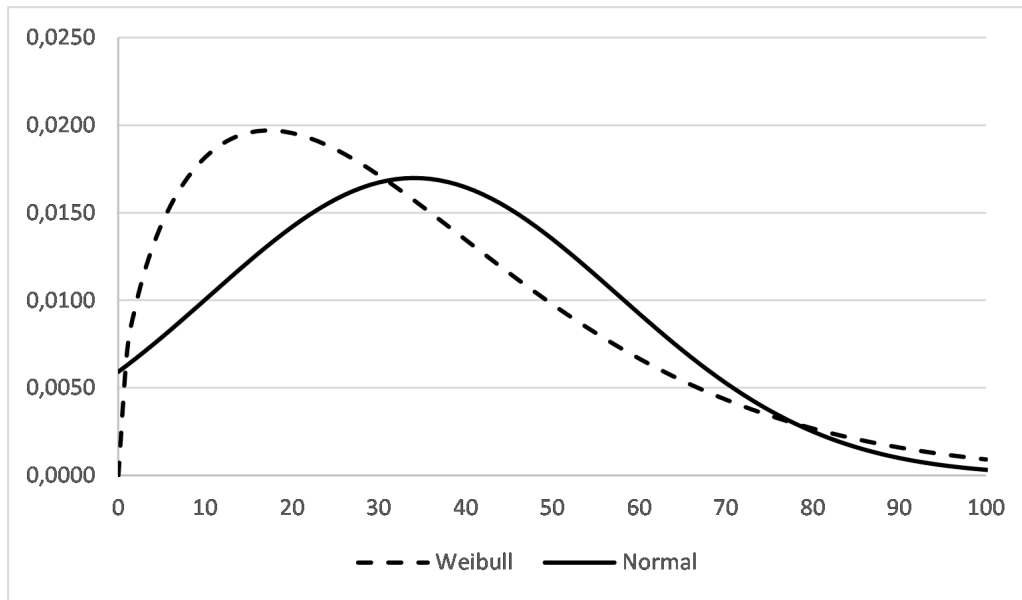


Figure A.8: Example of Weibull and normal distributions with a mean value of 34.1 and a standard deviation of 23.5 as observed for Chinese urban residential buildings in Zhou et al. (2019)

In-use stock or in-use stock per capita saturation assumptions are observed in many studies through logistic or Gompertz approaches. They depict a three-phase behavior of infrastructure and raw material stocks using an S-curve profile. These mathematical tools were originally developed to analyze the evolution of the population (Verhulst, 1845 Gompertz (1825)). Applied to infrastructures, these curves outline a gradual change towards a state of saturation. In a first phase, the stock grows slowly, before seeing its evolution explodes in a second period, and finally reaching saturation in a last phase. This allows us to understand the progressive penetration of products in society, and the physical reality of their consumption. It is indeed intuitive to perceive the limitation of demand per capita for consumer goods such as housing, vehicles, etc. The difference between these two tools lies in the speed of growth. The Gompertz curve enables to describe accelerated logistical developments, with an earlier occurrence of the inflection point than for a logistical curve.

In materials-related literature, these two mathematical tools are used to model the evolution of an infrastructure stock (Yoshimura and Matsuno (2018); Cao et al. (2018); Yin and Chen (2013); Huang et al. (2013); Shi et al. (2012) - referred to as the technological approach in the rest of the study - or of a material stock - referred to as the material approach. The first models of material in-use stocks over time are based on logistic approaches. Toi and Sato (1998) is the first study found in the research field. The authors modeled the evolution of the steel stock in Japanese society between 1920 and 2120 using a time-dependent logistic curve eq A.3.1. An assumption was made on the total saturation stock, and the curve was fitted on past data.

$$S_t = \frac{S_{sat}}{1 + \exp(\alpha - \beta \cdot t)} \quad (A.3.1)$$

In this equation, S_t is the total stock in the year t , S_{sat} is the saturation level of the stock and α and β are parameters influencing the growth rate. The three parameters of the right side of the equation are independent. A similar approach has been adopted by Igarashi et al. (2008) for an estimation of steel consumption in Japan and Asian countries between 2005 and 2030. They set a S_{sat} value of 14 t/capita, corresponding to the saturation level observed in the United States. An evolution of time-dependent logistic towards GDP-dependent logistic was then observed in the literature. Hatayama et al. (2009) provide a logistic modeling of the per capita in-use stock of aluminum for China, Japan, the United States and Europe. The three independent parameters are derived from past data curve fitting. The authors note, however, that it is not possible to determine s_{sat} with this method for countries whose stock is in its logistic initiation phase. Saturation data from other regions are then required.

$$s_t = \frac{s_{sat}}{1 + \exp(\alpha - \beta \cdot GDP_t)} \quad (A.3.2)$$

In eq A.3.2, $s(t)$ is the per capita in-use stock in year t , s_{sat} is the saturation value of the per capita in-use stock, GDP_t is the per capita GDP in year t , and α and β are parameters. A similar approach was used by [Oda et al. \(2013\)](#) for the apparent demand of crude steel per capita in 8 countries. The methodology for determining the parameters was further improved using a nonlinear regression between the GDP and per capita stock data in [Hatayama et al. \(2010\)](#), finally evaluating aluminum recycling potential for the same areas. [Hatayama et al. \(2012\)](#) used both technological and material approaches to estimate the future steel stock for three end-use sectors: civil engineering, building and vehicles. The eq A.3.2 was used to calculate the civil engineering and building in-use stocks of steel, and the evolution of the vehicles stock was estimated using a Gompertz curve which equation is shown in eq A.3.3.

$$s_t = s_{sat} \cdot \exp(\alpha \cdot \exp(\beta \cdot GDP_t)) \quad (A.3.3)$$

The three parameters s_{sat} , α and β are defined as in eq A.3.2, and also calculated using a nonlinear regression. The Gompertz function was found to best fit the evolution of vehicles stock by [Huo and Wang \(2012\)](#), and is therefore frequently used in this research field as in [Gutiérrez et al. \(2009\)](#), [Singh et al. \(2020\)](#), [Lian et al. \(2018\)](#) or [Wu et al. \(2014a\)](#). In order to use the latest data to fit the historical and the future data, [Pauliuk et al. \(2012\)](#) considered a different set of parameters. They carried out a time-dependent logistic modeling of steel stock between 2009 and 2100 based on eq A.3.4

$$c(t) = \frac{S}{1 + \left(\frac{S}{c_0} - 1\right) \cdot \exp\left(-\frac{S \cdot \dot{c}(t=t_0)}{c_0 \cdot (S - c_0)} \cdot (t - t_0)\right)} \quad (A.3.4)$$

in which $t_0 = 2009$, $c(t)$ and c_0 are respectively the per capita stock in year t and the per capita stock in 2009, \dot{c}_{t_0} is the per capita stock change in 2009 and S represents the saturation level of the stock. The previous three-parameters equations require hypothesis about the saturation stock value, either based on a coupling to economic development or experts' opinions. The GDP-correlation modeling was criticized by [Pauliuk et al. \(2013\)](#), stating that this only represents a shift to another exogenous parameter and would create a dependency towards population and GDP scenarios. A four-parameter combined logistic and Gompertz function was developed by [Liu et al. \(2012\)](#) (eq A.3.5) in order to make hypothesis about both saturation level and saturation time independently. They modeled the global aluminum stock between 1950 and 2100.

$$s_t = \frac{s_{sat}}{1 + \left(\frac{s_{sat}}{S_0} - 1\right) \cdot \exp(\alpha \cdot (1 - \exp(\beta \cdot t)))} \quad (A.3.5)$$

In eq A.3.5, S_t represents the per capita stock in the year t , S_{sat} is the per capita saturation stock, S_0 the initial per capita stock and α and β are numerically determined parameters depending on a boundary condition (98% of the saturation value at a given time). A similar approach was considered by [Pauliuk et al. \(2013\)](#) to depict the evolution of regional steel stocks between 1950 and 2100 adding a condition of a tangential behavior of the curve to the historic data. A summary of these studies is presented in Table A.3.

