Stock-driven scenarios on global material demand: the story of a lifetime
Deetman, S.P.

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The Story of a Lifetime

Sebastiaan Paul Deetman

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1.

Introduction

1.1 Material use, a global challenge

The story of a lifetime is rooted in a story of stuff. It is defined by the house we grow up in, the toys we play with, the bike we learn to ride on. The objects that facilitate our lives provide protection, convenience and opportunities; they give us a feeling of ownership, dignity, and wonder. The excitement of an adventurous road trip starts with packing our stuff, and the vehicle we use becomes an indispensable travel companion. Whether it is a family heirloom or a fancy new phone, we form a connection, become attached. Sometimes invisibly, we can become dependent on or even slightly obsessed with the stuff around us.

The downside of this story is that the demand for materials used in products seems insatiable so far. It drives resource depletion and causes environmental impacts such as climate change during mining, processing and waste management (Van der Voet et al. 2019; Watari et al. 2021). These concerns about the impacts of our current consumption patterns and resource use are expressed in recent studies such as the Global Resource Outlook (IRP 2020). However, they date back to the early Limits to Growth book from 1972, which was the first study to highlight the unsustainability of unchanged growth trends in population and corresponding resource depletion (Meadows et al. 1972). While a lot has changed since then, the global environmental challenges related to the consumption of resources and materials still exist. They have become an intrinsic part of the sustainable development goals (SDG), which are presented as a *"blueprint for shared prosperity in a sustainable world"* (United Nations 2019). Challenges related to consumption and material demand are directly addressed in SDG 12, aiming to "*Ensure sustainable consumption and production patterns"*. However, strong connections to other SDGs exist, such as SDG 9 that aims to "*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*". This objective depends on material input but is also essential in supporting more sustainable production of materials. There is also a strong interaction with SDG 11 (on Sustainable cities and communities), SDG 2 (on sustainable food supply), SDG 6 (access to clean water), SDG 7 (on clean and affordable energy) and SDG 13 (on climate action), as each of these objectives are related to resource consumption and require the deployment of new infrastructure and technologies, which contribute to material demand. So, while materials play a crucial role in achieving the SDG's, the trade-off in terms of material demand should not be overlooked. The production of materials such as metals and cement is energy-intensive and responsible for about a quarter of global energy use (Hertwich et al. 2019) and well over 10% of total global greenhouse gas emissions (Fischedick et al. 2014). Global production of all materials represents an increasing share of global emissions, currently at about 23% (Hertwich 2021). So, seemingly paradoxically, material use is both part of the challenge and the solution to achieve the Sustainable Development Goals. Hence there is a need for a better understanding of what drives global material demand in the long-term. This thesis will discuss the importance of the built environment, transport and the energy sector as a driver of material demand towards 2050.

Figure 1.1. *Sustainable Development Goals (SDGs). The SDGs relevant to material demand and production are highlighted in color. While SDG 2 & 6 relate to material demand, they are not specifically addressed throughout this thesis.*

The global challenge of increasing material demand is also related to the concept of the *Circular Economy*. Current supply chains often represent a rather linear system: production, consumption and finally waste generation ('take, make, dispose'). The circular economy aims to reduce resource inputs through lower product demand, product sharing and product services, stimulating material efficient designs, and optimizing remaining resource use through product reuse, repair and material recycling (Gallaud and Laperche 2016). In other words, the circular economy is a new economic system (Kirchherr et al. 2017) that introduces a cycle in the production, use, reuse and recycling of materials. It presents perhaps the most comprehensive attempt to define an encompassing solution-oriented approach to deal with the environmental challenges related to resource consumption.

Material stocks play a fundamental role in satisfying human needs while their production might, at the same time, impact the climate considerably (Müller et al. 2013). Therefore, the promise of a more circular economy may be vital in reconciling the SDGs on development and those SDGs aiming to reduce climate- and environmental impacts. However, assessing the potential of transitioning towards a more circular economy requires a basic understanding of current material use and the trends that drive future global material demand. And, while the global metabolism of energy and its role in climate change mitigation is well described (Cullen and Allwood 2010; Kalt et al. 2019; Kriegler et al. 2014), this is not the case for most materials. To illustrate this: the integrated assessment models that are often used to study global environmental issues often lack a representation of global material flow accounts (Pauliuk et al. 2017; Fishman et al. 2021).

This thesis addresses some of the groundwork needed to incorporate material cycles more explicitly and consistently in integrated assessment models. It also provides a perspective on some of the key drivers of global material demand, by exploring three material end-use sectors in detail. Clearly, more work will be needed to address the full potential of the circular economy in mitigating climate change and fulfilling the SDGs; still, this work provides a first overview of the sectoral challenges to achieving a circular economy and on the broader implications of stock dynamics, which are crucial to global material metabolism. Environmental impacts are not addressed explicitly, but they are ultimately the motivation behind the research, as will be detailed in the following section.

1.2 Material use in environmental assessment

Over the 20th century, in-use stocks of materials have increased by more than a factor of 20 (Krausmann et al. 2017) and human-made mass has surpassed the weight of all living biomass on earth (Elhacham et al. 2020). Given the continued increase in consumption and material use and a limited potential for mitigating impacts compared to other sectors (Sharmina et al. 2020; Luderer et al. 2018), material production will likely play an increasingly important role as a driver of climate change (Hertwich et al. 2019) and other environmental impacts (Van der Voet et al. 2019). This means that a better understanding of the long-term global demand for materials is urgently needed.

Several tools can be used to study the demand for materials and the options to mitigate primary resource use. Material flow analysis (MFA), Environmentally-Extended Input-Output Analysis (EEIOA), Life Cycle Assessment (LCA) are typical tools used in the field of Industrial Ecology. But Integrated Assessment Models (IAMs) may also cover material demand and production as part of industrial energy demand modelling. Each of these models and tools deals with material flows using a different scope and perspective.

Environmental assessment tools typically used by industrial ecologists, such as Material Flow Assessment (MFA) (Graedel 2019) and Environmentally Extended Input-Output Analysis (Tukker et al. 2018) are based on historical data and observations. They can provide detailed insights into recent relationships between material use and the potential improvement of related environmental impacts, but their coverage of material use has often been limited to historical periods (Wiedmann et al. 2015; Schandl et al. 2018) or particular regions (Wiedenhofer et al. 2015). Other Industrial Ecology tools, such as Life Cycle Assessment (LCA), deal with the current environmental impacts of materials required to produce products but typically lack the scope to assess total global impacts in a changing context. Hybrid modelling approaches have been used to achieve *best-of-both-worlds* combinations, for example by combining long-term scenarios from integrated assessment models to provide a more dynamic perspective in Life Cycle Assessment, either through changing the background system (Mendoza Beltran et al. 2020), or by assessing the effects of a changing foreground system on material demand (Kleijn et al. 2011). Various other hybrid approaches exist, but so far none of them have achieved a combination that provides both a long-term, forward looking, global perspective, while accounting for the fully connected supply chain of all materials at a level of detail that is relevant to dynamically assess and explore the potential of a circular economy.

The circular economy paradigm and the promise of reducing environmental impacts through reusing, reducing and recycling strategies have recently attracted increasing attention in Industrial Ecology research. A meta-analysis of environmental impacts of circular economy interventions by Aguilar-Hernandez et al. (2019) shows potential for environmental gains, accompanied by modest growth in gross domestic product and employment. Typically, however, these comprise *what-if* explorative scenarios studies, which tend to look at only one or few changes in the system without addressing the impacts of a changing background system. In other words, there is a clear need for a more encompassing and dynamic perspective on long-term future material demand to fully assess the effects of increasing material demand on the environment and in order to assess the potential of circular economy policies. Dynamic material flow assessment could provide this perspective since it incorporates the use of materials throughout the lifetimes of products over an extended period of time. However, the availability of stock-driven prospective studies with a global scope has been limited until recently (Müller et al. 2014). The growing availability of dynamic MFA studies in industrial ecology is a promising body of knowledge that other research fields can draw from.

Integrated Assessment Models (IAMs) may provide a relevant basis to incorporate dynamic material flow perspectives. While no single definition of IAMs exists, they describe future human systems, i.e. mainly the energy and land-use system in relation to global environmental change, i.e. mainly climate change and loss of natural area. To do so, these models include a dynamic description of change (e.g. population, economy, technology, policies, lifestyle), for instance, to identify attractive long-term climate strategies (Kriegler et al. 2015) or policy trade-offs. While some integrated assessment models provide an explicit description of physical material demand (van Ruijven et al. 2016), this is not routinely the case (Fishman et al. 2021). So, an expansion of detailed material demand modelling, based on Industrial Ecology tools, could pave the way to a better understanding and improved modelling of material & energy use, and in turn allow to relate the challenges of climate change to the opportunities of sustainable development and a circular economy.

In an attempt to bridge different research fields, this thesis adopts a dynamic MFA approach by using the long-term global scenario context provided by the IMAGE IAM (Stehfest et al. 2014) to generate material demand scenarios, including stock dynamics. This will ultimately facilitate incorporating stock dynamics into integrated assessment models itself, as called for by Pauliuk et al. (2017). Because there are multiple ways to approach this, the following section will shortly reflect on the methodological choices before outlining this thesis's main aim and questions.

1.3 Long-term scenarios on global material demand

Hashimoto and Moriguchi (2013) suggest that estimating future material demand can be approached in several different ways:

1) *Through extrapolation of past trends into the future.* An example of this approach applied to future metal demand is presented by Henckens et al. (2014).
2) *By correlating GDP and (per capita) annual material demand, to derive future material demand under a given GDP scenario*. This approach is, for example, applied by van Vuuren et al. (1999) and van Ruijven et al. (2016) in the IMAGE model and by Elshkaki et al. in the so-called Yale Major Metal scenarios (Elshkaki et al. 2018).
3) *Using a service-oriented approach relating the demand for materials to the demand for services, such as housing and transportation.* This approach, for example, discussed by Hertwich et al. (2019), details how the fulfilment of human needs translates to service demand, and in turn, to demand for physical devices and infrastructure.

Hashimoto et al. indicate that the latter is arguably "*the most reasonable way*" to approach material demand modelling, but it may be hampered by data availability. Nevertheless, the service-oriented approach to material demand modelling allows making an explicit connection between the growing demand for services and the societal stocks required to fulfil them. This is preferred over the second method for two reasons. First of all, instead of deriving an *observed* relation between per capita material demand (kg/cap. · yr-1) and income, it uses an *explanatory* relation between per capita in-use stocks (kg/cap.) and income development. Secondly, while this approach requires details on the specific material end-uses (i.e. the purpose that the materials are used for), that is precisely the type of information needed to assess the potential of new technologies or circular economy solutions to change the global demand for materials over time. This yields not only a complete perspective on the in-use stocks and the corresponding annual material demand relevant to energy and climate modelling but also naturally provides insights into the volume and timing of waste flows, which are yet another important determinant of the potential for closing material cycles in accordance with the circular economy (Haas et al. 2015). In other words, the stock perspective is becoming an indispensable part of global scenarios on environmental change because it adds information on what drives material demand and what can be done to curb it.

Such a stock perspective has increasingly attracted attention in Industrial Ecology research (Pauliuk and Müller 2014). For example, Muller et al. note the large impact of stock development by showing that infrastructure expansion might claim about half of the remaining carbon budget towards 2050 (Müller et al. 2013). More recently, Watari et al. showed that, conversely, there is a maximum level of per capita in-use stocks of metals corresponding with an emission pathway to stay within a 2 °C global climate goal (Watari et al. 2020). More generally, there is increasing need and attention for mapping the relations between services and the materials stocks and flows to fulfil them (Haberl et al. 2017) as well as for the formal tools and models used to dynamically describe the relations between stocks and flows (Lauinger et al. 2021).

Given this context, this thesis explores the service-based perspective on in-use material stocks, and the corresponding annual material flows by applying it in a scenario context provided by the IMAGE integrated assessment model (Stehfest et al. 2014). As such, this work aims to provide a better understanding of the drivers and development of global material stocks and flows and the implications for achieving a circular economy, which will be discussed in more detail in the following section.

1.4 Thesis

1.4.1 Aim

This thesis aims to contribute to a better understanding of how global demand for services drives the in-use stocks of materials and how stock dynamics dictate corresponding material flows, both in terms of annual demand and annual waste-flows, towards 2050. While the environmental impacts of material production and processing are the main reason for exploring this topic, this thesis focuses only on the material stocks and flows, without addressing the implications in terms of energy use or environmental impacts. In doing so, we focus on making the first few steps in an endeavor to ultimately enable the assessment of circular economy policies in integrated assessment models, including their effects on environmental impacts. This endeavor starts with the following main question:

1) How is the future global material demand expected to develop towards 2050 and how does this affect the prospects of achieving global policy goals related to climate change, the SDGs and the circular economy?

This main question is specifically addressed for the use of materials in vehicles, electricity generation technologies and buildings, using a dynamic approach that captures the effect of the lifetimes of those products on the demand for new materials and the consequential availability of waste flows. So, before the main question can be answered, a representation of in-use stocks and their resulting waste-flows needs to be established. Therefore, this thesis also aims to answer the following sub-question:

2) How do stock dynamics affect the availability of waste flows, and what does this mean for the potential to reach a circular economy by 2050?

Finally, this thesis presents a pragmatic attempt to better connect two modelling approaches (dynamic MFA and IAMs) and bridge two research fields (Industrial Ecology and the Integrated Assessment community). While this work covers only part of the total material demand, it provides a blueprint for filling in the blanks about other stock-forming material use. This thesis aims to facilitate future model development by reflecting on the lessons learned throughout that process by addressing the following question:

3) What type of data and data sources are essential to better understand societal material flows and assess the implications of a circular economy?

1.4.2 Methods

Throughout most chapters in this thesis, the IMAGE integrated assessment model will provide the context for the developed material demand scenarios. Here, the IMAGE model and the so-called Shared Socioeconomic Pathways scenario will be briefly introduced. This is followed by an elaboration of the key methods used to derive the material demand scenarios.

IMAGE

Integrated Assessment Models (IAMs) explore the dynamics and interactions relevant to long-term global environmental change and possible policy responses. They can explore climate impacts, biodiversity loss, air quality or the trade-offs between multiple environmental goals. Based on a wide variety of scientific methods and approaches (Kriegler et al. 2015), IAMs integrate the knowledge of multiple research fields to present an encompassing perspective on global environmental change. The IMAGE model is an integrated assessment model based on integrating a land-use model, a carbon-cycle model, an energy systems simulation model and several tools to assess climate (policy) impacts (van Vuuren 2007).

Though the explicit coverage of material use is not comprehensive in the IMAGE model, demand for some key materials such as steel and cement is already modelled as a driver of industrial energy demand based on van Ruijven et al. (2016). While IAMs are sometimes criticized for lacking an explicit representation of capital stocks and material metabolism (Pauliuk et al. 2017), the work by van Ruijven et al. does partially account for essential stock dynamics through lifetime tracking in order to estimate scrap availability and maximum recycling potentials. However, the annual demand for steel and cement is based on a regression-based relation between per capita annual steel demand and GDP per capita. Thus, suggesting that people need a certain amount of materials each year to sustain their lives. While that premise might be questionable, there is yet another downside to this approach to material demand modelling based only on developments of population and GDP. Climate policy scenarios do not typically affect population or GDP trajectories, so under the current material demand model climate policies do not affect material demand.

In contrast, this thesis starts from the premise that the fulfilment of human needs is often, and increasingly, achieved through stocks rather than annual flows. The need for shelter is provided through a house; the need to move around by means of a vehicle or another mode of transport. The annual demand, in turn, can be seen as consequential of having to maintain and expand that stock. This does not apply to all material use. Food, packaging and fuels are examples of consumptive products. However, the calibration of at least a fraction of material demand to underlying demand for services and the corresponding material stocks may provide a better way of estimating future material demand, while at the same time providing an explanatory, rather than an observed relation between material demand and global drivers such as population and affluence. In addition, this allows assessing the effects of climate policies on material demand more explicitly.

The evolution of detailed sectoral energy demand models in IMAGE, such as a transport model (Girod et al. 2012; Edelenbosch et al. 2017) and a residential energy use model (Daioglou et al. 2012) provides an opportunity to use the known development of demand for services (such as residential floorspace or total demand for travel in terms of person kilometers) as a basis for these calculations. Thus, detailing what sectors are responsible for what part of the total material demand. To do so, the IMAGE model uses a variety of assumptions on the regional development of population and affluence described by the Shared Socio-economic pathways as detailed below.

Scenario analysis and the SSPs

Scenarios are a way to tell *"plausible, challenging, and relevant stories about how the future might unfold"* (Reid et al. 2005). They are not necessarily quantitative and should not be seen as forecasts, but rather as a tool to envision future pathway, their implications and the uncertainties involved. This utilitarian perspective on scenarios is also emphasized by Wiseman et al., who indicate that scenarios can be *"a key instrument with a role to play in stimulating, guiding and accelerating initial, pre-development phases of transitions"* (Wiseman et al. 2013). Scenario analysis, in the context of environmental sciences, includes the effort of developing, comparing and evaluating scenarios to *"anticipate future developments of nature and society and to evaluate strategies for responding to these developments"* (Alcamo and Henrichs 2008).