References	Function	Approach	Materials	Time scale
Toi and Sato (1998)	Logistic	Past data curve fitting, time dependent, saturation level hypothesis	Steel	1920-2120
Igarashi et al. (2008)	Logistic	Past data curve fitting, time dependent, saturation level hypothesis	Steel	2005-2030
Hatayama et al. (2009)	Logistic	Past data curve fitting for all parameters, GDP scenario	Aluminum	2000-2050
Hatayama et al. (2010)	Logistic and Gompertz	Past data curve fitting for all parameters, GDP scenario	Steel	2005-2050
Hatayama et al. (2012)	Logistic	Past data curve fitting, GDP scenario	Aluminum	2006-2050
Pauliuk et al. (2012)	Logistic	Time and stock dependent logistic, hypothesis about saturation levels and life-time	Steel	2009-2100
Liu et al. (2012)	Combined logistic and Gompertz	Saturation time and saturation level hypothesis	Aluminum	1950-2100
Pauliuk et al. (2013)	Combined logistic and Gompertz	Saturation time and saturation level hypothesis	Steel	1950-2100
Oda et al. (2013)	Logistic	Saturation level assumption, GDP scenario	Steel	1980-2050

Table A.3: Summary of materials stock modeling using logistic and Gompertz functions in the literature.

A.3.1 Uncertainty and sensitivity analysis

The uncertainty analysis aims at assessing the possible errors in the outputs depending on the uncertainties in the inputs, while the sensitivity analysis describe the impacts of an input variations on an output, and show which independent variable has the most impact. The local sensitivity analysis is the initial methodology. It is deterministic and based on derivatives ([Saltelli, 2008](#); [Iooss and Lemaître, 2015](#)). Given input variations - around the mean value - allow to assess its impact on an output. This methodology however only displays variations in given points of space, and are limited by unknown linearity of the model and uncertainty of the input. In order to prevent these limitations, global sensitivity analysis was developed in the late 1980s. The input varies in its whole value range, allowing to compute the average response of the output ([Saltelli, 2008](#); [Iooss and Lemaître, 2015](#)). Moreover, the Sobol decomposition of the variance gives indications about the effects of interaction of inputs. The first order term of the variance measures the impact of a single input, while the second order assesses the impacts of the interaction of two inputs etc...([Mara and Tarantola, 2008](#)). Following the Sobol decomposition, the sum of first order variances are equal to unity in a set of non-correlated parameters. A higher than unity value of this sum therefore indicates a correlation of inputs [Buchner et al. \(2015\)](#), and a lower value informs about a lack of parameters and/or correlation considerations in the sensitivity analysis ([McMillan et al., 2010](#)). Uncertainties are not well defined in the selected publications because of a lack of traceability of data. They are commonly studied from assumptions about the data quality, Gaussian error propagation ([Bader et al., 2011](#)) or Monte Carlo approach ([Soulier et al., 2018b](#)). These studies focus on input uncertainties, and model uncertainties are rarely addressed. They are defined as the uncertainties related to the intrinsic imperfection of models ([Buchner et al., 2015](#)), with a special focus on initial stock values, and lifetime definition. Conversely, sensitivity analysis are usually well addressed. Most of the studies consider a local sensitivity analysis, with a variation of one of several input parameters by a fixed rate ([Fishman et al., 2014](#); [Carmona et al., 2021](#); [Streeck et al., 2021](#); [Dong et al., 2019](#); [Pauliuk et al., 2013](#); [Hu et al., 2010](#); [Yin and Chen, 2013](#); [Spatari et al., 2005](#)). A growing use of global sensitivity analysis is however observed, based on the Monte-Carlo approach ([Glöser et al., 2013](#); [Soulier et al., 2018b](#); [Buchner et al., 2015](#); [Soulier et al., 2018a](#); [Cao et al., 2017a](#)) or the FAST method ([McMillan et al., 2010](#)).

A.3.2 Material cycle and ratios

The cycle used in this section is simplified, and further sub-rates can be defined. In a publication outside the scope of this review, [Ciacci et al. \(2015\)](#) differentiated between the metals "lost by intent" -e.g. dissipative uses- from those "lost by design" -e.g. selenium in glass.

1. The old scrap collection rate (EOL-CR) is the share of metals embedded in end-of-life products actually collected:

$$CR = \frac{F}{D} \quad (A.3.6)$$

2. The recycling process efficiency rate (EOL-PR):

$$EOL-PR = \frac{G}{F} \quad (A.3.7)$$

3. The end-of-life recycling rate (EOL-RR) is defined as the proportion of metals embedded in end-of-life products actually recycled:

$$EOL-RR = \frac{G}{D} \quad (A.3.8)$$

4. The recycling content (RC):

$$RC = \frac{K}{A+K} \quad (A.3.9)$$

5. The fraction of old scrap in the recycling flow (OSR):

$$OSR = \frac{G}{G+J-K} \quad (A.3.10)$$

6. The dissipation index (DI), defined by [Lifset et al. \(2012\)](#):

$$DI = \frac{H}{H+A} \quad (A.3.11)$$

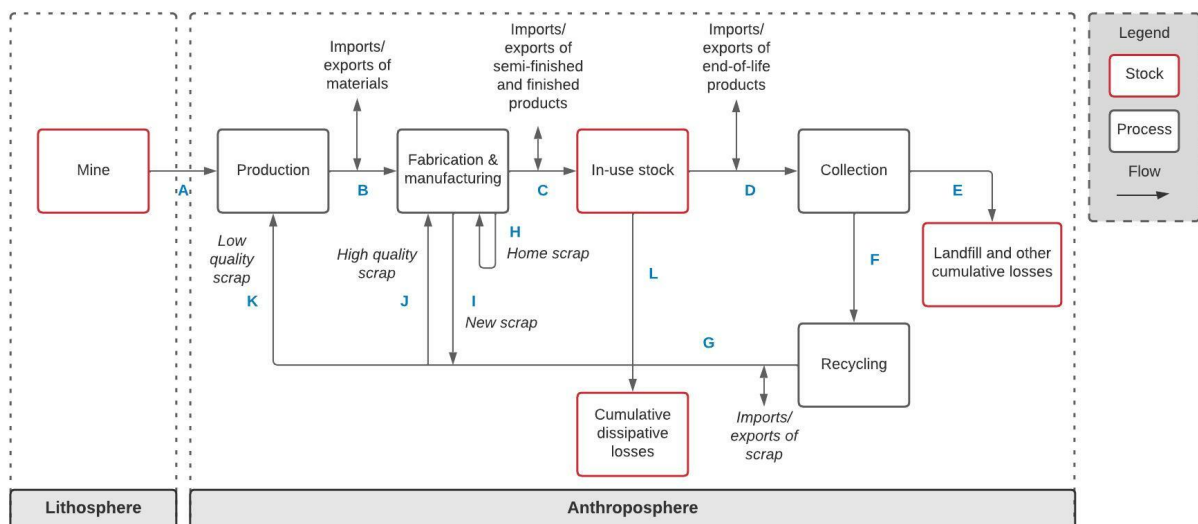


Figure A.9: Simplified metals stocks and flows cycle (Adapted from [Graedel et al. \(2011\)](#); [Glöser et al. \(2013\)](#) and [Maung et al. \(2017\)](#)). A : Primary metals, B : Refined metals, C : Semi-finished and finished products, D : End-of-life products, E : Losses in the collection, F : Collected metals, G : Recycled metals or old scrap, H : New scrap.

Appendix B

Appendix to Chapter 3: *The DyMEMDS model*

Article

Modelling the Demand and Access of Mineral Resources in a Changing World

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Abstract: Humanity is using mineral resources at an unprecedented level and demand will continue to grow over the next few decades before stabilizing by the end of the century, due to the economic development of populated countries and the energy and digital transitions. The demand for raw materials must be estimated with a bottom-up and regionalised approach and the supply capacity with approaches coupling long-term prices with energy and production costs controlled by the quality of the resource and the rate of technological improvement that depends on thermodynamic limits. Such modelling provides arguments in favour of two classically opposed visions of the future of mineral resources: an unaffordable increase in costs and prices following the depletion of high quality deposits or, on the contrary, a favourable compensation by technological improvements. Both views are true, but not at the same time. After a period of energy and production cost gains, we now appear to be entering a pivotal period of long-term production cost increases as we approach the minimum practical energy and thermodynamic limits for many metals.



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Keywords: raw materials; mineral resources; demand; production energy; price

1. Introduction

The per capita consumption of global resources has doubled between 1950 and 2010 [1], and the consumption of raw materials and mineral resources (gravel and sand, cement, ores, industrial minerals) used to build the energy, transportation, and building infrastructures and consumer goods of modern societies has increased at an average rate of 2–5%/year over the past century. Humanity is now using mineral resources at an unprecedented level, with 70 billion tons of material extracted from the ground per year [2–6]. This acceleration naturally raises the question of supply sustainability, which has been discussed repeatedly since the 1950s [7–16]. Recurring predictions of the short-term depletion of fossil resources have so far not been verified by actual shortages. On the contrary, and despite the exponential growth in consumption observed for more than a century, metal reserves have never been higher than they are today. The increase in reserves, despite the strong growth in consumption, can be explained by technological progress, which makes it possible to exploit new fossil resources of lower quality at the same cost. Unconventional hydrocarbons, which were undevelopable at a competitive cost a few decades ago, are now a major source and most metal deposits developed today are less concentrated than those developed in the past [17]. Because the amount of low-grade deposits is much greater than concentrated deposits, reserves have increased with technological improvements. This trend gives the misleading impression that perpetual growth is possible in a finite world, the Earth: misleading because there is a thermodynamic limit to the potential of technological improvements, and what was possible in the past will not necessarily be possible in the future.

The future availability of fossil resources depends on production capacity, which, in turn, depends on production technologies, the type and quality of ore deposits controlling production costs, and the proportion of recycled products at the end of their lives. It also depends on demand, which, in turn, depends on population and standard of living, economic and geopolitical cycles, and technological development associated with energy and digital transitions. All these parameters define the conditions for economically viable production. They vary over time, are coupled, and should not be analysed separately. Over the past decades, the demand for non-energy materials has been intensively studied through material flow or input–output analyses. The development of materials databases [18–21] has enabled a comprehensive understanding of metal and mineral stocks and flows within society at different scales through top-down studies (e.g., [22–27]). Many recent efforts have been devoted to estimating future demand for raw materials through bottom-up, stock-based analysis in the energy (e.g., [28–37]), transportation (e.g., [31,38–42]), and construction sectors (e.g., [39,43–47]), its energy demand and production cost (e.g., [6,39]), environmental impacts (e.g., [39,48–50]), or to reserve estimation (e.g., [51–53]) and production capacities. However, very few studies have attempted to combine all these dimensions into single models. Notable exceptions are the dynamic models World7 [54,55] and MEDEAS-World [56], which couple global gross domestic product (GDP) and demographic changes with commodity and energy demand. These models are valuable and powerful tools for discussing the global resource issue in relation to socioeconomic changes. However, they sometimes rely on disputable empirical assumptions such as the linear dependence of the total demand of metals on GDP evolution assumed in MEDEAS [56]. This assumption, based on an empirical fit of global historical data covering too short a period, is in conflict with the historical evolution in developed countries [57–59]. Moreover, it assumes that the future demand for metal per GDP will be the same as in the past, whereas new technologies that did not exist two decades ago are developing fast in the sectors of energy, transport, and information and communications. The estimation of global demand requires a comprehensive bottom-up approach, i.e., by technologies whose material intensities, use intensities, energy consumption, and efficiencies change at different rates over time and by geographic regions with contrasting transportation patterns and material intensities. The modelling of raw material supply can also be improved by developing standardized approaches coupling long-term resource prices with energy and production costs [60]. The minimum production energy and the minimum practical production energies can be estimated from the quality of the resource exploited (ore grade) and on technological improvement constrained in the last resort by thermodynamic limits that cannot be overstepped. Finally, and before attempting to apply the models to future developments, it must be demonstrated that they are capable of reproducing the historical evolution of the demand for infrastructure and raw materials over long periods of time, by country or geographical region. These different points are discussed in the present contribution, along with a brief review of anticipated future needs and production capacities. Our objective is not to provide a single answer to the complex issues raised by the consumption and supply of mineral resources but rather to identify some of the key points that seem important to consider in their modelling.

2. The Drivers of Mineral Resources Consumption

2.1. The Base Metals and Cement Consumption from Traditional Applications

The prospective analysis of metals and minerals in society requires a dynamic model describing the evolution of stocks and flows. An inverted U-shape of demand with economic growth was first proposed in the late 20th century [61] and later validated for steel for middle-income countries [59]. Growing stock analysis has led to a better understanding of stock and flow dynamics, and to the identification of a three-stage model of the stock curve in use: growth, maturation, and saturation [57]. The first stage of economic growth in all countries is characterized by the construction of raw materials demanding infrastructures of heavy industry, housing, transport, communications, and energy. This

phase of development mainly consumes “structural” raw materials produced in present global quantities of more than one million tons per year (Mt/yr), such as sand and aggregates, concrete, steel and iron, aluminium, copper, manganese, zinc, chromium, lead, titanium, and nickel. Then, the annual consumption of structural raw materials levels off when the gross domestic product (GDP) per capita reaches about 15,000 USD/cap (maturing stage) and eventually declines as the in-use stock reaches its saturation limit (saturation stage) [57,58]. When the saturation level of in-use stocks is reached, the size of the infrastructure becomes mainly controlled by the evolution of population and the material content of technologies. The number of technological units per capita (number of cars, trucks, planes, ships, m² building, etc.) as a function of GDP/capita thus follows the sigmoidal pattern of a logistic function, whose parameters can be constrained by fitting the historical evolution of each technology by countries (e.g., [46,62,63]). These parameters depend on the geography, population density and lifestyle of the countries, with average values in the order of 0.7 LDV/cap, 7×10^{-5} locomotive/cap, 1.5×10^{-5} aircraft/cap, and 90 m²/cap. From these figures, the future evolution of infrastructure can be estimated for given future GDP and population evolutions. This is illustrated in Figure 1, which shows the number of observed and estimated light vehicles, locomotives, airplanes, and the surface of buildings in the USA and China from 1950 until 2100. The results were obtained with the model DyMEMDS (dynamic modelling of energy and matter demand and supply) available online <https://www.dropbox.com/sh/ws85dgbelt9ceyf/AAC8fYnglzzINREp27xvwFnra?dl=0> (accessed on 13 December 2021). DyMEMDS is a stock and flow model that links the energy consumption, GDP, and population with raw materials consumption, greenhouse gases emissions, global warming, and additional environmental impacts such as the consumption of water and used land for mining. It includes about 50 technologies of transportation, construction, and energy; 10 metals, cement, and gravel; and 9 geographical regions covering the world. From the evolution of infrastructure calculated for imposed future GDP and population evolutions (Figure 1), the stocks of materials by technologies are estimated using dynamic raw material intensities in kg of material per technological unit.