The Shared Socio-economic Pathways (or SSPs) are a set of five of such scenario descriptions, comprising of five narratives with details on the corresponding drivers such as population and economic activity, developed to provide a common set of assumptions about the future in exploring how societal developments affect greenhouse gas emissions (O'Neill et al. 2017; Riahi et al. 2017). The adoption of the SSP scenarios by a broad range of research fields facilitates exchange and a common understanding in exploring long-term global environmental impacts.

The differentiation between future pathways is made across two axes: 1) how difficult it will be to adapt to climate change and 2) how difficult it will be to avoid or mitigate climate change. While the results for a range of different SSPs and the implications of climate policy are explored occasionally, this thesis will mostly focus on the second SSP (SSP2) baseline, which represents a 'middle-of-the-road' scenario with moderate growth assumptions on population (KC et al. 2017) and GDP (Dellink et al. 2017). This is because this thesis aims to generate new material demand scenarios from *whatever available* scenario background. Therefore, most of the efforts presented here aim to document the basic model development and assumptions rather than its application in the broadest possible scenario context.

The broad range of possible material demand trajectories related to the different SSP scenarios has recently been explored in a study by Schandl et al. (Schandl et al. 2020). While this work presents a very relevant expansion of the SSP scenarios by introducing a material dimension, it is not based on the service-based approach as detailed in Section 1.3, nor does it effectively capture stock dynamics as discussed below.

Dynamic Stock Modelling

The integration of stock dynamics through the explicit modelling of product lifetimes and the resulting age structure of in-use stocks by vintage or age cohort is becoming an essential part of dynamic material flow analysis. This method is applied throughout this thesis based on literature-based lifetime distributions using a software package developed in the Python programming language, developed by Pauliuk and Heeren (2019).

The default approach applied here is a stock-driven model. The physical stock is provided or derived from indicators on service-demand in the IMAGE model elaboration of the SSP scenarios (van Vuuren et al. 2017). The corresponding annual demand for materials (inflow) and annual waste generation (outflow) are consequentially derived based on the Python dynamic stock model, using age groups of one year.

Other methods & data

This thesis applies a few other methods, which are shortly elaborated. For commercial and public buildings, explored in Chapter 5, the IMAGE model does not provide stock- or service demand indicators. Therefore, a relation between per-capita floor space demand in service-related building types and service value assed was derived using regression analysis to model future floorspace demand in the service sector.

Where needed, we apply a few other tools such as a cost-driven investment model to derive the expected market share of technologies and an optimization-based allocation model to match the supply and demand volumes for tantalum in Chapter 2.

Finally, an approach applied throughout each chapter is the use of literature review and life-cycle inventory databases to compile a dataset on product lifetimes and their material compositions. This applies to all material end-uses covered and is similar for both critical & bulk materials.

1.4.3 Thesis outline

This thesis starts with a somewhat narrow focus by exploring the critical material tantalum in Europe in Chapter 2. The criticality of tantalum stems from the vulnerability to disruption of the metal's supply chain, largely sourced from conflict-affected areas and is used indispensably in various electronics (Mancheri et al. 2018). This chapter shows how final products and end-use applications of relatively small volumes of tantalum can be identified as drivers of annual material demand. It also shows how limited the understanding of material flows can still be and how getting a grasp on them can sometimes be a puzzle. The study of tantalum and the analysis of generated wastes also introduces the importance of product lifetimes, which will play an important role throughout the following chapters.

Chapter 3 covers a broader selection of critical materials, including copper and neodymium, and addresses their demand in cars, appliances, and electricity generation towards 2050. This global scenario analysis uses the context of the IMAGE Integrated Assessment Model and the Shared Socio-economic Pathways to derive the annual demand for materials using dynamic stock modelling, using detailed product content & lifetime data based on literature review. This approach forms a blueprint for the last three chapters, with more sectoral detail.

The expected development of material stocks in buildings and the annual material demand from the construction sector is explored in Chapters 4 and 5 through a detailed analysis of material use in both residential and commercial buildings. Here, the focus is shifted from critical materials to bulk materials. Furthermore, the existing data on residential floorspace demand is complemented with a regression-based estimate of the required per capita floor space in the service sector. Chapter 5 will also detail the regional dynamics of construction material demand and demolition waste generation.

Chapter 6 builds upon the modelling of the electricity sector as presented in chapter 3, but it expands the coverage of the material demand scenarios in two ways. First, it provides results on a broader selection of materials, including bulk materials such as steel, concrete and aluminium. Secondly, the coverage of electricity generation technologies is complemented by the coverage of materials in transmission and distribution lines and materials in the required electricity storage capacity, which becomes especially relevant under ambitious climate policy assumptions and at a higher share of renewable electricity generation.

Finally, Chapter 7 presents a baseline scenario for global material use in a broad range of vehicles. While some critical metal use in cars is already covered in Chapter 3, Chapter 7 expands the coverage of materials by including bulk materials such as steel and aluminium. The coverage of vehicles is also expanded by modelling the materials used in public transport vehicles, bicycles and freight vehicles. Given the lifetime of vehicles, which is generally shorter than that of buildings or infrastructure, this chapter identifies some specific vehicle types and regions for which the in-use stocks are expected to become a net source rather than a sink of materials before 2050.

Given the similarities in the methods, coverage, and level of detail of the analysis presented in Chapter 4, 5, 6 and 7, the synthesis chapter presents the results of these chapters in a comparative overview. Here, the main results regarding the development of material use in buildings, electricity infrastructure and vehicles are presented before continuing with the subsequent Discussion and Conclusion chapters.

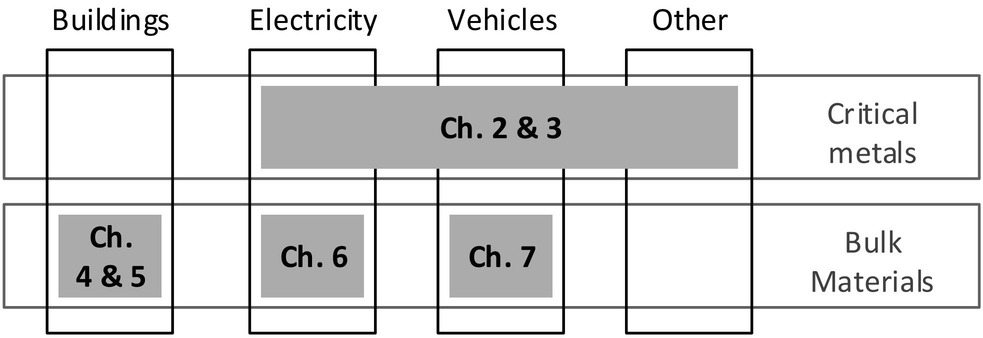

Figure 1.2 *Thesis overview, coverage of materials and end-use sectors throughout the chapters.*

2.

Deriving European tantalum flows using trade and production statistics

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Ester van der Voet
Arnold Tukker

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Abstract

Even though tantalum has a high economic importance and is associated with armed conflict, the use of tantalum throughout the supply chain of importing economies is not well understood. This chapter adds to existing qualitative descriptions of the tantalum supply chain by performing a quantified substance flow analysis (SFA) of tantalum for Europe in the year 2007. The exercise is meant to show how readily available statistical information could be used along with simple and transparent assumptions on product composition and allocation, to yield an enabling and visual representation of the supply chain for critical materials. The case of tantalum shows some surprising results. First of all, this study shows that tantalum in computer hard disks and artificial joints may be more relevant than found in previous studies. Further, we find that the tantalum consumption in Europe may be larger than expected based on geological survey reports, attributed to a high fraction of tantalum being imported in subcomponents and final products. Further research is needed to substantiate this claim, but what is clear is that a detailed SFA provides valuable insights into the consumption of tantalum as a critical material, throughout the stages in the supply chain related to the production and use of tantalum containing products. The exercise also allowed production of waste generation profiles and enabled identification of e-waste as an important focus group in order to improve tantalum recycling rates and eventually to reduce society’s dependence on scarce or conflict related raw materials.

2.1 Introduction

Tantalum is often considered a critical material because it has a high economic importance, but also a high supply risk and a problematic substitutability. Modern alloys and digital components are increasingly dependent on the availability of tantalum whereas its supply is insecure because a considerable fraction of its ores are sourced from African countries (an estimated 37% in 2008, according to Nest (Nest 2011)), where mining is sometimes associated with armed conflict (HCSS 2013). In particular, the tantalum containing Coltan mineral ores, sourced from the Democratic Republic of Congo (DRC), have become a much quoted example of a “conflict mineral” given that the revenues of artisanal Coltan mines have likely been a source of income for paramilitary groups in the east of the country. Because of the illicit nature of the mining activity, numbers on production volumes of Coltan in the DRC are quite uncertain and fluctuate wildly across the years, but they have historically reached over 50% of total African production (Nest 2011). Though environmental impacts occur, concerns about the social impacts of mining have been the primary reason that the use of tantalum and several other critical metals is now subject to certification schemes on responsible sourcing (Bleischwitz et al. 2012; Young 2018) as well as stringent regulations in the United States (Dodd-Frank 2010) and Europe (EC 2014). However, whereas the social impacts of tantalum mining are high on the international political agenda, the use of tantalum throughout the demand side of the supply chain of products is still not well understood.

Though there have been numerous studies describing the flows of critical materials (Busch et al. 2014; BIO by Deloitte 2015; Guyonnet et al. 2015), existing literature on the supply chain of tantalum is limited. Previous studies discussing the use of tantalum in various products have been able to describe the tantalum supply chain at a high level of detail, but only in a qualitative sense (Jeangrand 2005; Espinoza 2012; EU 2014). An exception to this is a study by Moran and colleagues (Moran et al. 2015), who used a hybrid life cycle assessment approach to quantify the trade of the tantalum-containing mineral ores sourced from the DRC, to the processing countries and eventually to the industries supplying the final consumption in the year 2000. Moran and colleagues show that it is possible to track where the conflict-related tantalum ends up, but their study lacks detail in importing economies because the categorization of industries gives no insight on the amounts of tantalum imported (just their value), nor does it indicate which particular products generate the final demand. The lack of detail in quantitative elaboration of the tantalum supply chain in importing regions means that policy makers have little practical information to act upon a regions dependence on the conflict-related and, possibly, supply-restricted material. There is a clear need to better understand how metals flow through the whole supply chain, as also emphasized by Bloodworth (Bloodworth 2014).

We aim to improve this understanding for tantalum in Europe, as an importing region, in the hope to contribute to solving the region's vulnerability to supply restrictions. According to Espinoza (Espinoza 2012), the European tantalum processing industry generates approximately 250 to 300 metric tonnes (t) of tantalum in different raw material forms; this is equal to roughly 27% of the average total global production of tantalum concentrates from 2005 to 2010 (1,033 t according to the U.S. Geological Survey (USGS 2012), 2007–2012). However, the relatively large share in the consumption of tantalum concentrates does not give any insight into the European dependence on tantalum in all its applications. For that purpose, we need to quantify the use of tantalum throughout the part of the supply chain that is yet unknown, being its use in products and their components.

This study provides insights into tantalum flows in Europe in the year 2007, by performing a substance flow analysis (SFA) at a high level of detail, presented in a practically enabling way. The reason for choosing this year is that the level of detail in trade and production data is highest for the year 2007 (see also Appendix 2). Based on the description of the tantalum supply chain in this year, we give an indication of the expected waste generation profile over time. Together, the SFA and the waste generation assessment should better enable European policy makers to judge the size of the European tantalum flows and give insights into the relevance of product groups when aiming to secure the material supply through, for example, recycling (Zimmermann and Gößling-Reisemann 2014; Buchert et al. 2012), redesign (Peck and Bakker 2012), or substitution (Graedel et al. 2015). The method used is relatively straightforward and mostly based on readily available statistical information from (Eurostat 2016), so the analysis could simply be repeated for other critical materials in the future. The downside of using an SFA methodology as presented here is that it is nonattributional. So, though the reason for our attention for tantalum is the social conflict related to its mining, we do not account for the origin of the imported metal, and simply present a static overview of total metal flows imported into Europe in 2007, the majority of which was produced in officially regulated mines, such as in Australia and Brazil (Nest 2011).

To complete the overview of tantalum flows, a great number of assumptions had to be made, especially on the tantalum concentrations in products and the market share of tantalum containing products in aggregated product statistics, in order to describe the tantalum flows through Europe. For some cases, we were not able to quantify flows. This shows that the knowledge on the use of critical raw materials and their economic importance is not matching the current political attention, and so we require more insight to reduce society's dependence on scarce or conflict-related raw materials. It is in the light of that discussion that we make our assumptions, crude as they may be, and describe them as transparently as possible. The Discussion section will elaborate on this and will address why we feel that the SFA approach presented here adds to existing studies on critical raw materials.

2.2 Method

In order to derive tantalum flows through Europe, we first used the available trade statistics and production statistics to determine the apparent consumption of tantalum-containing products, as discussed under Production and Trade Statistics. We define the apparent consumption as the imports plus the production, minus the exports. Second, we performed a review of tantalum concentrations in those products, as described under Section 2.2.2 (Product Composition). Combining these steps yielded the apparent consumption of tantalum through various European products (see Results), which were then categorized into production stages to result in a highly detailed flow diagram of tantalum in raw materials, semifinished products, as well as in products for final consumption, as described in the section on the *Sankey* Diagram. Finally, we assessed the expected future tantalum recycling potential from consumer wastes by assuming suitable lifetime distributions, as discussed in Section 2.2.4 (Consumer Waste Assessment). Figure 2.1 indicates how the method comprises of 13 subsequent steps and how these are covered in the sections throughout this chapter.

Essentially, we drafted a list of products containing tantalum based on pre-existing qualitative studies (step 1). For this list of products, we extracted European trade and production data from the Europroms database of Eurostat (step 2) and completed the available information to yield total weigths traded or produced (steps 3 and 4). Using the product compositions, we translated the weigths of all product flows into a list of total tantalum flows (steps 5 and 6) and subsequently allocated each flow to the relevant product in downstream production stages (steps 7, 8, and 9), so that a Sankey diagram could be drawn (step 12). Finally, we show how results from the stocktaking in the previous steps could be used to produce useful results for environmental policy and management by applying product lifetime distributions (steps 10 and 11) to show how the tantalum in products bought in a certain year becomes available as waste over time (step 13). The following sections describe these steps in more detail. It is important to state that such a stocktaking exercise is only possible under the following assumptions: First of all, we assume that no losses occur in the production of tantalum containing subcomponents and final products, neither as environmental emissions nor as preconsumer waste streams. The losses during raw material conversion are dealt with separately (see step 5). Further, we assume that tantalum inventory stocks remain constant over the year 2007, which means that we assume that all the raw materials consumed are fully transformed into consumed tantalum products and that no stocks of raw materials, components, or products were generated or addressed or to fulfill demand.

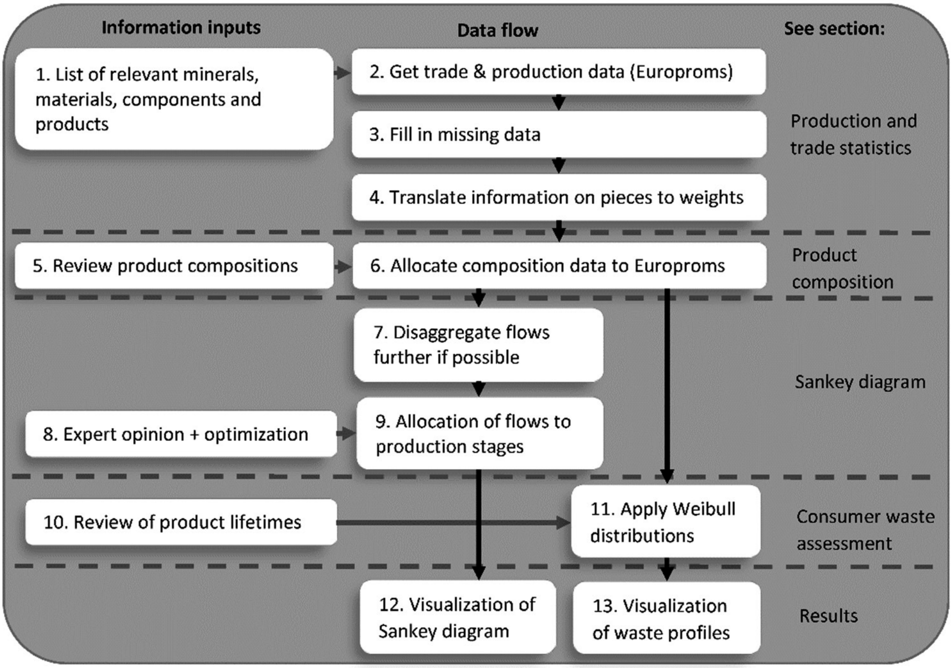

Figure 2.1. *Overview of methodological steps in this study and the sections describing them.*

2.2.1 Production and trade statistics

1) As a first step, we drafted a list of materials, products, and components that were considered relevant for tantalum, based on the two most recent qualitative studies on the tantalum supply chain (Espinoza 2012; EU 2014). Only the product descriptions that could be linked to a concrete product and a source on their tantalum concentration were used in this study, as can be seen in Table 2.1. That means that, in some cases, for example for broad categories like "tools and machinery" and the various products with "corrosion resistant surfaces," we did not include the products listed in the qualitative studies, simply because the description is too vague to determine which fraction of these tools, valves, tanks, etc., actually contain tantalum and how much. Some other products were excluded, because we could not find any information on the product composition, even though the description was rather precise, like in the case of X-ray film and diagnostic equipment, for example. Two aggregate product categories were identified in order to accommodate the multiple applications of tantalum in both aerospace and automotive products.

Table 2.1. *Materials, sub-components & products relevant to tantalum, mentioned in previous studies.*

Espinoza (2012)	EU (2013)	Used in this study
Alloys	High Temperature Alloys	Yes
Surgical clips/medical applications	Prosthetic devices (hip joints, skull plates, mesh, clips, stents)	Yes, as one category
	hearing aids & pacemakers	Yes, separately
Capacitors	capacitors	Yes
Cutting tools	cutting tools	Yes
Aerospace and avionics applications	jet engine discs, rocket nozzles	Yes, as Aerospace
Aircraft turbines	Aerospace/gas turbines	Yes, as Aerospace
Furnace parts	High temperature furnace parts	Yes, as Furnaces
Tantalum carbides		Yes
Glass (high refractive/low scattering)	Lenses for spectacles, digital cameras and mobile phones	Yes, as Vision correction lenses & Other lenses
Surface acoustic wave filters	surface acoustic wave filters	Yes
X-rays diagnostic equipment	X-ray film	No, no information
Catalysts		No, too vague
Ingots		Yes
Tools & Machinery		No, too vague
Micro-electronics for engine management	Automotive ABS, airbag activation, engine management modules, GPS	Yes, as Automotive
Micro-electronics in safety & military equipment	Military explosive missiles	No, no information
Corrosion resistant surfaces	lining, cladding, water tanks, valves, screws, nuts, bolts	No, too vague
	laptop computers, mobile phones, digital cameras (video & still)	Yes, separately
	DVD players	Yes
	mobile phone signal masts, oil well probes	No, no information
	semi-conductors	Yes
	Ink jet printers	No, no information
	Computer hard drive discs	Yes

Finally, because the application of tantalum in GPS devices is mentioned, we decided to add them as a separate category, because global positioning system (GPS) devices are available as independent consumer electronics (one could think of the non-“built-in” use of navigational devices). We feel that, altogether, this list of products covers the most relevant uses of tantalum in society, considering that most excluded products are minor or specialty applications, whereas the bulk applications like consumer electronics and cars are covered.

2) In step 2 of the process, the items on the list were matched to their proper representation in the available statistics so that the weight of imports, exports, and total production for 2007 could be downloaded from the annual Europroms reports (Eurostat 2016). The Europroms data set conveniently combines the Eurostat production statistics, with information on imports and exports at a high level of detail (identifying 88 products, at the eight-digit level of the Prodcom classification). In most cases, the identified products were represented by multiple items in the available data. For example, the automotive category is represented by a selection of data on 12 passenger car types, four public transport vehicle types, and six freight vehicle types. Only for the raw materials, the level of detail was insufficient, so an additional disaggregation of the category “tantalum articles” had to be made, based on the British Geological Society (BGS) (BGS 2011), as will be discussed in the section on the *Sankey* Diagram (step 7). The full link between the selected product categories and the Europroms database is disclosed in Appendix 2.

3) Step 3 (see Figure 2.1) consisted of filling in the missing data. In a few cases, the Eurostat data extracts contained information on both the value and the weight of European production of the tantalum-containing products, but only the value of the imports and the exports. In those cases, we assumed the European price as a representation of the price of the imports and exports, to derive the physical amount of products from the given value of the trade.

4) In the fourth step, the units were harmonized, so that all Europroms production and trade data were expressed in kilograms (kg). Roughly half of the data in the database provided information on products by pieces. If available, the average weight, as provided by (Eurostat 2010), was used for the conversion. In six cases, an external source was used to determine the weight of the products; these are described in Table A2.2 of Appendix 2.

2.2.2 Product composition

5) Given the list of kg of products imported, exported, and produced, the next step was to review the tantalum concentrations for each of these products. We used a single number per product, thus assuming that the material content of imports products is equal to the content in domestically produced goods. Given that many of the tantalum-containing products are common household appliances, the review of compositions of electronic and electrical equipment by Oguchi and colleagues (Oguchi et al. 2011) proved to be very useful. Table 2.2 shows the full list of sources used, including a few company data sheets. In case the sources only specified the volumetric or chemical composition, the weight percentage of tantalum was derived as elaborated in Appendix 2.

Table 2.2. *Tantalum concentration in the selected products. A source is provided if applicable, if the concentration was derived using additional assumptions this is indicated in the last column.*

Product description	Concentration (kg Ta/kg product)	Source of concentration data	Assumptions
concentrates	0.00211456	*Derived*	The content of tantalum concentrates is a balancing factor on the raw material supply side, so we increase the concentration in order to fulfill the demand of tantalum ingots, powder, metal and oxides.
articles	1		Assuming tantalum articles are made of 100% tantalum metal
carbides	6.794E-05	*Derived*	Based on the (BGS 2011) we assumed that tantalum articles represent 76% of tantalum consumption, in addition, the carbide consumption represents 7%, so the carbide concentration is adjusted to match 100% of the consumption of carbide tools, which was the only application of carbides found in the tantalum supply chain matrix in the (EU 2014) study.
capacitors	0.367	(Ecoinvent 2007)	
HDD	0.019	(Nunney and Baily 2011; Hitachi 2007)	Assuming a 10,5% weight of the data platter (Yan et al. 2013). And an average tantalum content of the (perpendicular recording) platter according to the two sources.
Artificial joints	0.175	(Zardiackas et al. 2006)	Based on new medical alloys discussed in source
camera lenses	0.046	(Kodak 1941)	Assuming a 50% market share of tantalum containing glass lenses (containing 9.3 wt% tantalum based on the source).
vision correction lenses	0.00184		assuming 2% market share for glass lenses (myeyeware2go.com), assuming Kodak glass (same as 'camera lenses', see above).
other lenses	0.00184		Same as vision correction lenses
Mobile phones	0.00041	(Christian et al. 2012) & (Oguchi et al. 2011)	Average of 39 phones in two studies (additionally assuming 130 grams/phone based on (GSM Association 2006).
Laptop PCs	0.00103	(Oguchi et al. 2011)	The values here, given by the study by Oguchi only describes the tantalum content in the printed wiring boards of notebooks & PCs (thus capturing the tantalum content in the micro-electronics, but not in the harddisk). The tantalum content in their hard disks is accounted separately.
Desktop PCs	0.00088	(Oguchi et al. 2011)	
Cameras	0.00142	(Oguchi et al. 2011)	Similar to PCs, the tantalum composition of cameras given here applies only for the printed wiring board. The tantalum contained in the camera lenses is simply added to the overall camera composition in the results.
hearing aid	0.04667		We assumed 3 tantalum capacitors of a weight of 0.14, based on (engineeringprojects.com 2014) and an average of two types, according to (Ecoinvent 2007) in a total product weight of 9 grams (Alibaba.com 2015)
pacemakers	0.0186		Based on (Haddad and Serdijn 2009), we assumed the use of 10 tantalum capacitors of a weight of 0.14 g (average of two types, according to (Ecoinvent 2007)) in a total product weight of 28 grams (Medtronic 2015).
GPS	0.0043		According to (Philips 2009) a GPS device contains 6 tantalum capacitors of a weight of 0.14 g (average of two types, according to (Ecoinvent 2007) in a total average product weight of 195 grams (Carver 2016)

Product description	Concentration (kg Ta/kg product)	Source of concentration data	Assumptions
DVD players	0.00001078	(Oguchi et al. 2011)	
furnaces	6.2E-05	(Moss et al. 2013)	
carbide tools	0.0007966	*Derived*	Assuming that all tantalum carbides are used in carbide tools, the tantalum content was derived as the tantalum input divided over the mass of the tools.
TVs	0.000008	(Oguchi et al. 2011)	
Automotive (vehicles)	5.8E-06	(Cullbrand and Magnusson 2012)	The concentration was determined as the weighted average of three vehicle types: passenger cars, public transport vehicles and freight vehicles. We assumed that each vehicle contained 8 grams of tantalum, regardless of their weight.
Wavefilters	0.3305		Average material content of two types of surface acoustic wavefilters described by (Abbott et al. 2005) and (Strijbos et al. 2007)
Semiconductors	0.286		See assumptions based on (Chaneliere et al. 1998) in the SI
Aerospace	0.00092		High-temperature alloy application in aircraft engines, see SI for details

Table 2.2 shows that, in some cases, the concentration of tantalum is derived; this means that we were unable to find information on the concentration in the product or material, but that it could be derived using the amounts in connecting flows. In the case of tantalum concentrates, for example, we knew the volume of flows and we knew the required amount of tantalum in the materials requiring inputs of concentrates, because we knew the outgoing amounts of tantalum. The content of tantalum in the concentrates was set so that it fulfills this demand.

As such, we assumed no losses, similar to the assumptions further downstream, but we made sure that we at least fulfill the demand of products with a known tantalum content, without propagating uncertainty downstream through assumptions on losses during raw material processing. The uncertainty is offset to the concentration of tantalum in imported raw materials, which may therefore be slightly underestimated.

6) The list of tantalum concentrations cannot be directly multiplied with the data on product weights, because of two reasons. First of all, in some cases, only part of the considered product sales actually contain tantalum. For example, only very few semiconductors contain tantalum whereas the Europroms database does not distinguish “tantalum containing semiconductors”; it only provides the sold volumes of various semiconductors (diodes, transistors, and others). So, when we found information on the composition of tantalum-containing semiconductors, such as given in Table 2.3, we needed to also provide an assumption on the market share of the sales of semiconductors that contain tantalum, as indicated in Table A2.3 in Appendix 2. We also needed to provide a conversion factor in case the Europroms data consider products for which the concentration only applies partially. For example, “central storage units” were considered relevant because they contain hard

disk drives (HDDs), but given that they represent the usually much larger professional stacked server racks, the concentration found for a simple consumer HDD does not apply. In such cases, an additional assumption was made to determine the fraction of the subcomponent in the product to which the available concentration data apply, as listed in Appendix 2. Finally, these steps lead to the overview of tantalum flows in imports, exports, and production, thus giving the derived apparent consumption of tantalum as in Table 2.3.

Table 2.3. *Tantalum containing products & their trade and production flows (expressed in tonnes tantalum) for Europe in 2007 according to* (Eurostat 2016).

Tantalum products	Production stage	Export	Import	Production	Apparent Consumption
Concentrates	Raw material	7	597	10	600
Carbides	Raw material	3	10	31	38
Articles	Raw material	345	493	254	401
wave filters	Sub-component	2	3	2	3
Semiconductors	Sub-component	46	39	32	25
other lenses	Sub-component	3	6	5	8
camera lenses	Sub-component	21	151	16	147
HDD	Sub-component	103	635	5	537
Capacitors	Sub-component	183	100	398	315
Cameras	Final product	16	196	5	185 (331 incl. lenses)
TVs	Final product	0	1	2	2
DVD players	Final product	0.1	2.2	0.3	2
Artificial joints	Final product	53	61	184	192
hearing aid	Final product	15	28	30	42
pacemakers	Final product	4	6	9.5	12
GPS	Final product	0.5	0.6	2.6	3
vision correction lenses	Final product	3	18	12	27
Mobile phones	Final product	122	213	216	307
passenger cars	Final product	7	16	90	98
public transport vehicles	Final product	0.5	0.1	0.3	0
freight vehicles	Final product	4	3	26	24
carbide tools	Final product	3	2	38	37
furnaces	Final product	6	1	15	9
Laptop PCs	Final product	21	149	61	189
Desktop PCs	Final product	138	123	209	195

2.2.3 Sankey diagram

7) In order to present these flows in an overall tantalum flow scheme, additional assumptions had to be made to further disaggregate and allocate the tantalum flows. First of all, information on the raw material forms of tantalum was available from the BGS (BGS 2011), which allowed us to disaggregate the lump category of "tantalum articles" into different forms of tantalum, being ingots, powders, oxides, and pure metal form. Second,

the supply of tantalum in raw material form was matched with their demand by adjusting the concentration of tantalum in the concentrates. Finally, a detailed allocation of raw material forms into final and semifinished products was applied, using the allocation rules as discussed below.

8 & 9) Except for the case of hard disks, the distribution of raw materials over subcomponent production and the subsequent distribution of subcomponents over final products was derived using an optimization routine in Microsoft Excel software based on a generalized reduced gradient algorithm (Lasdon et al. 1974) in combination with conditions set by the available qualitative studies (EU 2014). The goal-function was set to minimize the square of the mismatch between intra-European inputs and reported production (also known as the least square error approach). In simpler words, it tries to distribute the apparent consumption of a component in such a way that it fulfils the demand from all receiving final products produced in Europe, where equal importance is given to all applications of tantalum. The optimization thus does not minimize the mismatch in volume of the tantalum flows, but minimizes the error between the tantalum supply and the demand for tantalum in the production of each product (no matter if it is a major or a minor application). An example of an applied condition in the form of a discrete choice is that the metal form of tantalum is only used in hard disks and artificial joints, whereas the tantalum oxides are allocated over lenses and acoustic wave filters. The full set of applied conditions and outcomes of the two optimization steps can be found in Table 2.4a and 2.4b.

It should be noted that this allocation of flows did not always lead to a matching supply and demand. The use of flow-allocation factors from the optimization procedure simply assures that the mismatch is minimized per product. The remaining balance shortages or surpluses are reported separately in the results section. For an elaboration of the size of these flows, we refer to Appendix 2.

Using these allocations, we constructed a tantalum flow scheme for the European Union (EU) (considering the 27 member state description, or the EU27). As mentioned before, we assumed that no losses occur and that the *production* of tantalum-containing products in Europe is responsible for the apparent consumption of raw materials and subcomponents. The final overview was visualized in the form of a Sankey diagram (see step 12 in the Results section), using a javascript library for data driven documents (or d3), as inspired by and adapted from (Bostock 2012).

2

Table 2.4. *a) Allocation of the (apparent) consumption of raw materials to sub-components and b) Allocation of the (apparent) consumption of sub-components to final products. Determining factor is the demand from the production within Europe. Some raw materials are directly processed into final products, as indicated with an (F). The allocation of hard disks over final products is based on the indicated study, the rest is an outcome of the optimization routine as discussed in the text.*

Table 2.4a		**Allocation of tantalum raw materials**				
		FROM				
		carbides	Pure metal	oxides	powders	ingots
TO	Carbide tools (F)	100%				
	Artificial joints (F)		92%			
	Other lenses (F)			9%		
	Vision corr. lenses (F)			35%		
	Capacitors				100%	
	Semi-conductors					58%
	Wave filters			2%		
	HDDs		8%			
	Camera lenses			54%		
	High-temp. alloys					42%

Table 2.4b		**Allocation of tantalum containing sub-components**					
		FROM					
		Capacitors	Semi-conductors	Wave filters	Hard disk (Coughlin 2006)	Camera lenses	High-temp. alloys
TO	Mobile phones	13%	39.4%	8%			
	Cameras	1.5%	0.15%			100%	
	Desktop PCs	17%	2.3%		34%		
	Laptop PCs	11%	49%	0.06%	39%		
	External HDD				19%		
	Central storage				8%		
	DVD Players	0.09%	0.001%				
	GPS devices	1%		1%			
	TVs	19%	0.9%	82%			
	Hearing aid	8%		2%			
	Pacemaker	3%					
	Vehicles	19%	2.5%	5%			
	Furnaces						65%
	Aerospace						35%

2.2.4 Consumer waste assessment

10 & 11) To find out how consumer purchases of tantalum containing products in 2007 contribute to the recycling potential over time, we used the apparent consumption of final products based in Table 2.3 to represent the amount of tantalum going into the use phase. Even though the outcomes of the allocation method, as described in the previous section, did not provide a 100% match between tantalum supply (embedded in subcomponents) and its demand (through the production of final products requiring using those components), this provides the most robust estimate. Given that different products have different expected lifetimes, we assumed a Weibull lifetime distribution for each of the final products. The Weibull distribution is chosen because of its high analytical traceability and because it has the best fit of lifetime distributions for most products (Wang et al. 2013); it is a common distribution in reliability applications, next to the log-normal distribution. The Weibull probability density function $f_w(t)$, in this case representing the failure rate of a product, t years after its purchase, is given by the following equation (equation 1):

$$f_W(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{\left(\frac{t}{\eta}\right)^{\beta}} \quad ; \quad \eta > 0, \beta > 0, t > 0 \qquad \text{(eq. 1)}$$

The first distribution parameter, β, generally called the shape parameter, determines whether the mode (being the top of the bell shape) is toward the right or the left of the mean; it also determines the skewness (i.e., the sharpness of the distribution peak). The second parameter, η, determines the spread, or the statistical dispersion, of the function. Note that it is not the same as the mean (or average) lifetime. The sources for the Weibull parameters for each product are shown in Table 2.5 below. The Results section elaborates on the implications to waste generation and presents the resulting lifetime distributions in Figure 2.3a.