The same material intensities were used for all countries except for the building sector, which shows strong disparities between countries. The concrete and steel intensities are for instance lower in the US than in China [64]. The stocks of materials in the infrastructure of all regions are obtained by adding up the needs of all technologies, and the global demand by adding up the demand of each geographical region (Figure 2). The annual consumptions are then obtained by deriving the stocks over time and the annual flows of primary, recycled, and lost materials are calculated for imposed lifetimes of goods, collection, and recycling rates (Figure 3). This full bottom-up approach starting from regional GDP and population evolutions makes it possible to link the global raw material consumption with the economic development and the population and technological evolutions of each geographical region. It reproduces the incremental increase in demand for base metals, cement, and gravels observed since World War II. The period 1950–1970 was marked by a strong increase in global consumption driven by the construction of the infrastructure of currently developed countries. Consumption growth declined during the 1970–2000 period, as saturation thresholds were approached in rich countries, and no poor country was economically emerging. Then the rapid economic emergence of China in the late 1990s led to a second period of increase in global consumption (Figure 3). China’s consumption is expected to level off over the next decade, and then decline between 2030 and 2050. After 2050, the need for new infrastructure in this country is no longer controlled by the evolution of GDP/capita because the saturation thresholds are reached. Moreover, the amount of recyclable material that was negligible before 2030 increases after 2030 as fast as the increase in consumption observed between 2000 and 2025. The amount of steel available for recycling between 2050 and 2075 is even higher than the apparent consumption. A peak in steel consumption was also observed in the US in the 1970s, although less pronounced than in China in 2030 because previous growth was slower. Since then, the US steel consumption has remained relatively constant, which is a common observation made for

all rich countries, as well as in China after 2050. An incremental evolution of demand is also observed for Ni, Cr, and Mn, which are mainly used as alloying elements of steel. The incremental evolution is less clear for other base metals such as copper and aluminium involved in a variety of new applications with lower lifetimes than steel since the 1950s. The decrease in Chinese consumption in 2030–2050 is likely to be compensated by the increase due to the economic emergence India and African countries. Assuming that these countries will achieve their economic development within the century, the Indian peak of cement and steel consumption might occur in 2050 and 2100, and those of copper and aluminium one or two decades latter. The African consumption peaks are expected to occur 15 years latter. In this scenario, the yearly global demand for steel and cement in 2100 is fourfold the present value and sixfold the present consumption for aluminium and copper.

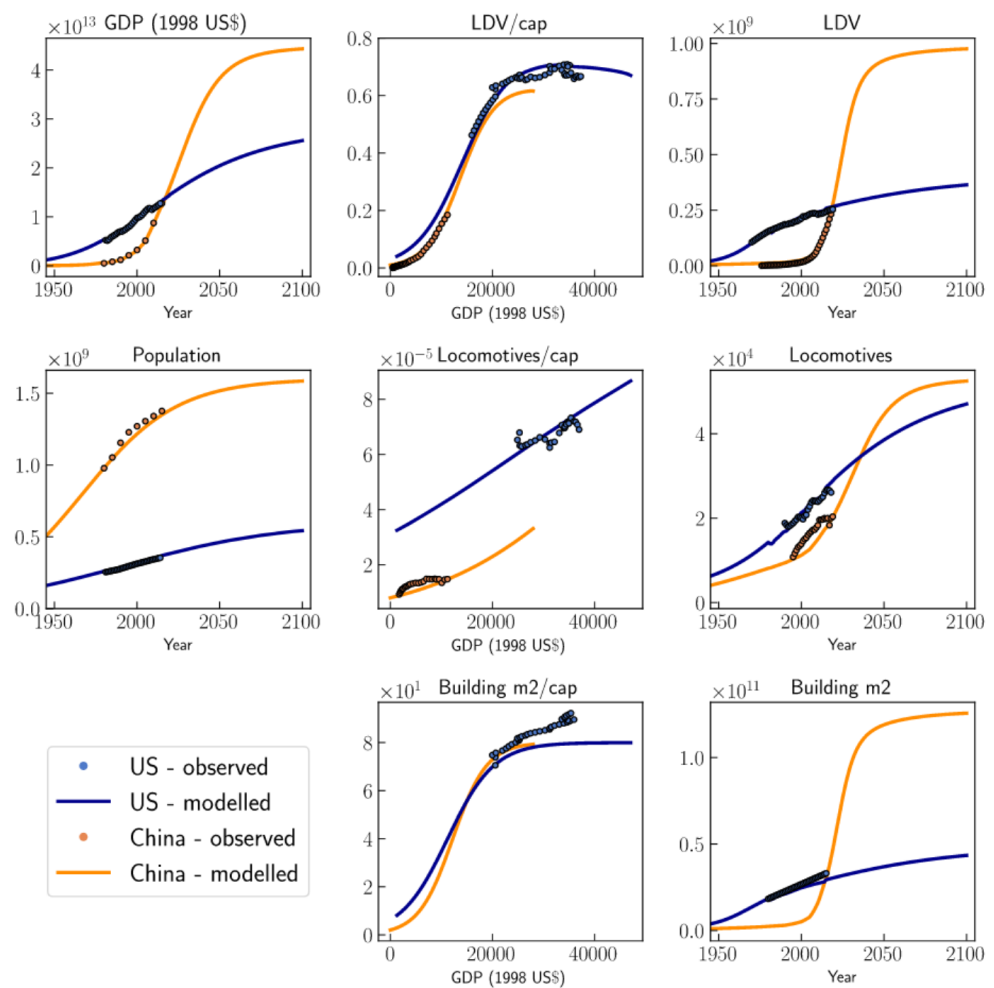


Figure 1. Evolution of the demand in infrastructure per capita in function of GDP/cap or time in China (grey lines and open circles) and the USA (black line and black circles).

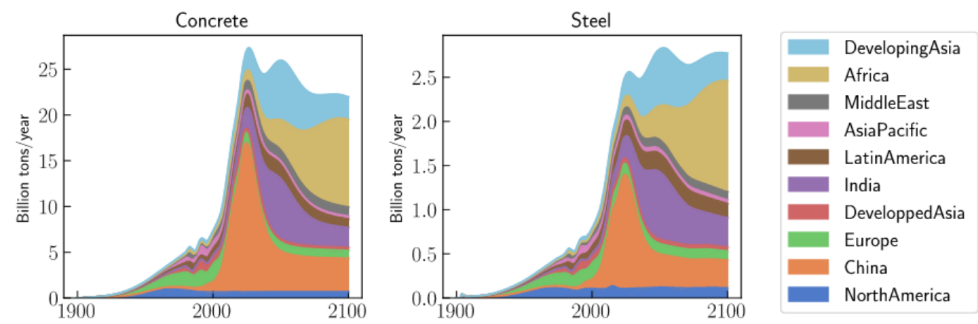


Figure 2. Concrete and steel consumption by geographical regions based on a logistic growth of regional infrastructures calculated for logistic GDP and population growths (Figure 1).