2.3 Results

12) The results of the SFA for tantalum, as described in the previous chapter, is shown by means of a Sankey diagram in Figure 2.2. The diagram shows the imported flows (in light green), the exported flows (in light red), and the intra-European flows of tantalum (in light blue). It shows the cascading of the consumed tantalum in raw material form (in the blue bars) through the demand for subcomponents (in green) and final products (where the color of the bars indicate different product categories).

Table 2.5. *Weibull parameters & distribution of failure rates for Tantalum relevant products*

Final product	Shape (β)	Scale (η)	Average lifetime (yr)	Reference category & source
vision correction lenses	1.4	7.6	6.9	Small medical, (Wang et al. 2013)
Cutting Tools	2.6	15.7	13.9	Small tools, (Wang et al. 2013)
Furnaces	2.218	26.7	23.6	(EERE 2008)
Mobile phones	3.66	7.59	6.8	(Polák and Drápalová 2012)
Cameras (video/still)	1.4	8.2	7.5	(Wang et al. 2013)
Desktop PCs	2.1	9.6	8.5	(Wang et al. 2013)
Laptop PCs	1.5	5.2	4.7	(Wang et al. 2013)
External HDD & servers	2.30	13.74	12.2	(Pasha et al. 2006)
DVD players	1.7	10.5	9.4	Video & projection, (Wang et al. 2013)
GPS	1.7	9.6	8.6	Small monitoring, (Wang et al. 2013)
TVs	2.1	12	10.6	FPD TVs, (Wang et al. 2013)
Hearing aid	1.4	7.6	6.9	Small medical, (Wang et al. 2013)
Pacemakers	1.4	7.6	6.9	Small medical, (Wang et al. 2013)
Artificial joints	2.6	19.2	17.1	Prof. medical, (Wang et al. 2013)
Aerospace	0.65	10.2	13.9	Airplanes, (Nomura et al. 2013)
Automotive	1.89	10.3	9.1	Passenger cars, (Nomura et al. 2013)

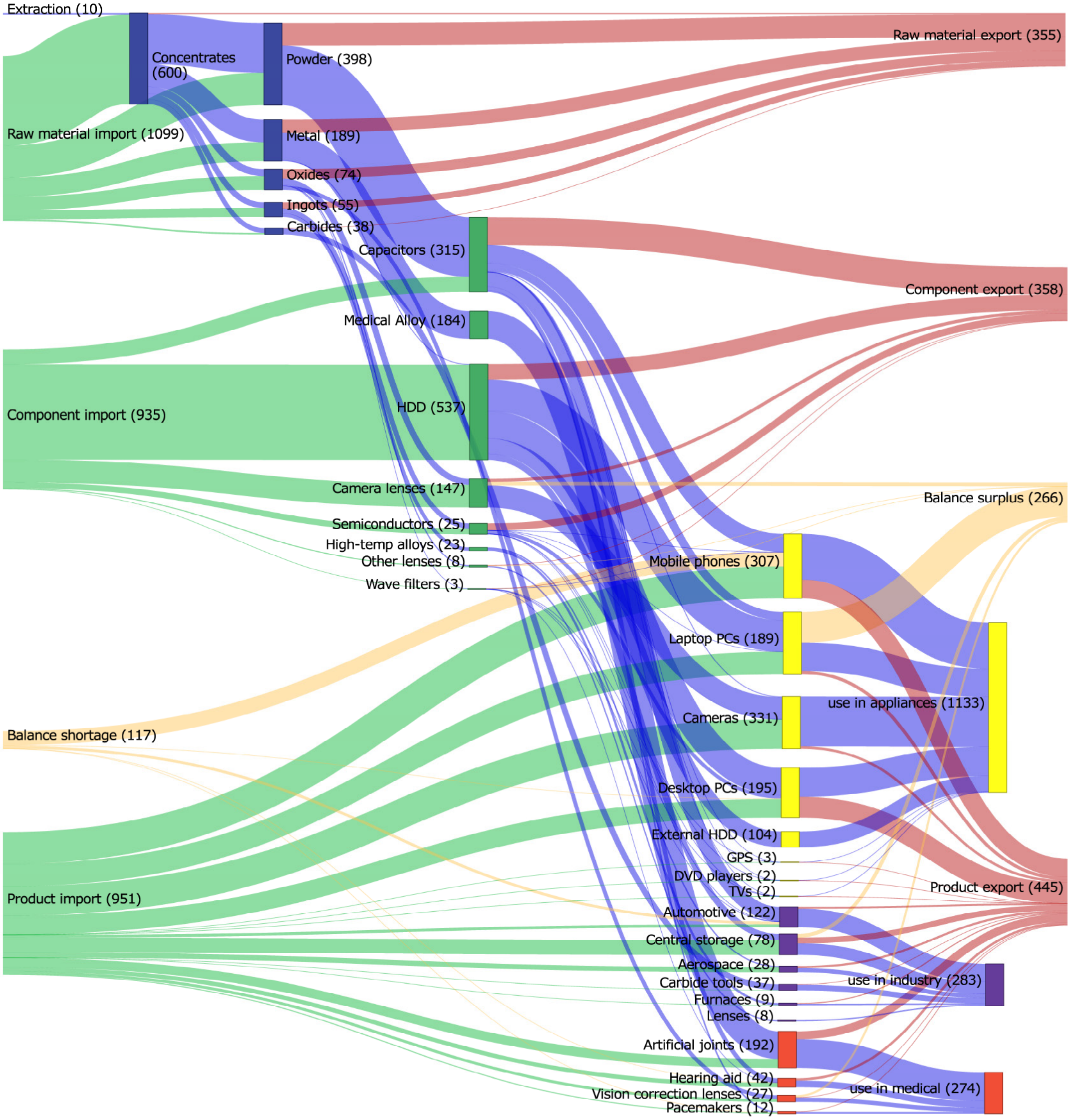

Figure 2.2. *Annual Tantalum flows through the EU27 in 2007, the numbers indicate the apparent consumption of tantalum in tonnes. For intermediate product categories this represents the production that remains within the EU27, or simply the size of the outgoing blue flow. For imports, exports and products going into use, the number indicates the total tonnes of tantalum. The template for this Sankey-diagram was inspired by and adapted from* (Bostock 2012).

Careful interpretation is required, given that the size of the bars as well as the indicated volumes for each product indicate the size of the tantalum flow through Europe (imports, exports, plus domestic production), so not its actual consumption. The actual consumption of raw materials and subcomponents is represented by the light-blue flows and are based on the allocation method as described for step 9 in the previous chapter. The resulting apparent consumption of final products is separately indicated using the bars in the lower-right corner. In the section below, these results are discussed and compared against existing studies.

Given that no previous studies made an attempt to quantify tantalum flows in Europe at this level of detail, it is difficult to compare the outcomes or even judge their quality. Something can be said, however, for example to compare the output of the European tantalum processing industry, which is 716 t, including exports in our analysis (considering tantalum powders, metal, oxides, ingots, and carbides). This does not correspond with the observation of Espinoza (Espinoza 2012, page 7), who states that this is *"between 250t and 300t tantalum per year*." Also, the total amount of tantalum going into use in Europe through final products (1,690 t) is much larger than expected based on the total global consumption of concentrates. In fact, this would be more than the global mine production (1,400 t) as reported by the USGS. This is surprising given that the current end-of-life recycling rate, and thus the potential for secondary material to fulfill demand, is minimal at less than 1% (Graedel et al. 2011). This mismatch of reported global raw material supply and European consumption may have two main reasons; either this study used assumptions leading to a too high estimate for the tantalum concentration in products or it may indicate that the real volume of tantalum mined is much larger than reported, which is not unlikely, given that tantalum is not traded on official spot markets and partially sourced from illicit mining operations in conflict areas (Nest 2011). An observation hinting in this direction is the fact that the reported total tantalum content in global concentrates for the year 2008 increases by over 70% between two reporting years according to the USGS (USGS 2011, 2012).

The European Commission (EC 2014) review of critical raw materials for Europe gives some more numbers that could provide a perspective. It mentions the total tantalum imports to be 604 t in 2010, but it remains unclear whether these are the raw material imports only (in that case, they compare to 1,099 t in our study) or imports in all product phases combined (in which case they compare to 2,985 t of tantalum). The EC study also indicates that 40% of tantalum is used in capacitors. If we assume that they compare the use to the total raw material consumption (754 t), our study finds that 53% of the tantalum in raw material form is consumed in capacitors. So, in general, it seems that the few currently known indicators on tantalum consumption are not very comparable to our outcomes. This brings up the question as to why the total tantalum consumption found is so much larger than expected.

One of the items that stands out in our analysis is the large consumption of tantalum in hard disks for storage of digital data. This is a category that has only been mentioned in one of the qualitative studies (see Table 2.1) and never as a crucial product. However, the results in this study indicate that hard disks are responsible for 537 t of tantalum, when assuming a tantalum content based on a patent (Hitachi 2007) and an X-ray based composition analysis (Nunney and Baily 2011) for consumer-type hard disks using a perpendicular recording mechanism. Our study is the first, to our knowledge, to highlight such a high importance of tantalum in hard disks, thus indicating a direction for further research.

Another interesting finding is the relatively high importance of tantalum in artificial joints. Though the assumption on tantalum concentration for this product category is based on a selection of medical materials in a single source (Zardiackas et al. 2006), so insights may be improved given further research, the fact that Europe would have a relatively high demand for prosthetic devices seems plausible given the high occurrence of hip-and-knee replacement surgery (OECD 2011) and the prominent demographic aging trends (Walker 2010).

It is clear that the results presented in Figure 2.2 contain both expected and unexpected elements, but the lack of quantitative data to check the outcomes shows that the supply chain of tantalum, like many critical raw materials, is still not well enough understood. An exercise like the one presented here generates valuable insights on the relevance of individual products and into the importance of product imports. The true value of the SFA, however, lies in identifying ways to overcome the dependence on tantalum in Europe and in solving its criticality through recycling, for example. The next section goes into this topic.

13) Applying the Weibull distributions discussed in step 11 of the method section to the apparent consumption of final products, as found in Table 2.5, gives the expected amounts of tantalum waste as a consequence of European consumption in 2007. As an example of what is possible when combining the SFA with information on product lifetimes, Figure 2.3 presents a waste generation profile for the seven products containing the most tantalum.

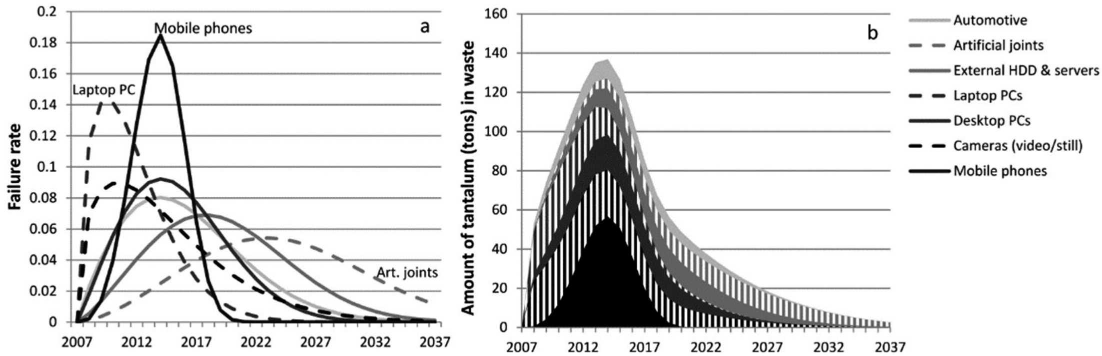

Figure 2.3a-b. *Expected waste generation profile of tantalum contained in seven major applications consumed in Europe in 2007. Major applications are defined as those products with an apparent consumption above 100 tonnes per year (see Figure 2.2), where external hard disks and central storage in servers are shown as one product category. a) shows the probability density function of the product failure rate in the form of a Weibull distribution based on the parameters in Table 2.5; simply said, it shows which fraction of the products are discarded in a particular year after purchase. b) shows the resulting expected volumes of tantalum in wastes as a result of purchases in 2007 only.*

The waste generation profile in Figure 2.3 shows that some of the major tantalum-containing products purchased in 2007 will be discarded and thus become available for recycling over a very long time period, spanning up to 30 years. The good news, however, is that the majority of tantalum is contained in household and consumer electronics, which have a relatively high collection rate estimated at 85% (EU 2012), a relatively high recycling and reuse rate (generally above 80%; see (Eurostat 2015)), and average lifetimes that are mostly limited to around 15 years. Based on this graph, which builds upon the detailed elaboration of the tantalum supply chain above, we identify consumer e-waste as a potential hotspot in terms of recycling potential for tantalum. One can imagine that the application of lifetime distributions to SFA results, like we have done here, may have several other useful applications. We will elaborate on this and on the more-general conclusions of our research in the following section.

2.4 Discussion and conclusions

The results section showed that performing an SFA based on detailed production and trade statistics gives insight into the use of tantalum throughout Europe. It allows identification of current knowledge gaps, whereas the visualization in the form of a Sankey diagram highlighted the importance of imported tantalum-containing products and components. Additionally, the identified hotspots for recycling are useful outcomes of this exercise, given that they provide clues on how to efficiently improve recycling rates and eventually to reduce Europe's dependence on tantalum as a scarce and conflict-related raw material.

However, the results presented here should be interpreted carefully for several reasons. First of all, we have not been able to cover the full extent of tantalum-containing product categories as found in the previous qualitative literature. Though only a limited number of minor products were excluded based on the lack of data, further research into the tantalum content of these products could help alleviate uncertainty. Second, the availability of data in the Europroms database only allowed for the full analysis of relevant products for the year 2007, which is probably not a very accurate description of the current situation. It should be stressed that the Eurostat data are simply indispensable, but application in SFA requires maintenance of trade and production statistics at the highest level of detail. Finally, and perhaps most important, during this research we found that gathering information on product compositions is surprisingly tedious. This study uses information on tantalum concentrations for products and components from a wide variety of sources, often nonscientific, and often requiring rough assumptions or interpretation. The sheer difficulty of gathering concentration data is an indication that the uncertainty of these numbers is high. This is a possible explanation to why the size of tantalum flows in our results are much larger than expected, but the uncertainty in benchmarks of total global consumption defining these expectations may be just as uncertain.

More generally, one could say that though the complexity of products, in terms of the components and materials they contain, has increased rapidly over the last decades, our understanding of their elemental compositions is clearly lagging behind. For many products, neither consumers nor producers simply have any clue what they contain. So although the discussion on the scarcity, responsible sourcing, and criticality of many materials is still high on the political agenda, research into their supply chains is stuck to a case-by-case approach, without a reliable source for benchmarking results to global numbers. For the case of tantalum, one suggested approach may be to attempt to reconcile data about the supply of tantalum (similar to the study by Moran et al. (2015)) and the data presented here. This would require harmonization of the years of study as well as an extension of focus to include both regulated and conflict-related tantalum mining.

Regardless of the approach, we feel that dealing with criticality questions in a more encompassing manner calls for a comprehensive product composition inventory for multiple critical materials. Such a proposed database should allow storage of information on product compositions at various levels of detail (raw materials, subcomponents, and final products) and should enable documentation of the change of product compositions over time as well, given that we found that the material content of products can be quite dynamic.

Concluding, we found that it is currently possible, yet tedious, to perform a detailed SFA for tantalum in Europe based on the available trade and production statistics by Eurostat. We provided a step-wise approach, which could serve as an example of how to draft SFAs for a variety of other scarce or critical materials. Based on the tantalum example, we feel that doing this gives valuable insights into both the economy-wide dependence on these materials as well as clues on how to reduce this dependence most efficiently. For tantalum, we have shown that the European market is highly dependent on imports of product components and final products, which leads to a much higher consumption than expected based on previously available indications. We identified computer hard disks and artificial joints as items with a surprisingly large contribution to the use of tantalum and have shown that consumer electronics should be the main focus when aiming for an improved recycling rate. The application of lifetime distributions to SFA results may have numerous applications. One of them may be the dynamic assessment of recycling potential over multiple years, which could inform a cost-benefit assessment when planning for effective deployment of tantalum-specific recycling and processing capacity in a European context.

Two factors play a crucial role in facilitating future analyses of other materials in a similar way, one being the availability of the detailed trade and production data, both for raw materials and products, beyond the year of our current analysis and the second being the suggested development of a product composition inventory. Given the two, we feel that it should be possible to rapidly increase our knowledge on the demand side of supply chains of critical materials other than tantalum.

Acknowledgements

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3.

Scenarios for demand growth of metals in electricity generation technologies, cars and appliances

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Abstract

This study provides scenarios toward 2050 for the demand of five metals in electricity production, cars and electronic appliances. The metals considered are copper, tantalum, neodymium, cobalt and lithium. The study shows how highly technology-specific data on products and material flows can be used in integrated assessment models to assess global resource and metal demand.

We use the Shared Socio-economic Pathways as implemented by the IMAGE integrated assessment model as a starting point. This allows us to translate information on the use of electronic appliances, cars and renewable energy technologies into quantitative data on metal flows, through application of metal content estimates in combination with a dynamic stock model.

Results show that total demand for copper, neodymium and tantalum might increase by a factor of roughly 2 to 3.2, mostly as a result of population and GDP growth. The demand for lithium and cobalt is expected to increase much more, by a factor 10 to more than 20, as a result of future (hybrid) electric car purchases. This means that not just demographics, but also climate policies can strongly increase metal demand. This shows the importance of studying the issues of climate change and resource depletion together, in one modeling framework.

3.1 Introduction

Several studies have assessed raw material resource availability based on concerns regarding the security of supply of nonfuel minerals (Speirs et al. 2013; Northey et al. 2014; European Commission 2017; Sykes et al. 2016). These concerns are related to factors such as geological accessibility, geo-political risks, material substitutability (Graedel et al. 2015), recycling rates (Espinoza 2012; Graedel et al. 2011) and current economic importance (Graedel et al. 2012). Another key question in determining the supply risks for different specialty metals, which has received limited attention so far, is whether the available resources are sufficient to meet future demand. Interestingly, future demand for metals remains somewhat of a blind-spot in the criticality discussion. Against this backdrop, this chapter focuses on developing quantitative scenarios for the demand of five specialty metals toward 2050 for a number of crucial applications: appliances, cars and electricity generation technologies.

A number of studies have tried to quantify the global long-term demand for metal resources (Moss et al. 2011; Marscheider-Weidemann et al. 2016). Such studies are based on different approaches and therefore difficult to compare. Some studies assume that the metal demand will continue to grow with a fixed percentage each year over the coming decades (Henckens et al. 2014). This method is severely constrained for long-term trends as it does not account for underlying changes in consumption patterns resulting from development of population and affluence for example, which ultimately drive metal demand. Van Vuuren et al. (1999) as well as van Ruijven et al. (2016) account for these factors by simulating the saturation of metal demand through a set of scenarios assuming changes in intensity of use curve for steel and alloying metals as a function of development. This stock-saturation effect for steel is also observed by Muller et al. (2010) and can be used as an exogenous scenario driver to extrapolate material cycles (Hatayama et al. 2010; Pauliuk et al. 2012b). However, the approach in such studies requires calibration based on long historic time series and cannot capture radical introduction (or phase-out) of new demand categories such as electric cars. More technology-explicit approaches can account for this. An example is the study by Elshkaki and Graedel (2013), who calculate the demand of various technology metals in electricity generation technologies. They find an impressive growth in demand for all considered metals, but only describe a fraction of total demand. Kleijn et al. (2011) also expect a huge growth in metal demand, but again focus only on the electricity generation sector. Their findings are based on life cycle assessment and assumptions on metal demand expressed in grams per kWh. This approach makes it difficult to discern which part of the demand stems from the generation capacity and which stems from upstream production requirements; also, this approach ignores stock dynamics which are relevant to derive actual annual metal demand. De Koning et al. (2017) take a different approach by specifying scenarios for global metal demand based on an environmentally extended Input-Output table, thus covering demand from a wide range of product categories, but without accounting for long-term economic shifts or saturation of product demand at higher levels of income.

Though this chapter does not aim to overcome all constraints of existing studies, we observe that there is presently no comprehensive approach to generating scenarios for global resource use. Moreover, there is a lack of studies and approaches that link macro-scenarios, such as the Representative Concentration Pathways (RCPs, see van Vuuren et al. (2011a)), with scenarios for specific resources such as bulk and specialty metals. So far, only one study has tried to combine macro-scenario information with demand forecasts for copper, using UNEP's GEO-4 scenario family as a starting point (Elshkaki et al. 2016). Such a link would allow studying the linkages between material use, energy use and climate change in a more detailed way than current models allow (Pauliuk et al. 2017).

In this chapter, we address the first steps toward integrating the dynamics of material demand into existing global energy models by developing an approach to generate metal demand scenarios using information from the global integrated assessment model IMAGE. We estimate the metal demand for three application groups that are relevant for energy demand (cars and appliances) and supply (electricity generation). The related research questions are, first, how can we link the outcomes of integrated assessment models to generate metal demand scenarios? Second, what is the expected annual demand for copper, tantalum, neodymium, cobalt and lithium for cars, appliances and electricity generation by 2050? Answering these questions helps to improve the understanding of the combined energy-resource system, which is relevant for both climate policies as well as resource oriented policies.

In the following section on the methodology we discuss how we used the detailed implementation of the Shared Socio-economic Pathways (SSPs) by the IMAGE integrated assessment model (van Vuuren et al. 2017) to produce metal demand projections. Readers interested only in the results and discussion could skip to section 3.3.

3.2 Methodology

3.2.1 Model framework

The starting point for our methodology is the data available from the IMAGE scenarios. IMAGE is an integrated assessment model describing global environmental change based on a detailed description of both energy and land use (Stehfest et al. 2014). The IMAGE model is often used to create scenarios for 26 world regions for energy and land use, and the underlying drivers. Both the activity data of the energy system and the underlying socioeconomic drivers can be used to create metal demand scenarios. On the basis of the available model detail, we used a dynamic stock model to compile the available product and capital stock data from IMAGE into data on the annual demand for cars, appliances and energy generation technologies. Subsequently, we added information on the metal composition of these products (Hawkins et al. 2013; Habib 2015; Widmer et al. 2015; Cullbrand and Magnusson 2012; Moss et al. 2013; Elwert et al. 2015; U.S. Department of Energy 2011; Schneider Electric 2011; Oguchi et al. 2011; Zhang et al. 2012; Truttmann and Rechberger 2006; Namias 2013; Tickner et al. 2016; Patrício et al. 2015; Arai et al. 2011; Seo and Morimoto 2014; Crock 2016; Schulze and Buchert 2016; Sprecher et al. 2014; Deetman et al. 2018; Chancerel et al. 2015; Moss et al. 2011; Öhrlund 2012; Singh et al. 2015; Meier 2002; S&T2 consultants 2006; Pihl et al. 2012; BBF Associates; Kundig 2011; Flury and Frischknecht 2012; Dones et al. 2007; Weitzel et al. 2012; Bhaduri et al. 2004; National Research Council 1986; Alonso et al. 2012; Long et al. 2012; Elshkaki and Graedel 2013) in order to derive the annual demand for five metals; which were selected based on data availability. The information flow is summarized in Figure 3.1. Key data used from IMAGE are the global total person kilometers driven by passenger car annually, the global total number of in use appliances per household and the newly installed power generation capacity, globally. Below we describe the key elements of our method, that is, the IMAGE model and the scenarios created by IMAGE, followed by a detailed description of the use of this data to create metal demand scenarios.

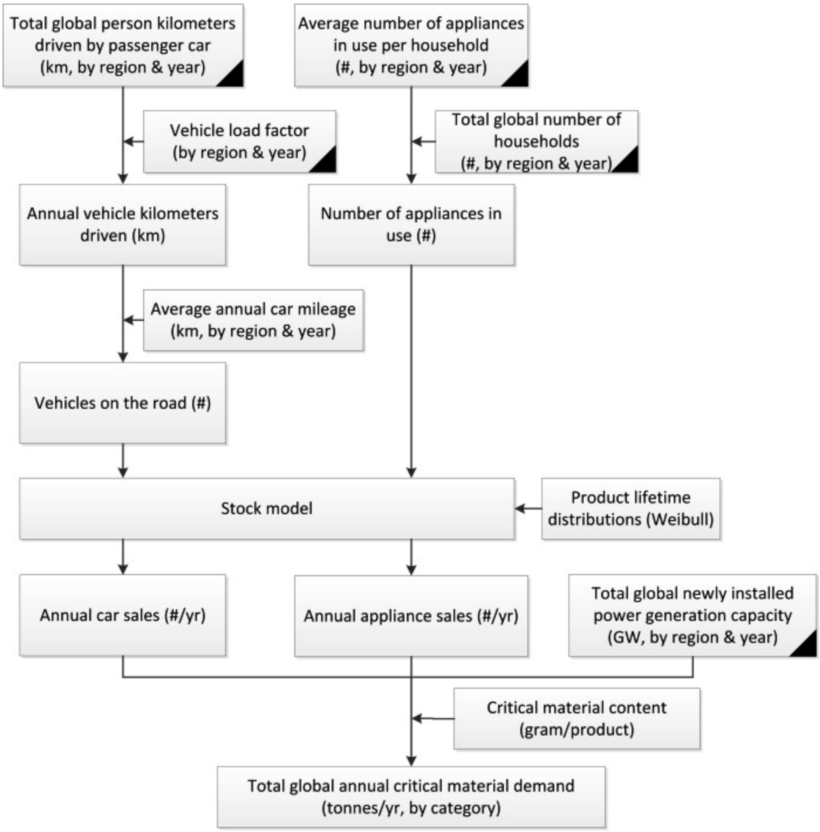

Figure 3.1. *Overview of the calculation steps to translate IMAGE model output (indicated with black triangles) into total metal demand for appliances, cars and electricity generation technologies. Vehicle "load factor" refers to the average car occupancy. Though the input data is specified per region, this study only presents numbers on global metal demand.*

3.2.2 The IMAGE model

The IMAGE model provides a consistent framework to assess how drivers such as population and welfare influence environmental issues. To provide insight into future greenhouse gas emissions the IMAGE model contains a highly detailed energy demand model, which among other things describes the development of households and private transport related energy consumption as well as the stock of power generating capacity in high technological detail. Because the contribution of domestic appliances to overall household electricity consumption is increasing, the IMAGE energy demand model contains indicators on the amount of appliances in use for the given 26 world regions, over the scenario period toward 2050 based on income relation as developed by Daioglou et al. (2012). Similarly, the submodel on transport emissions accounts for the number and the type of cars that are in use, because these determine the efficiency and thus their greenhouse gas emissions (Girod et al. 2012). Regarding power generation the IMAGE model identifies the annually required newly-built capacity for 27 different power generation technologies using a simplified stock model based on technology specific lifetimes, but not lifetime distributions, as described by van Vuuren (2006). The IMAGE model is developed and maintained by The Netherlands Environmental Assessment Agency and a detailed description of the data and the modeling approaches used can be found in the model documentation (Stehfest et al. 2014).

To use the IMAGE scenario output as input for metal demand scenarios we need to take two conversion steps:

1) First, we need to find a match between the level of product detail in the IMAGE model and available information on metal composition of products. Details on this step can be found in Appendix 3.
2) Second, we need to convert the current in use stock of cars and appliances to a demand for new products using a stock model. This also requires assumptions on the lifetimes and distribution of failure rates for all appliances and car types.

The required calculation steps are depicted in Figure 3.1 and are implemented in a dedicated python model, including a dynamic stock model based on work by Pauliuk (2014), for which the source code is available with the original publication. Though the IMAGE model provides the scenario results in regional detail, we focus on aggregate and global indicators.

3.2.3. The SSP scenarios

We use the available detail in model output by taking the IMAGE implementation of the shared socioeconomic pathways (SSP) as a starting point (van Vuuren et al. 2017). The SSPs present a new set of quantified long-term scenarios for climate change research with varying assumptions on the costs of climate change mitigation and adaptation, each leading to different levels of radiative forcing, thus posing different challenges in terms of climate policy (O'Neill et al. 2014; van Vuuren et al. 2014; Riahi et al. 2017). The SSP2 is a middle-of-the-road scenario in terms of the main developments, it represents moderate population growth and a path in which "social, economic, and technological trends do not shift markedly from historical patterns" (Riahi et al. 2017). We used the SSP2 baseline which assumes no additional climate policy. In the literature, the SSPs are combined with forcing targets consistent with the Representative Concentration Pathways (RCPs) to look into the impact of climate policy. In addition to the SSP2 baseline we also use the SSP2-2.6 climate policy scenario which leads to a radiative forcing of 2.6 W/m^2 by the end of the century, corresponding to the two-degree policy target (UNFCCC. Conference of the Parties (COP) 2015), by introducing climate policy. This entails deep greenhouse gas emission reductions (van Vuuren et al. 2011b). To show the impact of different baseline assumptions we also present results for two other baseline scenarios in the sensitivity analysis, that is, the SSP1 and the SSP3. The SSP1 baseline presents a future in line with a more sustainable development pathway, that is, a low population growth, high affluence, rapid technology development, and lifestyle change toward more environmentally friendly behavior. The SSP3 baseline assumes a fragmented world and has the opposite assumption for the key drivers as described for SSP1 (O'Neill et al. 2014). For an elaboration of the narratives behind these scenarios please see Appendix 1. Each of the scenarios present a different notion of the number as well as the types of cars and electricity generation technologies deployed towards 2050. To assess how these key scenario parameters (shown in Table 3.1) eventually influence annual metal demand we developed the methodology described in the following sections.

	SSP2				**SSP1**	**SSP3**
	2010	**2020**	**2030**	**2050**	**2050**	**2050**
Population (billion people)	6.87	7.61	8.26	9.17	8.53	9.96
GDP (trillion US$ per year, in 2005 PPP)	67.5	101.2	143.1	231.3	291.3	173.7
Energy (total primary energy, EJ/yr)	501	580	667	842	747	887

Table 3.1. *key characteristics of the shared socioeconomic pathways (SSP)* (Riahi et al. 2017). *PPP stands for purchasing power parity.*

3.2.4 Metal composition and demand scenarios

We reviewed a total of 36 sources to obtain a database on metal content for cars (Hawkins et al. 2013; Cullbrand and Magnusson 2012; Elwert et al. 2015; U.S. Department of Energy 2011; Habib 2015; Widmer et al. 2015; Moss et al. 2013), appliances (Zhang et al. 2012; Namias 2013; Tickner et al. 2016; Patrício et al. 2015; Arai et al. 2011; Schulze and Buchert 2016; Deetman et al. 2018; Chancerel et al. 2015; Schneider Electric 2011; Oguchi et al. 2011; Truttmann and Rechberger 2006; Seo and Morimoto 2014; Crock 2016;

Sprecher et al. 2014) and electricity generation technologies (Moss et al. 2011; S&T2 consultants 2006; Pihl et al. 2012; Dones et al. 2007; Bhaduri et al. 2004; National Research Council 1986; Long et al. 2012; Elshkaki and Graedel 2013; Öhrlund 2012; Singh et al. 2015; Meier 2002; BBF Associates; Kundig 2011; Flury and Frischknecht 2012; Weitzel et al. 2012; Alonso et al. 2012). The results are listed as ranges in an overview table, Table A3.1. The values in this table are applied together with the average of the minimum and the maximum values to represent three distinct scenarios on metal composition based on currently available data. We assume that the metal content of each product is constant over time. This means that we do not account for changes in specific metal requirements that may be a consequence of engineering efficiency or miniaturization trends over time. It would be beyond the scope of the study to assess all possible developments in engineering and design for all the products concerned. This exercise should hence be seen as a thought experiment, with a limited predictive value. We focus our conclusions on the change in demand and on the possible ranges in outcomes across the scenarios.

On the basis of the availability as well as the credibility of the data we had to make some assumptions as well as exceptions to derive a metal content for each product category found in the IMAGE model. For fuel cell vehicles (FCV), for example, we only had one available study with vehicle-specific metal content estimates (Moss et al. 2013), so the used metal composition is either from that study or based on the estimates for conventional vehicles using an internal combustion engine (ICE). When no information was available, for example, on metals in air-coolers and fans, we used our own estimates (e.g, 50% or 15% of the metal content of an air-conditioner respectively). An overview of all such assumptions made can be found in Appendix 3.

The three different sets of data on metal content (a low and a high estimate from Table A3.1 as well as the average of the two as a medium estimate), combined with the baseline scenario and the climate policy scenario from the elaboration of the SSP2, give us a selection of six different scenarios for the annual metal demand from three different demand categories. Before presenting the outcomes for these scenarios in the Results section (section 3.3), we first elaborate on the most important assumptions for cars (3.2.4.1), appliances (3.2.4.2), and electricity generation technologies (3.2.4.3), followed by an explanation of the dynamic stock model (section 3.2.5).