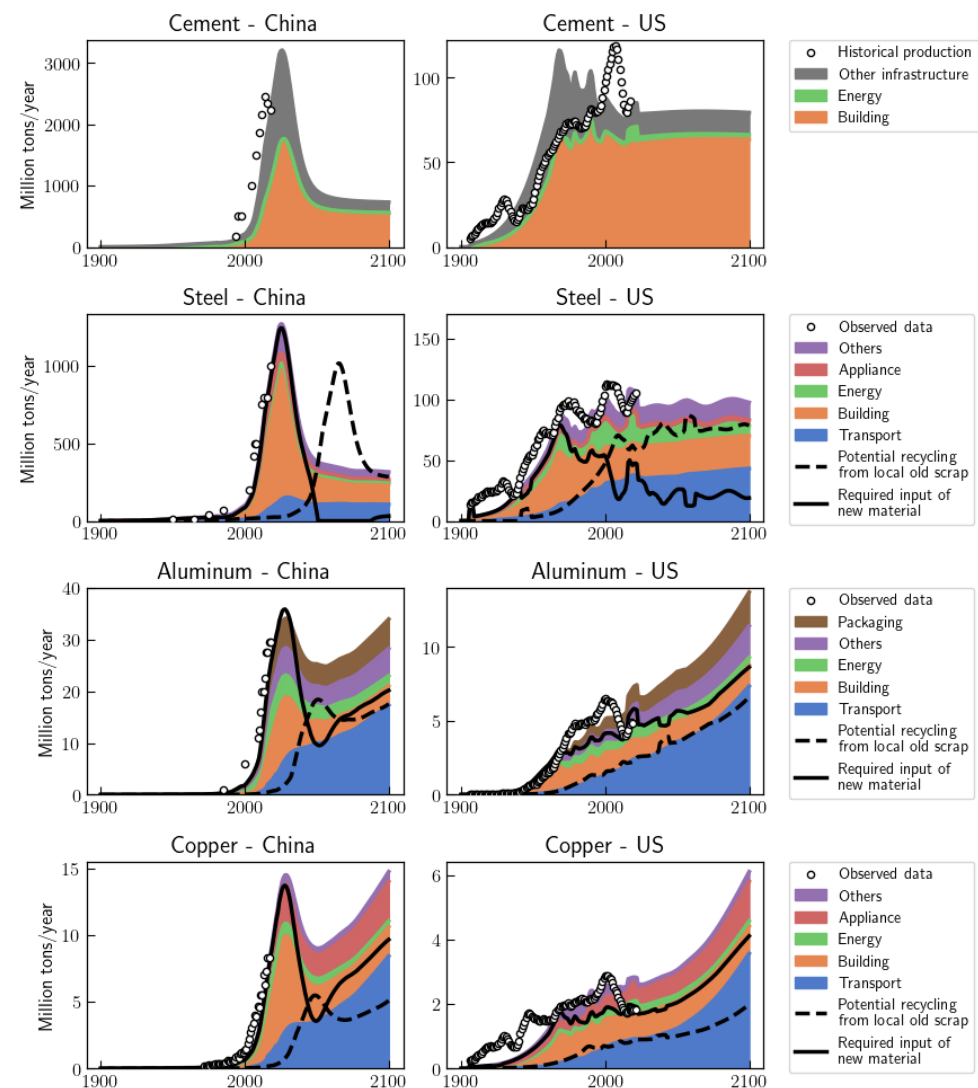


Figure 3. Raw material demand by sectors (Mt/year) calculated from the evolution of infrastructure (Figure 1) for China (Left panel) and the USA (Right panel). The plain and dashed black lines show the input and theoretical recycled flows, respectively (assuming no export or import of scrap). The dots show the historical data (USGS).

2.2. The New Applications and High-Tech Metals

In parallel or after building its basic infrastructure, economies are moving towards advanced technologies, which use many properties resulting from the electronic structure, catalytic, quantum, or semiconductor properties specific to almost all the elements of

the periodic table. Rapid changes in the use of metals have emerged during the last decades in the Information and Communication Technology (ICT) sector: In 2019, there were approximately 13 billion mobile phones and tablets [65] and 2 billion computers (1 billion in 2008) in use, Facebook had more than 1 billion users, and global data centre traffic was estimated at 4.8 zettabytes, representing more than 26,000 centuries of streaming video. This ICT sector is a large consumer of rare and high-purity substances (Cu, In, Ga, Sb, Ge, Co, Li, Ge, Ta, Nb, Au, Ag, rare earths, etc.) with dispersive uses resulting from high dilution in many short-lived devices, which limits the potential for recycling in the order of one percent. While the base metal consumption since 1990 has increased by 2–5%/year, the annual growth of rare metals production is about 10%/year. These huge growth rates and possible supply problems have attracted most of the attention over the last decade [66]. However, assessing the future of high-technology metals demand is difficult because it depends on rapid technical innovation, and the use of high technologies is much less dependent on GDP/capita than base metals. New technologies also concern the energy sector, which is evolving to reduce our greenhouse gases (GHG) emissions and comply with the Paris agreement. This agreement of COP21 aims at achieving the “carbon neutrality” in the second half of the 21st century, which implies a deep review of the existing fossil-based energy system. Unfortunately, solar and wind infrastructures require more raw materials per installed capacity and energy supplied than fossil fuel-based facilities [34,37,67–69]. The same observation is made for the storage of energy, its transport, and its use at the end of the energy chain. It follows that large amounts of structural and high-tech mineral commodities will be consumed for the energy transition.

Figures 2 and 3 have been calculated under the assumption that the penetration of low-carbon energy technologies will remain moderate. For the same evolution of GDP and population, and thus of building, transport, and energy infrastructure, the demand for metals will be different for a higher penetration of renewables. Examples are shown in Figure 4, which illustrate the differences in global Cu, Li, Co, and Ni consumption for the two contrasted energy scenarios RTS (Reference Technology Scenario) and B2DS (Beyond 2 °C Scenario) of the International Energy Agency (IEA) [70]. In contrast to previous estimates based on GDP/capita evolutions (Figures 2 and 3), the demand in raw materials in Figure 4 is calculated from the consumed energies listed in the scenarios, which are transformed into an infrastructure for assumed evolutions of energy consumption (−1%/yr) and material content. The evolution of infrastructure is then transformed into raw materials demand using the same material intensities as those used to build Figures 2 and 3. The demands in Cu, Li, Co, and Ni are noticeably higher for the B2DS scenario, which foresees a massive incorporation of renewable energy in the energy mix. Rare earth elements (REE), and in particular neodymium, are also elements of concern, as they are used in the permanent magnets of a wide variety of technologies using electric motors and in the generators of off-shore wind turbines. The estimates in Figure 4 must be handled with care because the present technologies, intensity of use and recycling rates are not necessarily representative of the future situation. The price of cobalt, used as a cathode in lithium-ion batteries, increased from 55,000 to 83,000 USD/t between March 2017 and February 2018. This situation has prompted manufacturers to find solutions to reduce or ban the use of cobalt in lithium batteries (increasing investments into cobalt-free batteries research and development and production are currently observed by small to large companies <https://cleantechnica.com/2018/07/03/tesla-panasonic-investments-in-cobalt-free-batteries-not-the-only-game-in-town/> (accessed on 13 December 2021)) and to develop efficient recycling solutions (such as the development of closed loop recycling processes <https://www.umicore.com/en/media/press/new-power-from-old-cells-audi-and-umicore-develop-closed-loop-battery-recycling> (accessed on 13 December 2021)). Similarly, during the rare earth elements (REE) crisis in 2011, engineers were able to find solutions to either reduce the amount of used REE while maintaining the efficiency of technologies or to change technologies. This illustrates the high potential of technological innovation to

reduce the use of rare elements in high or/and energy technologies. For these reasons, it is extremely difficult to provide reliable estimates of their future demand.

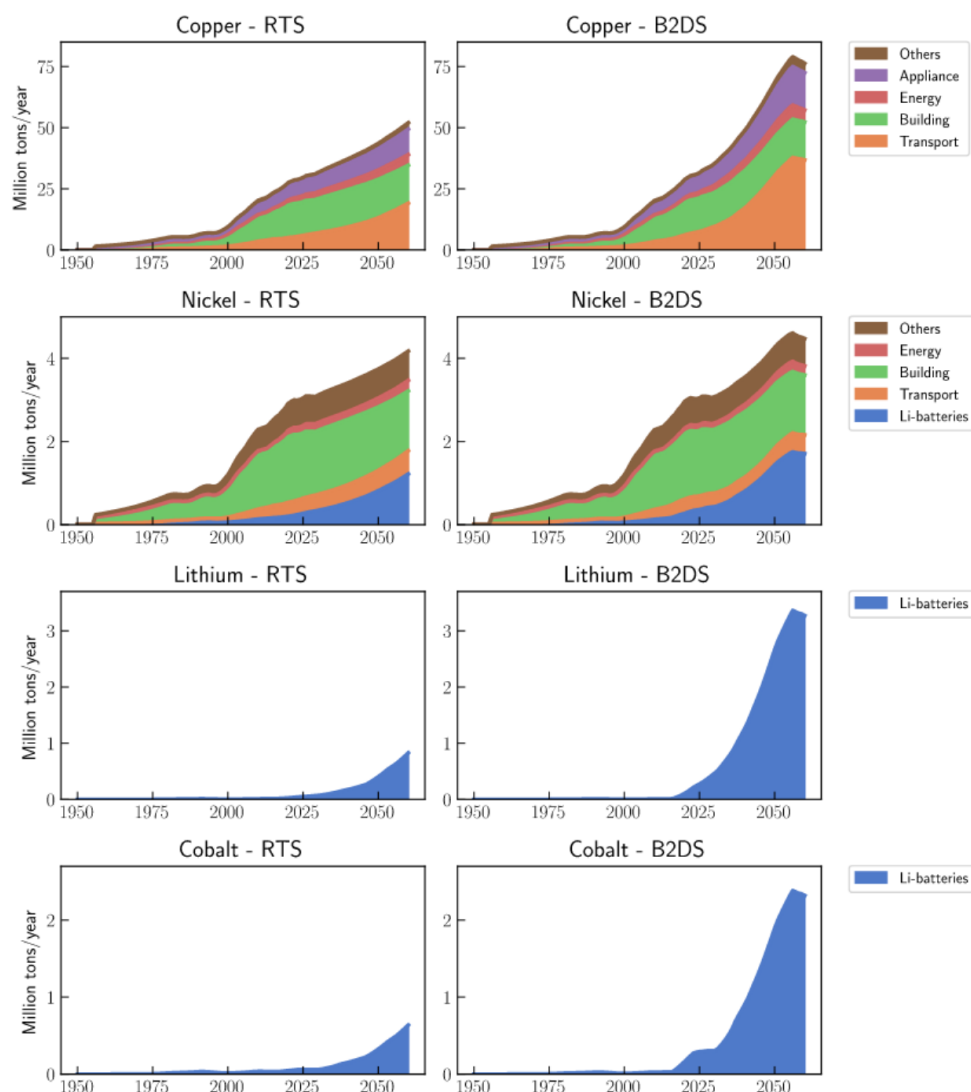


Figure 4. Annual demand for Cu, Li, Ni, and Co calculated for the evolution of infrastructure in the reference technology (RTS) (Left panel) and the “Beyond 2 °C” scenario (B2DS) (Right panel) of the International Energy Agency.

Even though it will depend on the rate of economic development and energy and numerical transitions, the estimated cumulative amount of metals to be produced over the next 35 years is likely to be equivalent or exceed the cumulative amount produced from antiquity to the present. These dizzying figures, which are consistent with previous estimates [2,3], illustrate the reality of a forever growth of GDP. For a constant growth rate of 5%/year, the quantity doubles every 12 years. It has been possible to double aluminium production since 2000, but will it be possible to quadruple it in the next 40 years? This question is addressed in the following section.

3. Can Future Production Meet the Demand?

Several studies suggest that the future supply of raw materials will not be able to keep pace with demand because the stock of exploitable non-renewable resources is declining over time and the production of several metals has already peaked or will peak in the near future [8,10–13,16,71,72]. Although it was initially developed for oil production, the application of Hubbert’s theory to mineral resources led Sverdrup et al. [72] to the

conclusion that the production of gold, silver, copper, nickel, zinc, molybdenum, iron, platinum, and indium should peak at or before 2050. The same authors described a similar situation for conventional fossil energy resources, and a peak of non-conventional oil by 2075. However, a major flaw of Hubbert's approach lies in the assumption that production is limited by the sole availability of resources at continuously growing demand. According to this logic, the observed decline in the growth rate of steel production between 1970 and 2000 (Figure 2) could have been misinterpreted as a sign of resource depletion, while it was actually resulting from the temporarily declining growth of demand. Another pitfall is the assumption that the "ultimate recoverable resource" (URR) is finite and quantifiable. Metals and minerals are currently exploited from a small fraction of the continental crust. The maximum value of reserves can be estimated from the log-Gaussian ore-tonnage (OT) versus ore grade (OG) relationship of ore deposits [73,74]:

$$OT = \frac{A}{OG \cdot \sigma \cdot \sqrt{2\pi}} \cdot \exp\left(\frac{-\log(OG) - \mu^2}{2 \cdot \sigma^2}\right) \quad (1)$$

where μ is the central tendency, σ the dispersion, and A is the scaling factor that determines the function amplitude. The additional amount of metal M_{OG} that can be extracted with varying OG reads:

$$M_{OG} = OT \cdot \frac{OG}{100} \quad (2)$$

M_{OG} is the amount of additional available metal deduced from its geological distribution in the crust, whatever the cost of its extraction. The integral of M_{OG} gives the evolution of reserves plus cumulative production, which increases exponentially as long as the average OG remains below the value of the peak of OT vs. OG (Equation (1)). By combining Equations (1) and (2) with the expected evolution of demand (Section 2), it is possible to estimate the required evolution of average OG and thus OT and metal reserves. Based on the historical evolution of copper reserves, production, ore tonnage, and OG with time, Vidal et al. [75] have estimated an URR of copper between 5 and 7.5 Gt in 2100 for a copper price ranging between 10 and 15 thousands USD(1998)/t. Although these estimated reserves are within the range of those made by [76–79], the approach is fraught with large uncertainties arising from equally large uncertainties in the distribution of metals in the Earth's crust. Vidal et al.'s estimates assumed a bimodal distribution [75], one centred at the average grade of copper in the crust ($OG \approx 30$ ppm [80]) and another corresponding to the peak OT of ore deposits centred at $OG \approx 0.3\%$ [73]. However, the bimodal OT vs. OG distribution is questionable [76], and if a unimodal distribution centred at the average crustal concentration is assumed, future reserves could be at least an order of magnitude higher. Estimates of future reserves and resources availability from geologic criteria and OT vs. OG distributions are thus quite uncertain. The question of availability is above all a question of price and environmental impacts we will be willing to pay. Historical data show that, so far, technological improvements have made it possible to mine less and less concentrated and accessible ores (deeper, offshore) without unaffordable increases in production costs and metal prices. Is this trend sustainable in the future? To answer the question, we must now understand the links between energy and production costs, between metal prices and OG, and between technological improvements and thermodynamic limits.

Energy of Metal Primary Production, Prices, and Reserves

Currently, about 12% of global energy consumption and about 35% of the energy consumed by industry worldwide is used for the production of iron and steel, cement, aluminium, and non-ferrous metals [81]. The production of mineral resources is therefore very energy-intensive. The energy of primary metal production can be estimated as the sum of three contributions [60,69]: (i) the comminution energy proportional to the inverse of the mass concentration of metals in ore deposits ($\frac{1}{C}$), (ii) the minimum energy to separate the metal-bearing minerals from the disaggregated ore given by the mixing entropy of an

ideal mixture of two components with no interaction (Es_i), and (iii) the minimum energy of metallurgy given by the Gibb's free energy of formation of the ore mineral from its constituents ($-\Delta G_{fi}^\circ$):

$$E_i(2005) = \overline{\eta(2005)} \cdot (-\Delta G_{fi}^\circ + Es_i + \frac{a}{C_i(2005)}) \quad (3)$$

where $\overline{\eta(2005)}$ is the inverse of the energy efficiency compared to the thermodynamic minimum ($\eta = 1$ at the thermodynamic minimum). Based on the observed evolution of the production energies of 20 metals (i) diluted from 1.9 (iron) to 2×10^5 (gold, platinum), average values of $\overline{\eta(2005)} = 3$ and $a = 0.2$ are obtained (Figure 5a). Several studies have shown that the average price of metals is proportional to the energy of their production, which also varies as a power law of dilution ($\frac{1}{C}$) [60,69,82–84]. For the 20 metals used to derive the values $\overline{\eta(2005)}$ and a in Equation (3), a plot of the observed production energies $E(2005)$ as a function of their price in 2005 ($P(2005)$) confirms this proportionality, and the following relationship is derived [85] (Figure 5c):

$$P(2005) = 26 \cdot \alpha \cdot E(2005)^{1.1} \quad (4)$$

A systematic deviation is observed between the observed and calculated price evaluated with Equation (4). The ratio of the observed to the calculated price is proportional to the metal dilution (Figure 6b), which suggests that the share of energy cost in price also depends on metal dilution. This effect is taken into account by multiplying the RHS of Equation (3) by $\alpha = \frac{2}{C(2005)^{0.2}}$ (Figure 5b).