3.2.4.1 Cars

We first needed to translate the number of person kilometers to vehicle kilometers driven by dividing by the vehicle load factor (or average occupancy, IMAGE model output).This was subsequently converted to the number of cars in the vehicle fleet to calculate the annual demand for cars by dividing by an average kilometrage (cf. annual car mileage) by region based mostly on Pauliuk et al. (2012a). In 2008, the global average kilometers driven per car per year is 18 000 km. The regionally specific numbers that were applied can be found in Table A3.2.

For the lifetimes of cars we assumed a Weibull distribution with similar distribution parameters for all five car types, as given in Appendix 3. The Weibull distribution parameters (10.3 shape parameter and 1.89 scale parameter) applied are those for “ordinary passenger cars (own use)”, as given by Nomura and Suga (2013), and lead to a relatively short average car lifetime of 9.1 years. The effects of assuming longer car lifetimes are discussed in section 3.3.3, in the sensitivity analysis.

3.2.4.2 Appliances

Since the use of appliances is already expressed in pieces in use per household, the information from IMAGE can be directly applied to back-cast the demand for new appliances using the stock model (as described below). The only issue is with respect to the definition of “other small consumer electronics”. The increasing adoption of high-end digital consumer appliances such as tablets and mobile phones is an important driver for the increase in demand for critical metals that have a high value, but are typically used in small amounts. However, their energy consumption remains low as they are typically battery operated and require little electricity to be charged. The IMAGE energy model therefore specifies a lump category of “other small consumer electrics”. The actual number of these appliances used in our analysis is therefore a rough estimate.

Similar to the approach for cars, assumptions on appliance lifetimes are based on Weibull distributions. The distribution parameters where obtained from Wang et al. (2013) and are listed in Table A3.1.

3.2.4.3 Electricity generation

The IMAGE model already includes stock dynamics on capital investments in electricity generation technologies, so the scenario output includes both an overview of total installed capacity as well as newly installed capacity for electricity generation technologies. The new capacity includes the expansion of the total capacity due to an increase in overall electricity demand, as well as the replacement of end-of-life capacity based on an average 30 year operational lifetime. To derive the annual metal demand from the power generation sector we can thus simply multiply the newly installed MegaWatts (MW) by the metal demand per MW from Table A3.1 of Appendix 3.

3.2.5 Dynamic stock model for passenger vehicles and appliances

To determine annual sales of passenger vehicles and appliances from their total stocks we applied stock-driven modeling originally based on Müller (2006) and Pauliuk (2014) to calculate the required product purchases (annual inflow, in products per year) to fulfill the total demand for cars and appliances (stock, i.e. the total number of products in use). The model tracks the different age-cohorts and uses a survival function based on the Weibull distribution to calculate how many of the cars and appliances bought in year t_0 survive after t years. The survival function (SF) equals 1 minus the cumulative distribution function (CDF) of the product lifetime distribution and is expressed as follows:

$$SF(t) = e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \quad (1)$$

where t is time, β is the Weibull Scale parameter and α is the Weibull shape parameter. The Weibull parameters used for each of the car types and appliances is given in Appendix 3. The survival function gives us the fraction of the products bought in year t_0 that are still in use in year t. For each model year (t), for each model region (r) and for each car or appliance, referred to as a product (p), we can then determine the total number of surviving products (SP) from all previous years (t') given the sales (y) of the previous years:

$$SP_{r,p}(t) = \sum_{t'=0}^{t} y_{r,p}(t') \cdot SF_{r,p}(t - t') \quad (2)$$

The sales (y) in the year of interest (t) are then determined from the stock balance:

$$y_{r,p}(t) = T_{r,p}(t) - SP_{r,p}(t) \qquad (3)$$

Where T is the model stock target value, given by the IMAGE stock (products in use). In Appendix 3 an overview of relevant global inputs to the stock model based on direct IMAGE scenario output is presented, as well as intermediate calculations for appliances and cars for the current situation and by the end of the model period.

3.3. Results and discussion

3.3.1 Annual demand for cars, appliances & generation capacity

Because of the continued growth in population and affluence, the number of appliances in use in the original SSP2 scenarios is expected to more than double between 2015 and 2050 (Figure A3.1). This finding also holds for the required electricity generation capacity as well as for passenger car transport demand. Figure 3.2 shows that the increased demand of cars and appliances leads to roughly a doubling of appliance and car sales. Even without considering the particular types of appliances, cars or electricity generation technologies that are deployed, it is clear that the demand for materials embedded in products will increase substantially.

There may be quite a difference between the shares in the stock (Figure A3.1) and the shares in the new product purchases (Figure 3.2). Currently, global capacity of solar and wind based electricity generation is expanding rapidly, hence the shares of these technologies in the purchases is much larger than for nuclear power, whose rate of expansion is decreasing (World Energy Council 2016). Similarly, the transformation toward a (hybrid) electric car fleet, requires a high share of (hybrid) electric vehicles in the new vehicle purchases. Though these are rather obvious conclusions from a stock-dynamic perspective, this exercise shows the importance of stock-dynamics when deriving long-term projections of annual demand for products.

Our results show that climate policy has no effect on the expected demand of appliances, but slightly decreases the demand for cars by 2050 (compared to baseline). This is because alternative modes of transport with a lower carbon footprint, such as public transport, will be favored. The effect of climate policy on the demand for electricity generation technologies is a little more complicated. Because even though the climate policy lowers the demand for total electricity through energy efficiency measures, the annual demand for new electricity generation capacity grows. This can be explained through the intermittency of the renewable energy sources (wind and solar in particular). The newly built capacity represents the peak capacity but, as intermittent energy sources such as photovoltaics and wind turbines operate well below their maximum capacity on average, the peak capacity has to be expanded more than in the baseline scenario, which relies more on baseload technologies such as coal fired power plants. This need for excess capacity offsets the effect of the lower electricity demand under a climate policy regime. The fact that the transition toward a renewable energy system requires more materials, especially while capacity is being expanded, represents an important driver for metal demand.

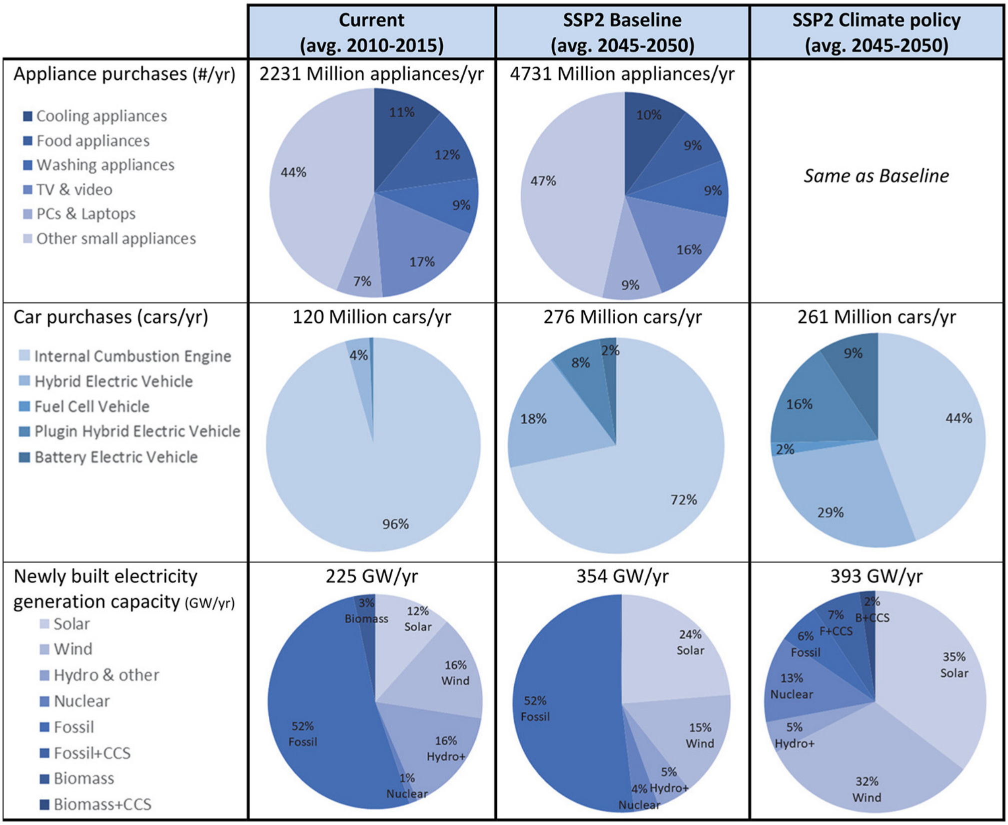

Figure 3.2. *Overview of scenario indicators on annual demand for cars, appliances & electricity generation capacity. i.e. their annual purchases/sales. The numbers above the charts indicate the total annual demand while the shares in the pie-charts indicate the relative market share of specific car types, appliance types or generation technologies.*

3.3.2 Resulting metal demand scenarios

We present a selection of graphs on the annual demand projections for copper and neodymium in a baseline and a climate policy case in Figure 3.3. The graphs for the other metals (for three different assumptions on metal content) can be found in the supplementary information of the original article.

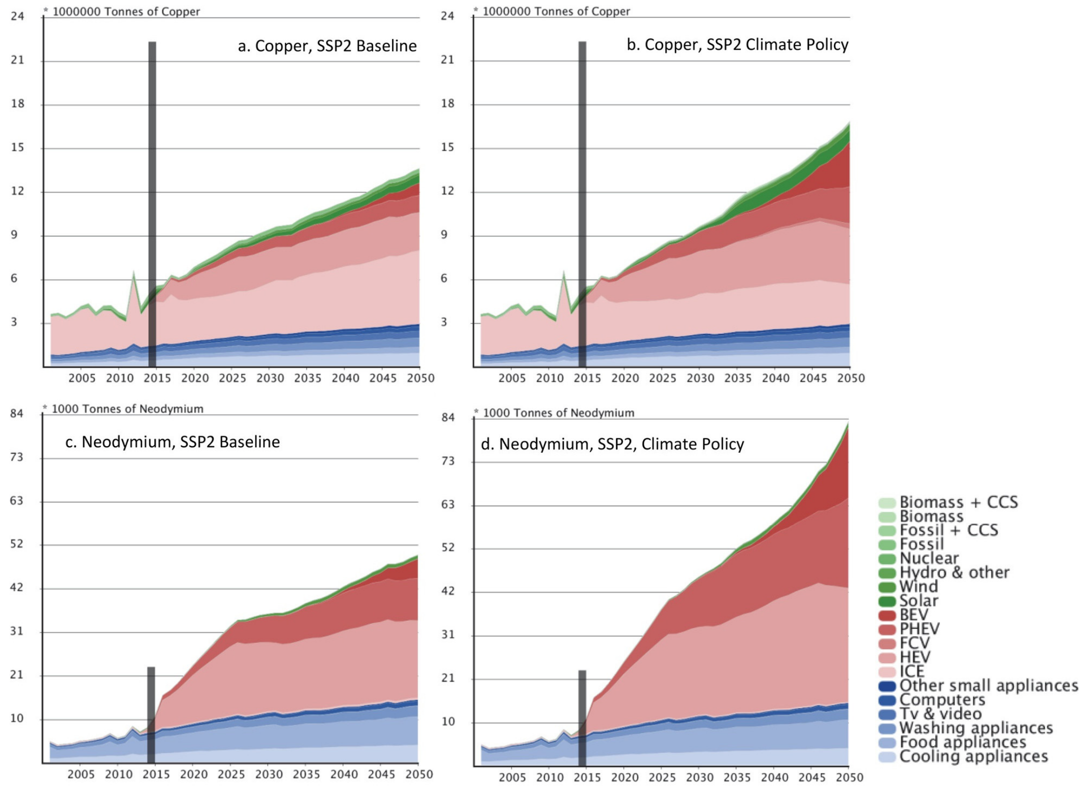

Figure 3.3a-d. *Metal demand projections for copper (a&b, using a medium metal content assumption) and Neodymium (c&d, using a low metal content assumption) in the SSP2 baseline scenario and in its corresponding 2-degree climate policy scenario (in tonnes/yr). Green represents all electricity generation technologies, red all car types and blue is used for appliances. The dark bar in 2015 represents the current total annual consumption estimates for copper* (Brininstool 2014) *and neodymium* (European Commission 2014)*. Since this study only addresses 3 categories of demand, the bar gives a feeling for the size of the 'rest' of the demand (e.g. construction, medical applications etc.). For elaboration and results for all other metals, please see the original publication.*

Figure 3.3 shows that both copper and neodymium demand are expected to increase and that climate policy is likely to boost the demand considerably for both metals by 22% (for Cu) and 60% (for Nd) compared to the SSP2 baseline scenario. By the end of the modeling period the metal demand for car production dominates the other two considered product categories. This is an interesting finding, given that much of the current concern about neodymium demand is focused on wind turbines. Two factors are important in understanding this result. First of all, wind turbines have a considerably longer assumed lifetime (30 years) than appliances and cars, thus the demand for windmills to replace the ones that reach end of life will be relatively low, especially because the large-scale deployment of windmills is only a recent development. Another reason for the low annual metal demand from electricity generation technologies is that they are not consumer goods and therefore show much higher ulitization rates. While a single wind turbine may provide power to hundreds of households, many households aspire to own a car, a washing machine and other consumer goods. The impact of appliance and personal transport demand on metal consumption is fairly consistent across all metals considered (Table A3.4). As elaborated in Appendix 3, however, the different metal content estimates may lead to scenarios for which the modeled demand in cars, appliances, and electricity generation technologies surpasses the reported current demand. This is the main reason that we emphasize the need for more knowledge and data on the metal composition of products in the discussion section.

The results as shown in Figure 3.4 indicate that demand for all five metals is going to increase, regardless of the anticipated climate policy ambitions. Apparently, socio-economic developments (GDP, population) and technological change are more dominant factors than climate policies. However, the uncertainty introduced by the range of assumptions on metal content (Table A3.1) is so large that for tantalum and neodymium the low baseline estimates for the period 2045-2050 may actually be lower than the high estimates in the current situation. In most cases the difference between outcomes for high and low metal content estimates is larger than the difference between the baseline and the climate policy scenario.

To explore the differences in metal demand we present the growth factors by product category in Figure 3.4, using a single (medium) set of metal content assumptions. The figure shows that the rise in cobalt and lithium demand toward 2050 are explained by the demand for cars, which is in turn explained by their requirement in battery packs of hybrid and full electric cars. The metal demand from cars is consistently higher in a climate policy scenario, because the metal requirement is higher in all low-emission vehicles. This is however not the case for electricity generation technologies, as the deployment of wind turbines and photovoltaic cells under a climate policy scenario increase the demand for copper and neodymium, while they decrease the demand for tantalum and cobalt. The latter are generally used as alloys in temperature resistant steels, which are only applied in combustion-based power plants. Figure 3.4 shows the metal demand growth index for the period 2015-2050. In appendix 3, an extended table with the absolute numbers for all metal contents is provided (Table A3.4).

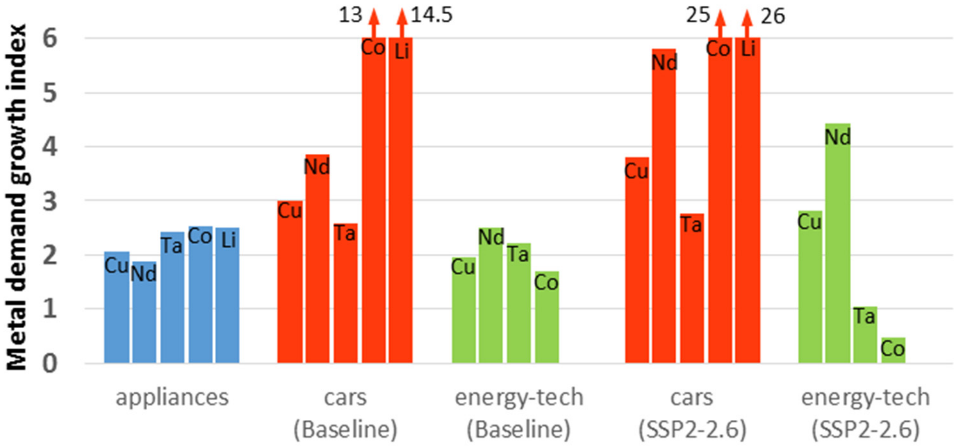

Figure 3.4. *Indexed growth factors of annual demand for five metals, by product category. The growth factor is based on the medium estimates, using the average of 2045-2050 over the average of 2010-2015. For cobalt and lithium in cars, the demand growth factors are much larger as indicated in numbers.*

3.3.3 Sensitivity analysis

To assess the impact of our modeling assumptions on the outcomes we performed a sensitivity analysis consisting of three parts. First, we complemented the results with outcomes for the SSP1 and the SSP3 baselines, to show how the range of outcomes changes under the assumption of different socio-economic baselines. Second, we assessed the importance of the lifetime assumptions for cars and third, the impact of metal content estimates for products that are based on only one reference value.

To provide some context regarding the effects of different socio-economic baselines we used the same approach as described in the Methodology section (Section 3.2) to calculate global metal demand for the SSP1 as well as for the SSP3. These baselines provide a wider range of possible developments in terms of population size, welfare indicators and energy use (see Table 3.1), thus leading to a different demand for appliances, cars and electricity generation technologies. Figure 3.5 shows the results for the total annual demand by product category under three different baselines and medium metal estimates.

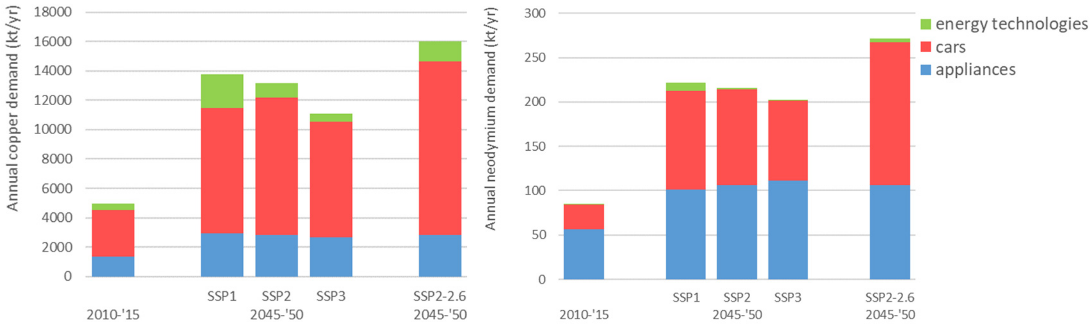

Figure 3.5. *Ranges in annual copper and neodymium demand from three product categories under three different socio-economic baselines. Similar to previous Figure 3.2, we present average annual demand for the period 2010-2015 and 2045-2050. The development of demand for the other metals under the SSP1 and SSP3 scenarios is available with the original publication.*

The changes in total metal demand across the three baselines is considerably smaller than the change between a baseline and a climate policy scenario (Figure 3.5). The total demand decreases consistently from SSP1 to SSP3, demonstrating that the SSP2 is indeed a middle-of-the-road scenario, also in terms of metal demand. In the case for copper the annual demand for the SSP3 baseline is about 20% lower as compared to the SSP1 (average of the annual demand over a five year period). For neodymium the demand is about 9% lower under the SSP3 baseline. A similar conclusion holds for the other three metals (shown in the supplementary information with the original publication), but the difference between baselines is even bigger in the case of cobalt & lithium, for which the annual demand in 2050 decreases by about 35% between the SSP1 and the SSP3 scenario assumptions.

Interestingly, the lower demand for energy in the SSP1 scenario (see Table 3.1) does not translate to a lower metal demand from electricity generation technologies because even in a baseline scenario the SSP1 shows a preference for low-carbon (but more material intense) types of electricity generation. This is in accordance with its storyline, which is oriented at sustainable development. Another consequence of this storyline is that the demand for copper in cars is lower in the SSP1 scenario than in the SSP2, because in this scenario the modal share is more dependent on public transport options, thus reducing the demand for cars, even though per capita income is higher. For neodymium this trend is offset by the higher demand for the (more expensive) battery electric vehicles, which in turn raises the demand for neodymium.

Another interesting result from Figure 3.5 applies to neodymium in appliances, for which demand is higher in the SSP3 scenario, even though the GDP is lower. The explanation is found in the population size, which is larger in the SSP3 scenario, but also the type of appliances purchased differ. Though the total number of appliances bought is larger in the SSP1 scenario, the growth there is mainly attributable to the demand for “luxurious” small appliances and laptops/PCs, while in the SSP3 the growth is mainly due to demand for more “basic” household appliances such as refrigerators and washing machines, which happen to contain higher amounts of neodymium according to the sources used (Arai et al. 2011; Seo and Morimoto 2014; Habib 2015).

The second part of our sensitivity analysis focuses on the lifetime of cars, which is a central model parameter because cars determine a large fraction of the total annual metal demand. The parameters of the Weibull lifetime distribution of cars were assumed to be the same for all considered car types, however, this may be an oversimplification considering the different technological basis of electric vehicles. For regular cars (ICE) and fuel cell vehicles (FCV) we increased the relatively short average lifespan from 9 years to represent the European average of 12.5 years based on Nemry et al. (2008); we did so by only changing the scale parameter of the lifetime distribution. For hybrid electric vehicles we found substantially different estimates for the lifetime distribution from Yano et al. (2016) and implemented their much higher average lifetime (21 years) for all cars with a (partially) electric drivetrain (HEVs, PHEVs and BEVs). This different set of Weibull parameters is applied to the SSP2 with the medium product content assumptions, resulting in much lower metal demand, as the number of scrapped cars is lowered, thus lowering the replacement car purchases. The resulting annual demand by the end of the scenario period (averaged over the years 2045 to 2050) is 24% lower for copper, 18% lower for neodymium, 9% lower for tantalum, 36% lower for cobalt and 45% lower for lithium. Though these numbers highlight the importance of the lifetime assumptions for cars, they should be interpreted carefully. The main reason for higher metal content in cars with an electric drivetrain is the requirement for a large battery pack. Previous studies have found different estimates for the battery lifespan ranging from 5 to maximum 15 years (Richa et al. 2014), which would imply that electric vehicle with a lifetime of over 20 years would have to replace their battery packs at least once during their lifetimes. Though the current model setup does not allow us to assess the effects of different lifetime distributions for product subcomponents, this may be an interesting direction for future research.

Finally, we tested the importance of missing content estimates for tantalum and neodymium (highlighted in gray in Table A3.1). We tested for the effect of introducing a probable range estimate, based on the average range within each metal column. Running the model with these numbers gives either a 4% higher or a 14% lower demand for tantalum over the five last years of the scenario. Using a similar procedure for neodymium, we find a change in average annual demand that is either 1% higher or 9% lower. For additional details, please see Appendix 3.

To provide some perspective, we compared our outcomes for copper to the study by Elshkaki et al. (2016) who found an expected growth in total copper demand of a factor 2.75 to 3.5 in 2045-2050 in comparison to 2010-2015. Our findings, even though they apply only to a fraction of all applications of copper in society, compare surprisingly well, given that over the same period in the SSP2 baseline we find a growth factor of 2.6 and a factor 3.2 when climate policy is considered. Similarly, the study by Henckens et al. (2014) finds an expected demand growth for annual copper demand of 3.3 by 2050. However, for other metals like lithium for example, we find very different results. For the three lithium applications considered in this study we find an expected growth in annual demand of a factor 10 by the end of the scenario, while the estimates for demand growth by Henckens et al. are similar to that of copper. The difference in growth factors underline the importance of distinguishing different metal applications and of using a high technological detail when making long-term scenarios for metal demand.

3.3.4. Outlook

Our analysis demonstrates that it is possible to link technology-rich output from an integrated assessment model to information on metal composition of products to derive scenarios for global metal demand toward 2050 for three product categories. This means that, given the availability of metal composition data, we can develop detailed scenarios for future metal demand that build upon the broad description of societal changes of existing global scenarios.

Baseline assumptions such as future population and demographic growth, can have a large influence on future metal demand, but the impact of climate policy and associated technology interventions could be even larger. The variations between scenarios can be explained by a changing demand for product categories as a whole (e.g., more cars but less energy), but also by the choice for individual products within these categories (less conventional cars, but more off-shore windmills). Our findings underline the importance of adopting a technology specific approach to metal demand scenarios. Our results support the earlier findings that climate policy will increase metal demand. Not renewable electricity technologies, but cars are the application responsible for the major share of the growth in metal demand. This is true for all considered metals, but especially for lithium and cobalt, and is the result of the transformation of the car fleet into an hybrid/electric one.

All five metals (copper, neodymium, tantalum, cobalt and lithium) face a strong growth in annual demand, regardless of the scenario, mostly as a result of population and GDP growth. The demand for lithium and cobalt is expected to increase much more as a result of the assumption of adopting GHG reducing technologies in the car fleet. The results show the importance of assessing the future metal demand under different socioeconomic frameworks and levels of ambition regarding climate change mitigation, while acknowledging the nonlinear dependencies from both the linkage between affluence and product demand modeled by IMAGE data as well as the development and dynamics of the in use stock of those products. This is, however, only a first step in the development of a comprehensive model.

Further research should first of all focus on improving the knowledge and data on the metal composition of products. The range of both the applications (e.g. construction and infrastructure) and the metals (major metals as well as critical ones) should be expanded to cover all relevant parts of societal metabolism, possibly even accounting for radical technological change. More accurate metal content estimates could be achieved by including numbers on the best available technologies, subcomponents and could even include the dynamics of changing product compositions. Having a more comprehensive coverage in metal demand scenarios would eventually allow a comparison of the findings with data about global resource supply. This may help to answer the question: “are global resources sufficient to meet future demand?”.

A next important step would be to translate demand scenarios into technology specific supply scenarios, including energy demand for mining operations, to enable assessing climate change impacts of resource extraction and production. The split between virgin raw material and recycled metals needs to be modeled to enable us to include resource efficiency policies and circular economy policies in the scenarios and to quantify the benefits of a larger share of secondary production for reducing GHG emissions. In this chapter, we generated the demand for the products using an integrated assessment model. Metal demand was calculated exogenously. A third development step could be to further integrate stock dynamic resource models into integrated assessment models used for energy and climate change scenario assessments. Fully internalizing resource demand in integrated assessment models, including their resulting price dynamics, would increase the coherence and relevance of global scenario exercises considerably.

Appendix

Appendix 1 contains an elaboration of the scenario narratives; Appendix 3 contains additional details to the methodology and product compositions applied in this chapter. The python model code as well as graphs for the resulting metal demand scenarios for all metals using the full range of metal composition data can be found in the supplementary information with the original publication.

4.

Global construction materials database and stock analysis of residential buildings between 1970-2050

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Note: a corrigendum to the article is provided in Appendix 4

Abstract

Huge material stocks are embedded in the residential built environment. These materials have the potential to be a source of secondary materials, an important consideration for the transition towards a circular economy. Consistent information about such stocks, especially at the global level, is missing. This chapter attempts to fill part of that gap by compiling a material intensities database for different types of buildings and applying that data in the context of a scenario analysis, linked to the SSP scenarios as implemented in the global climate model IMAGE. The database is created on a global scale, dividing the world into 26 regions in compliance with IMAGE. The potential use of the database was tested and served as input for modelling the housing and material stock of residential buildings for the period 1970-2050, according to specifications made for the SSP2 scenario. Six construction materials in four different dwelling types in urban and rural areas are included. The material flows related to those stocks are estimated and analysed in Chapter 5, based on companion paper (also exploring commercial buildings) by (Deetman et al. 2020). The results suggest a significant increase in the material stock in housing towards 2050, particularly in urban areas. The results reflect specific patterns in the material contents across the different building types. China presently dominates developments in the global level building stock. The SSP2 projections show a stock saturation towards 2050 for China. In other regions, such as India and South East Asia, stock growth is presently just taking off and can be expected to become dominant for global developments after 2050. The database is created to be used as input for resource and climate policymaking as well as assessment of environmental impact related to residential buildings and assessment of possibilities for urban mining. In the future, we hope to extend it as new data on materials in the built environment become available.

4.1 Introduction

The demand for primary materials has increased significantly during the last decades, driven by industrialisation and economic development. The demand for raw materials is forecasted to continue growing with the increase in global population and affluence (OECD), resulting in a growing in-use stock of materials. An important share of these materials is related to residential buildings. The residential building sector accounts for 30 to 50 % of the material consumption, forming a massive material stock which increased during the past years and is expected to expand further (Steger and Bleischwitz 2011). Demographic changes and increased Gross Domestic Product (GDP) are expected to lead to a growth in the demand for floor area and construction materials respectively (OECD), both per capita and in an absolute sense. The built environment is associated with considerable environmental impacts related to the construction and operation of buildings, ranging from the extraction and transformation of resources to the increased energy demand of the in-use buildings (Augiseau and Barles 2017). At the same time, it represents a huge urban mine of valuable raw materials for secondary resource providers. As yet, there is little insight into these stocks. However, knowledge of these stocks and their dynamics is essential information for a transition towards the circular economy (Müller 2006; Krausmann et al. 2017).

Individual estimations of stocks and flows of building materials on a national and regional level have been performed and described in various studies. However, so far, there is little harmonisation: each of these studies has its focus, uses its data and makes its own methodological choices. Material Flow Analysis (MFA) is the methodology widely used to quantify the materials flows and stocks in the built environment. The two main approaches of material stock assessment can be described as bottom-up and top down (Auping et al. 2015; Urge-Vorsatz and Ksenia Petrichenko, Miklos Antal, Maja Staniec, Michael Labelle, Eren Ozden 2012). The top down approach calculates stocks at the aggregate level, as the result of net-additions-to-stock of a material over a period of time. The bottom-up approach divides the stock into categories of products or applications and estimates the stock by characterizing each of its components with a material intensity ratio (e.g. kg/m^2).

Over the past years, efforts have been made to explore the dynamics of the stock (Olaya et al. 2017; Hashimoto et al. 2007; Müller 2006). For instance, Müller (Müller 2006) applied stock dynamics modelling to forecast the resource demand simultaneously with the related waste generation. Hu et al. (Hu et al. 2010) used Müller's dynamic stock model as a basis for the development of an MFA model which represents the changes in the residential buildings floor area in use in China between 1900 and 2100. A number of studies developed this approach further and explored the material composition of the stock while taking into consideration the generation of construction and demolition waste (Reyna and Chester 2015; Aksoezen et al. 2016; Hu et al. 2010; Hashimoto et al. 2007), as well as the spatial distribution of the stock (Heeren and Hellweg 2019; Tanikawa and Hashimoto 2009; Kleemann et al. 2016; Koutamanis et al. 2018).

Recognising the importance of the environmental implications of material demand, researchers assessed the relationship between the material stock and negative impacts related to the built environment such as energy consumption and greenhouse gas emissions. The most recent studies employ a Life Cycle Assessment (LCA) approach and take into account material and energy flows in addition to emissions related to the life cycle of the building itself (Stephan et al. 2012; Yang et al. 2018; Nemry et al. 2010).

In recent years, a small but growing number of studies has been conducted with the purpose to record, store and analyse information on the material content of the built environment. For example, Gontia et al. (Gontia et al. 2018) developed a material intensities database of residential buildings in Sweden. The study explores 46 buildings and separates them according to their building type, construction type and construction period. In addition, Kleemann at al. (Kleemann et al. 2016) developed a material content database in order to investigate the building stock in Vienna, Austria. Another study compiling a material database along with the investigation the total material stock and flows resulted from demolition waste is Miatto et al. (Miatto et al. 2019), recording detailed information of material intensities of buildings in one city (Padua, Italy). Besides, Heeren at al. (Heeren and Fishman 2019) compiled a material intensities database on a global scale by extracting information from 33 studies and recording approximately 300 data points from those studies.

Studies like these recognise the importance of the material stock but address it in individual case studies at various scale levels. On the global scale, the available literature associated with material stocks in the built environment is limited, and lacking in detail. To address this gap, this chapter aims to summarise the existing knowledge on the residential building stock composition, to integrate it into a global level material content database, and to test the usability of the database by applying it in a global material stocks model for residential buildings. To facilitate using these data for scenario assessments, we do this in relation to the IMAGE (Integrated Model to Assess the Global Environment) Integrated Assessment modelling suite as used by PBL (Netherlands Environmental Assessment Agency) for the assessment of global level climate change scenarios (Stehfest et al. 2014; Doelman et al. 2018; van Vuuren et al. 2017; O'Neill et al. 2017).

This chapter has the following objectives:

- Review of existing studies using different approaches to identify the material content in residential buildings.

- Compile a database of materials used in the construction of residential buildings at the global level in accordance with the IMAGE regions.
- Test the applicability of the database in a scenario context by modelling the past, present and future material stock in residential buildings based on IMAGE data and the materials database, using a bottom-up approach.

This chapter focuses on stocks of materials in residential buildings. In Chapter 5 we add two pieces of research, based on a companion paper (Deetman et al. 2020):

- A stock assessment of materials in various types of commercial buildings
- An assessment of inflows and outflows related to both residential and commercial buildings: the stock of building materials, and waste streams related to demolition.

4.2 Methodology and data

4.2.1 The building stock model

In order to assess the practical applicability of the database, we apply a stock model which aims to determine the in-use stock of construction materials used in the built environment and makes estimations of their future stock. In this chapter, we focus on the in-use stock of residential buildings. The starting point for the stock estimations is the total Useful Floor Area (UFA) specified for 26 world regions, as projected by the IMAGE model and described by Daioglou et al. (Daioglou et al. 2012). Section 4.2.2 describes this in more detail. The UFA is translated into material stock for the period between 1970 and 2050 by using material intensities per square meter UFA. Similar to Müller's model (Müller 2006) the main drivers in the system are population and lifestyle in terms of UFA per capita.