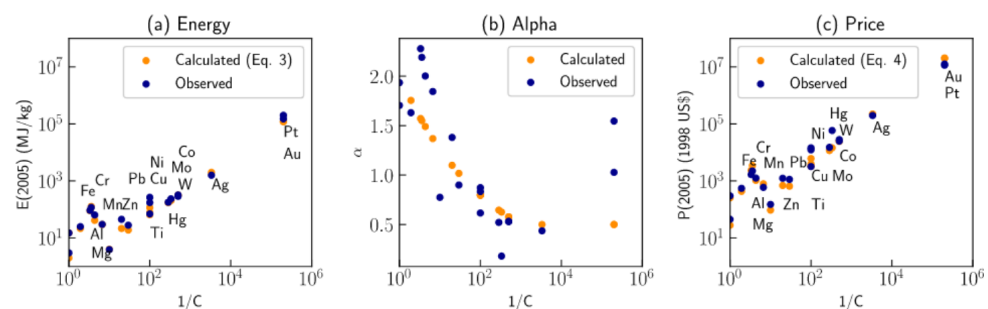


Figure 5. Energy (a), α in year 2005 (b), and price (c).

The evolution of production energy with time can be estimated with Equation (3) by replacing the 2005 values of η and C by their values at year t . In order to account for the variations of energy price with time, Equation (3) must also be corrected by the price of energy at time t ($PE(t)$) relative to 2005 ($PE(2005)$):

$$P(t) = 26 \cdot \alpha \cdot E(t)^{1.1} \cdot \left(\frac{PE(t)}{PE(2005)}\right)^\gamma \quad (5)$$

where γ is the elasticity of metals' price variations relative to the variation in energy price. Using the price of crude oil as a proxy of energy price, $\gamma = 0.7$ for copper and $\gamma = 0.1$ for aluminum.

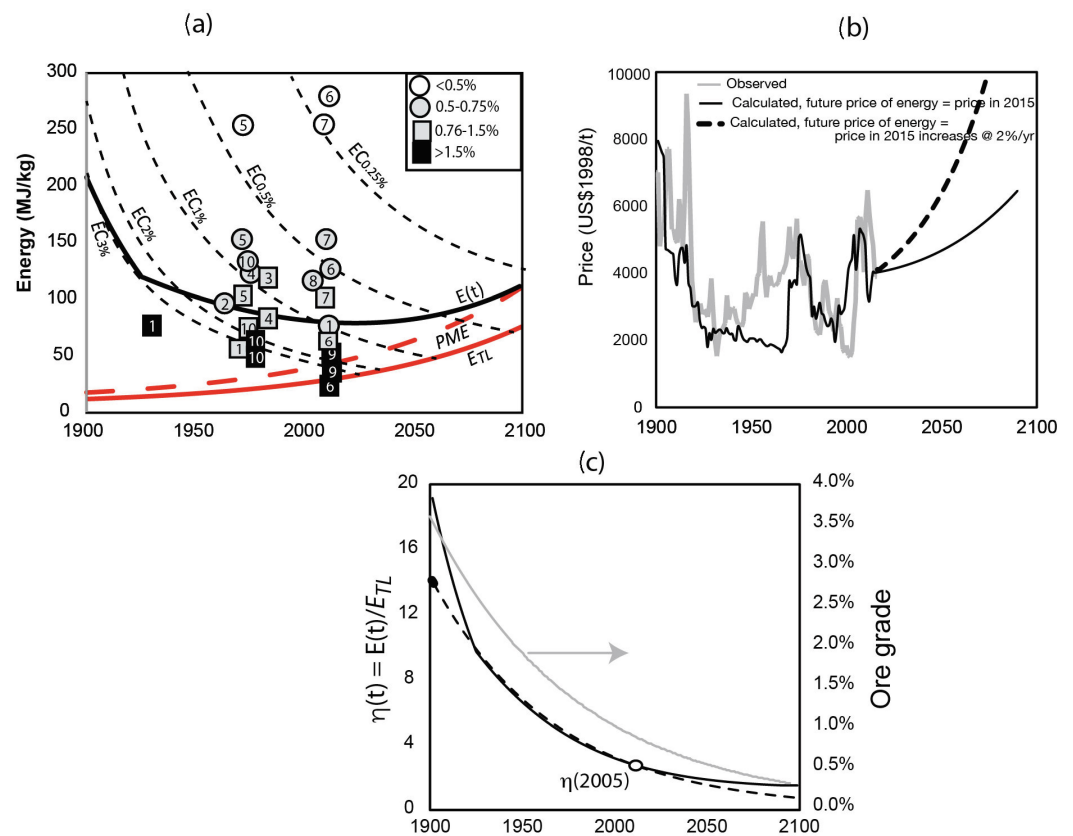


Figure 6. (a) Calculated and observed (numbers) energies of copper production: The heavy black line shows the energy of copper production with varying ore grade and technology $E(t)$, the thin black dashed line shows the energy at constant ore grade with varying technology (EC), and the red dashed and continuous lines show the practical minimum energy (PME) and thermodynamic limit (ETL), respectively. The observed data are plotted at the time of publication and reported ore grades: (1) Rötzer and Schmidt [89]; (2) Rosenkranz [90]; (3) Gaines [91]; (4) Kellogg [92]; (5) Page and Creasy [93]; (6) Norgate and Jahanshahi [86]; (7) Marsden [94]; (8) Office of Energy Efficiency and Renewable Energy [95]; (9) Rankin [96]; (10) Chapman [97]. (b) Observed copper price (grey line) and calculated price (black line). The future price is calculated at constant future price of energy (=PE2015, continuous line) or at 2%/yr increasing price of energy after 2015 (dashed line). (c) $\eta(t)$ (black continuous line, left scale) and ore grade (gray line, right scale) used to compute (a,b). The black dashed line in (c) shows $\eta(t)$ calculated from $\eta(2005)$ and a $-1.5\%/yr$ change.

At $C < 1\%$, the metallurgy and separation energies are negligible compared to the term $\frac{a_i}{C}$ that represents the comminution energy. It means that at constant technology and price of energy, the energy of primary production of precious metals, copper, or nickel are expected to increase exponentially with the decrease in ore grade observed over the last century [17,86]. Proponents of a looming shortage of metals often use this argument to claim that production will become prohibitively expensive in the future. However, long-term historical data do not support this figure, and the inflation-adjusted commodity prices have actually been falling between 1900 and 2000 [87]. This fall, also observed for copper or nickel, indicates that the expected increase in production energy due to falling ore grades has actually been offset by the improvements in energy efficiency and productivity at constant ore grade (EC in the Figure 6a). The improvement in energy efficiency was 1–2%/year between 1900 and 2000 [84,85,88], and until 2000, the energy gains of all metals production have more than compensated the decrease in ore quality. Since the regeneration of reserves increases with falling grade (Equations (1) and (2)), these figures explain why both the produced quantities of metals and their reserves have grown exponentially since 1900. However, this trend is not sustainable in the long term

because there is a thermodynamic limit (ETL) to the extraction of metals, which is given by Equation (3) with $\eta = 1$. This physical limit cannot be overstepped, whatever the technological improvement. Steel production consumed about 50 MJ/kg in the 1950 and it has been halved between the 1950s and 2000 [88]. It will most likely not be halved again by 2050 to reach the thermodynamic limit equal to about 10 MJ/kg for iron oxide ore (for metals at high concentration in ore deposits such as iron ($C = 30\text{--}50\%$) or aluminium ($15\text{--}30\%$), the energy demand of crushing and grinding ore ($\frac{a_i}{C}$) is negligible compared to the energy of metallurgy ($-\Delta G_f^\circ$) in Equation (3)) ($-\Delta G_f^\circ = 7$ MJ/kg of hematite), as the investment required to gain a few MJ when approaching this limit becomes prohibitive. More worrying, the thermodynamic limit of metals at $C < 1\%$ is expected to increase exponentially with falling ore grade due to the term $\frac{a_i}{C}$. In practice, this limit cannot be reached because industrial processes cannot be 100% efficient, and the minimum value of η in Equation (3) is unlikely to be lower than 1.5 (PME = 1.5·ETL). In the case of copper, η decreased at an annual rate of $-1.5\%/yr$ from about 10 in 1930 to 2 in 2000 (dashed line in Figure 6b). It will not be possible to continue on this trend because the minimum value of $\eta = 1.5$ will be reached before the end of the century (continuous line in Figure 6c). For an average ore grade of copper deposits decreasing at $1.5\%/yr$ since 1900, improving current mechanical crushing and grinding technologies will thus not compensate for the additional energy to switch to lower grade ore in the future, as it has been the case during the 20th century. The energy of copper production, which declined between 1900 and 2000, is thus expected to increase from 2000 onward and parallels the PME in the second half of the century (Figure 6a). Similar conclusions are drawn for precious metals and nickel, zinc, and manganese.

4. Discussion

The above overview of some parameters controlling the demand and primary production provides arguments for two classically opposed views of the future of mineral resources: an unaffordable increase in costs and prices following the depletion of high quality deposits or, on the contrary, a favourable compensation by technological improvements. Both visions are true, but not at the same time. After a period of gains in energy and production costs, it seems that we are now entering a pivotal period of long-term increasing production costs as we approach the practical minimum energy and thermodynamic limits for several metals. To reduce this increase in price, unknown breakthrough, but affordable, grinding technologies based on non-mechanical processes will have to be found. Another possibility is to reduce the price of energy. Renewable energies are virtually unlimited, and once the infrastructure of production is built, they are cheap. If we could use renewable energy sources at a low and stable price in the future, the increasing weight of energy intensity in the cost of production would no longer be an issue. This is illustrated by Iceland, which became in 2016 the world's ninth largest producer of aluminium from imported bauxite thanks to cheap geothermal and hydroelectric power, even though it has no ore and most of its production is destined to foreign markets. If the use of renewable energy sources were to become significant enough to cover the needs of the raw material production sector, it would become possible to exploit low-grade resources that cannot be exploited at an affordable cost today. However, energy transition scenarios present another constraint: In order to cope with the targeted decrease in CO₂ emissions, they generally assume a strong reduction in energy consumption. For example, the amount of energy available for the industrial sector in the scenario B2DS already used in Figure 2 is 65% that of RTS, while the energy consumed for the production of raw materials is similar. The future share of industrial energy consumed to produce the raw materials is thus higher in B2DS than RTS, and the remaining energy available for the other industrial sectors is lower. These figures will impact the intensive industries and in particular the raw material production sector, which will already face the problem of declining resource quality. It thus seems extremely difficult to switch to renewable energies while reducing global energy demand. Neither the developed countries, which are expected to replace their fossil fuel-based

energy infrastructure in two or three decades, nor the developing countries that produce raw materials to build their basic infrastructure will spontaneously follow this path. Until 2050, the demand for energy will thus continue to grow on a global scale. On the longer term, the energy demand for the production of raw materials is expected to decrease after 2050 in both scenarios B2DS and RTS. This is due to the combined effects of: (i) approaching the saturation levels of infrastructure at the global scale, which entails a reduction of the annual demand in raw materials; (ii) completing the energy transition; and (iii) rapidly increasing the share of less energy-intensive recycled metals at the saturation levels and unaffordable prices of primary metals.

The above overview of the parameters controlling the demand and primary production also indicates that the question of the future of mineral resources cannot be based solely on the knowledge of current geological availability for a constant rate of growth in demand and technology. It must be studied using dynamic models that integrate the value chain from primary production to recycling, coupling energy requirements and thermodynamic limits, geological, environmental, technological, social, economic, and geopolitical dimensions. Such models are intrinsically complex, but it is illusory to address complex issues with empirical and deterministic models such as Hubbert's model or any model neglecting the role of technological improvement, including the development of advanced exploration technologies, changes in resource quality, and variations in energy prices with time. Coupling material flows with GDP and population evolution is quite straightforward using sigmoid evolutions of the infrastructure/capita with GDP/capita and assumptions on the materials contents. The consumed energy can also be estimated for assumed intensities of use and energy efficiencies. In contrast, coupling the materials and energy flows with economic models is more difficult because economic models lack physical bases and constraints and are derived from observations made in growing economies. Since the industrial activities and consuming sectors are strongly coupled, it is difficult to analyse one sector of metal production isolated from the whole economic system. To circumvent the problem, a possible approach based on a prey–predator dynamic has been proposed by Vidal et al. [75], in line of the previous study by Bardi and Lavacchi [8]. This approach is also empirical, but it allows one to combine physical units (tons) with monetary units without requiring a detailed and comprehensive description of all economic sectors. It analyses the evolution of industrial capital (the predator, in monetary units) and the metal reserves (the prey, in tonnes) with two coupled differential equations involving four parameters controlling the yearly regeneration of reserves, metal production, regeneration and erosion of capital. Interestingly, the cost (price) of metal production is given by the ratio of two of them, corresponding to the capital growth to metal production. Applying the model to the case of copper, we showed that the expected price evolution is similar to the production energy-based independent estimate reported in Figure 6. Independently of any economic consideration, the long-term price of metals derived from the production energy calculated with the simple thermodynamic formalism proposed in Equations (4) and (5), thus providing first order constraints on the future evolution of metals production. In the case of copper, Vidal et al. [75] predicted a peak in primary production by 2050, followed by a rapid collapse if the future demand is assumed to follow the historical trends (+3%/year). In contrast, a scenario no longer based on a steady growing demand but on the need for a population stabilizing at 11 billion inhabitants in 2100 and an average GDP per capita of USD 10,000 provides more optimistic results. A peak in primary production is still observed, but it is a peak in demand. A decrease in primary production occurs in the second half of the century, when the saturation of infrastructures is approached and recycled copper becomes the major source. Here, again, this example shows that the future of natural resources cannot be dissociated from a scenario of demand, which is another illustration of the limit of Hubbert-like approaches. The prey–predator model applied to other metals suggests that the supply of most base and precious metals (except gold) should also meet the demand until the end of the century. The situation is much less clear

for rare metals, as historical data on reserves and production are missing, imprecise, or cover too short a time period to be used as reliable constraints for the models.

In addition to the reserves, price, and energy production issues, the environmental impacts of raw materials and energy production must also be integrated in the models. These impacts might become a limiting factor to production in the future. An emblematic example is given by El Salvador that made history as first nation to impose a blanket ban on metal mining in response to diminishing water sources from polluting mining projects (this decision was approved by the Parliament of El Salvador in early 2017 <https://www.theguardian.com/global-development/2017/mar/30/el-salvador-makes-history-first-nation-to-impose-blanket-ban-on-metal-mining> (accessed on 13 December 2021)). The huge expected increase in mineral resources consumption and primary production will increase conflicts and social opposition. The surface occupied by mines and quarries at the world level has been estimated to be about 400,000 km² [98]; it could be doubled by 2050 and quadrupled by 2100. The embodied water consumption and other environmental impacts are expected to follow the same trends. These figures are naturally concerning, especially in arid production areas. To our knowledge, no model currently exists that describes the local societal response to water and land use and more broadly to environmental impacts, even though this could significantly hamper future resource supplies. This response is expected to depend on the level of GDP/capita and population density, the industrial typology, the level of agricultural production, and the geographical characteristics of the producing countries, such as the availability of water. Modelling the feedback of resource consumption and environmental changes on social opposition is a very important research topic to address the issue of future mineral resource availability in a world of increasing environmental constraints and increasingly compromised access to water and arable land.

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