The building stock model distinguishes between urban (including suburbs) and rural areas, as well as different types of residential buildings: detached houses, row houses, apartment buildings and high-rise buildings (van Beers and Graedel 2004; Stephan 2013; Carre and Crossin 2015). The additional variables that feed the model are the distribution of the population over the different dwelling types, the total UFA per building type for the 26 regions, and the material quantity per building type expressed in terms of kg/m^2 UFA.

As mentioned above, the urban/rural distinction is made in the IMAGE-TIMER projections, while the distribution over the different dwelling types is calculated based on national statistics (Energy Information Administration 2019; Australian Government 2019; Eurostat 2019). The material intensity is based on the existing literature, reviewed and documented in a material intensities database. The different calculations steps and data sources are discussed in the next section and are illustrated in Figure 4.1.

4.2.2 The IMAGE model and the SSP scenarios

The IMAGE integrated assessment model (IAM) assesses the interactions between human development and natural systems. The model identifies the impact of energy consumption, land, water and other natural resources use on the natural environment and explores policy options concerning sustainable development, climate change and land use. IMAGE generate scenarios of socio-economic developments based on a set of drivers (Stehfest et al. 2014). The model operates on a global scale, dividing the world into 26 regions. IMAGE has various sub-models on agriculture, land use, energy systems etc. One of these sub-models is the IMAGE Energy Regional model or TIMER. TIMER simulates the composition and dynamics of the energy system and projects its potential future trajectories and greenhouse gas emissions. The main variables used as input for the model are population and sectoral activity (e.g. GDP, Private Consumption) as they are identified as the most important drivers of energy demand (van Vuuren et al. 2007). The model developed in this chapter makes a similar assumption and regards population and lifestyle (in this case expressed as Useful Floor Area (UFA) per capita) as a driving force for material demand.

IMAGE, together with similar IAMs, is used to project the narrative of the Shared Socio-Economic Pathways (SSP) scenarios (Riahi et al. 2017). The SSP scenarios describe five different trajectories of socio-economic development of the world and are used as a basis for assessing climate change and sustainable development at the global level (van Vuuren et al. 2017). Each trajectory has a baseline variant which includes future developments without considering extra climate mitigation policies. Each also has variants with different levels of ambition for reaching climate policy targets. All of the SSP scenarios can be linked to an estimation of the building and material stock. For the purpose of the current study, we consider only the SSP2 baseline scenario which assumes moderate population growth, economic and technological development and contains no specific efforts towards sustainable development. The SSP2 scenario is regarded as the “middle of the road” SSP scenarios, as it projects present trends and developments into the future (KC et al. 2017).

We use the IMAGE framework, and especially the TIMER model, to generate driving force data for stocks of materials in residential buildings. The TIMER model has detailed representation of the development of long term and global residential energy demand across urban and rural households, calibrated to historical data. The residential energy demand is linked to changes in demographic and economic development, as well as lifestyle parameters. These, in turn, affect "intermediate indicators" also generated by TIMER, including household sizes and residential floorspace (Daioglou et al. 2012).

Using the IMAGE framework has the advantage of enabling a link to globally recognised scenarios. Reciprocally, adding our model of the built environment to TIMER will enable to assess development scenarios on their consequences for resource requirements as well as environmental impacts in one modelling endeavour.

4.2.3 Data, variables and calculations

Figure 4.1 illustrates the calculation procedures as well as data sources. More details can be found in Appendix 4 and 5. The model involves four processes, depicted by hexagon and squares in the figure. The starting point for the material stock analysis model is IMAGE/TIMER. TIMER provides population numbers for all 26 regions over the period 1970 – 2050, divided into urban and rural population. TIMER also provides UFA per capita for the 26 regions and the period 1970-2050. By multiplying those, we obtain total UFA per region over time, divided into rural and urban population.

This information needs to be detailed further by allocating the thus obtained UFA data over the four different housing types (detached houses, row houses, apartment buildings and high-rise buildings). TIMER does not deliver that information. We derived multipliers for this allocation process based on population and housing statistics on the one hand, and our literature database on material intensities of buildings on the other hand. Statistics tell us the number of the population living in the four different types of dwellings ($P_{u/r}$), which we recalculate into the share of the population ($Fp_{u/r}$). The literature database provides, for the buildings investigated, square meters of UFA per house of each type, which we recalculate into m^2 UFA/cap and which we assume is an indicator for lifestyle (L) which is building type-specific (d,r,a,h). The UFA/cap varies across dwelling types and is different for rural and urban areas. These we use as weighting factors to obtain multipliers or allocation factors for distributing the total UFA over the different dwelling types (R). The stock or the UFA (S_{ufa}) is then obtained by multiplying the total UFA which we obtained from IMAGE-TIMER by these allocation factors R. This is done per region and per year over the 1970-2050 period, and for urban and rural areas.

Finally, the housing stock in terms of square meters is multiplied with the material intensity data in terms of kg/m^2 of the different materials, to determine the materials stocks (S_m), also per region and per year, and for six different materials.

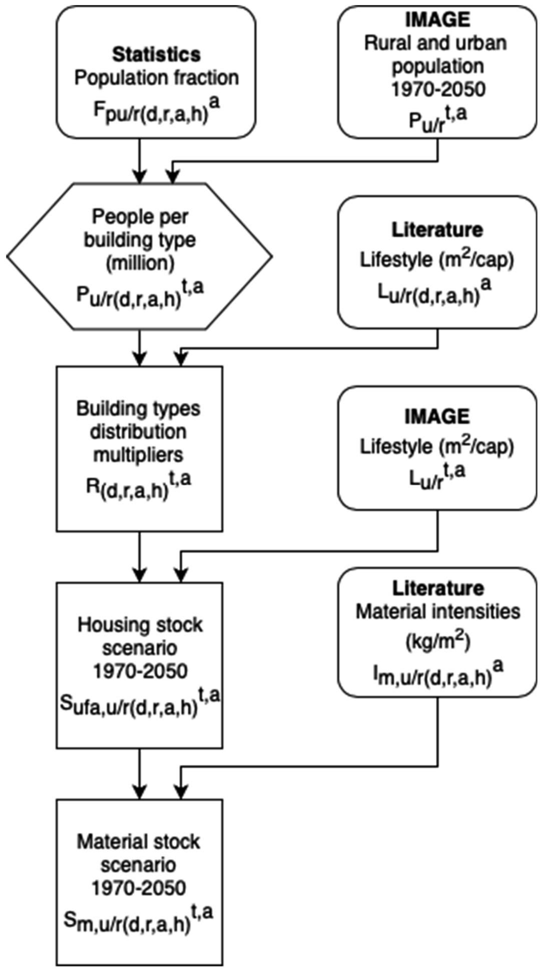

Figure 4.1. *Outline of the material stock analysis model. The rectangles represent the variables or drivers, the squares illustrate the stock and the hexagon is a calculation step. The data sources are written in bold.*

4.2.3.1 Population

The population data – historical numbers and projections until 2050 for each for the 26 regions – are extracted from TIMER, based on the SSP2 scenario, as mentioned earlier. The description of the regional classification can be found in Appendix 1. The historical data are based on United Nations' data and the projections on the assumptions made by the International Institute for Applied Systems Analysis (IIASA) (KC et al. 2017). The future population projections are based on various assumptions related to economic, educational, policy and technical development of the globe and the individual regions, and are shaped by demographic rates and migration flows (Dellink et al. 2017; van Vuuren et al. 2017).

4.2.3.2 Distribution of population over the different dwelling types

Based on the difference in the construction materials, construction practices and even climate conditions, the residential buildings can significantly vary. To increase the reliability of the database and facilitate its usage, we chose to break down the stock of residential buildings into types. Four different building types were identified for the purpose of the study: detached houses, semi-detached/row houses, apartment buildings and high-rise buildings. The distinguishing of the dwelling types is based on a study conducted by Kumar et al. (2015) (Kumar et al. 2015), which recognises the most common types of buildings in Canada and is supported by data from national housing statistics. We made the distinction between apartments and high-rise buildings based on the number of floors: apartment buildings are defined as comprised of separated units within a building with a maximum of four storeys. This assumption is made based on the difference in the construction of buildings above four storeys and the need for reinforcement (steel) which leads to changes in the material composition (SteelConstruction.info 2019). We exclude the informal dwelling types typical for many of the developing countries due to lack of data on the material quantities in these buildings. We acknowledge their importance and we hope more building types will be incorporated in the database in the future.

Furthermore, we acknowledge that not only the materials but also the average house size, in terms of square meters per capita, is different for each building type (i.e. detached houses tend to be more spacious than apartments) and even between urban and rural areas. We attempt to account for this by applying a weighted disaggregation of the stock based on regionally specified average per capita floor space, as found in reviewed literature discussed in Section 4.1. For further information on the disaggregation, please refer to Appendix 4.

Finally, another important note is that we consider that the population is not equally distributed throughout the four different housing types. In order to calculate the percentage of people living in different types of dwellings, data on the distribution of the population by dwelling type is collected from statistical sources. This type of information is not available at the global level. We used statistical information from Europe, North America, Australia and Japan, respectively from Eurostat, EIA's Office of Energy Consumption and Efficiency Statistics (Energy Information Administration 2019), the Australian Bureau of Statistics (Australian Government 2019) and Statistics of Japan (EStat Japan 2015). The data can be found in Table 4.1.

The statistical information presented in Table 4.1 originates from a selection of developed countries. For most regions, such data were not available. For these regions, we applied global averages which we calculated from the available information. The representativeness thus may be questioned. In the future, as more data become available, the quality of these assumptions can be improved.

Table 4.1. *Population share (P_d) by building type according to various statistical offices.*

Region	Area	Detached Houses	Semi-detached / Row Houses	Apartment Buildings	High-rise Buildings	Comments
North America	Urban	52.7%	5.7%	7.1%	13.8%	Based on (Energy Information Administration 2019)
	Rural	19.8%	0.3%	0.5%	0.1%	
Western Europe	Urban	15.9%	22.3%	17.3%	20.0%	Based on (Eurostat 2019)
	Rural	13.6%	6.1%	3.6%	1.3%	
Eastern Europe	Urban	19.4%	3.8%	5.2%	29.8%	Based on (Eurostat 2019)
	Rural	34.2%	2.4%	2.1%	3.1%	
Australia	Urban	21.9%	40.3%	16.0%	5.9%	Based on (Australian Government 2019)
	Rural	14.5%	0.8%	0.7%	0.0%	
Japan	Urban	37.1%	1.2%	17.7%	12.9%	Based on (EStat Japan 2015)
	Rural	27.5%	0.5%	2.8%	0.3%	
Average	Urban	29.4%	14.7%	12.6%	16.5%	Applied to other regions
	Rural	21.9%	2.0%	2.0%	1.0%	

Note: Though the numbers are expressed as the share of the total population, our model maintains the urban and rural population fractions as prescribed by the IMAGE elaboration of the SSP2 scenario, so only the relative fraction within the urban or the rural population is used to disaggregate stock across the four building types.

4.2.3.3 Lifestyle

The floor area per capita is one of the United Nation's indicators to trace the progress towards meeting the goals of the Global Strategy for Shelter (UN-HABITAT 2013). We, therefore, use the floor area (UFA) per capita as an indicator of lifestyle. An increase in this indicator implies an improvement in the living conditions of the population.

The per capita floor area (L) provided by the IMAGE-TIMER model increases towards 2050 for all regions. The minimum values found in the set are for urban India: 7 m^2 per capita for the present (average of 2000 to 2015), increasing to 16 m^2 per capita towards the end of the modelling period (2035-2050). On the other end of the scale we found rural United States, currently showing an average of 57 m^2 per capita, which increases to 63 m^2/cap towards mid-century.

Both the population share and the average per capita floor space for different building types (four building types in urban and rural areas) are static assumptions. This is most probably not realistic; however, we have no grounds to make different assumptions. In the scenario calculations, changes in this distribution originate only from urbanisation: an increased share of urban areas.

4.2.3.4 Materials intensity database

No official statistical datasets are available for material quantities in buildings. There is, however, a modest body of studies focused on the material contents in residential buildings (Gontia et al. 2018; Miatto et al. 2019; Heeren and Fishman 2019). We used these studies to create our database, by translating this information into material intensity indicators (I_m): the material content per square meter UFA. We included six materials in our database: concrete, steel, aluminium, copper, wood and glass.

In order to create the database, a list of publications was reviewed and a total of 56 studies was selected from this list to be included. The studies selected for the database were chosen based on their purpose, spatial and time scale, materials studied and the level of detail. The literature research process is described below.

First, we reviewed publications focused on compiling material intensities data for buildings. For the purpose of this chapter, we used two studies containing material intensities databases (Gontia et al. 2018; Heeren and Fishman 2019). One of the studies has a national scope as it includes a database of material contents in residential buildings in Sweden (Gontia et al. 2018). The other presents a database at the global level (Heeren and Fishman 2019).

Second, we explored MFA studies including flows and stocks of residential buildings and construction materials. The studies investigating stocks were preferred given that this chapter focuses on stocks and does not look into material flows. Eleven studies from this category were included in the database (Condeixa et al. 2017; Johnstone 2001; Mesta et al. 2019; Tanikawa and Hashimoto 2009; Huang et al. 2013; Stephan and Athanassiadis 2018; Reyna and Chester 2015; Hashimoto et al. 2007; van Beers and Graedel 2004; Gontia et al. 2018; Miatto et al. 2019). Some of them assess materials in the existing in-use building stock at a local scale (Johnstone 2001; Condeixa et al. 2017; Reyna and Chester 2015; Miatto et al. 2019). Other papers have a more general character as they focus on the material stock in entire countries (Hashimoto et al. 2007; van Beers and Graedel 2004). The assessment of the spatial distribution of the material stock using Global Information System (GIS) is the purpose of four of these studies (Mesta et al. 2019; Tanikawa and Hashimoto 2009; van Beers and Graedel 2004; Kleemann et al. 2016). Estimating the material in- and outflows by using data on the material demand together with construction and demolition activities is the aim of several other papers (Stephan and Athanassiadis 2018; Huang et al. 2013).

Third, studies dealing with the LCA of residential buildings were reviewed. We identified various studies conducted with different purposes in the broad context of energy efficiency, efficient use of materials and the possibilities for their recovery (Zhang et al. 2014; Reza et al. 2014; Blanchard and Reppe 1998; Mosteiro-Romero et al. 2014; Evangelista et al. 2018; Oyarzo and Peuportier 2014; Ortiz-Rodríguez et al. 2010; Henry et al. 2014; Ezema et al. 2015; Nemry et al. 2008; Asif et al. 2007; Cuéllar-Franca and Azapagic 2012; Buyle et al. 2015; Pajchrowski et al. 2014; Atmaca and Atmaca 2015; Stephan and Stephan 2014; Asif et al. 2017; El Hanandeh 2015; Pinky Devi and Palaniappan 2014; Bansal et al. 2014; Sharma and Marwaha 2015; Ramesh et al. 2012; Shukla et al. 2009; Lee et al. 2017; Jeong et al. 2012; Lee et al. 2015; Chen et al. 2001; Li et al. 2016; Su and Zhang 2016; Yang et al. 2018; Jia Wen et al. 2015; Abd Rashid et al. 2017; Utama and Gheewala 2009, 2008; Suzuki et al. 1995; Rauf and Crawford 2015; Carre 2011; Aye et al. 2011; Fay et al. 2000; Bhochhibhoya et al. 2017; Kumar et al. 2015; Reyna and Chester 2015; Stephan 2013; Johnstone 2001; Carre and Crossin 2015). Whenever they included data on the material composition of buildings, we used them in our database. We found that the most abundant sources are the LCA studies estimating the environmental impact of residential buildings (Kumar et al. 2015; Cuéllar-Franca and Azapagic 2012; Evangelista et al. 2018; Jeong et al. 2012; Ortiz-Rodríguez et al. 2010; Oyarzo and Peuportier 2014) and investigating the performance of the residential buildings in terms of energy as well the possibilities for energy optimisation using alternative materials (Lee et al. 2017; Pajchrowski et al. 2014; Blanchard and Reppe 1998; Zhang et al. 2014; Kumar et al. 2015; Mosteiro-Romero et al. 2014).

Next to those studies, we included various publications specifying material intensities of particular houses. These publications were often useful since they are very specific and contain field data. The downside of these papers is that they lack representativeness. If necessary, we recalculated the data from these studies into kilograms of specific materials per square meter of UFA. The calculation steps can be found in the database, provided with the original publication. A full list with all of the papers can be found in there as well.

We used those studies to compile a database containing material intensities (kg/m^2) per building type and region. For 9 out of the 26 regions, the review did not yield any relevant studies. When no information was available for a specific region, material or housing type, we applied a global mean value based on the other regions with available data, as shown in Table 4.2 in the Results section.

4.3 Results

In this section, we present the main results. All numbers and further details can be found in Appendix 4 and in Chapter 5 (Deetman et al. 2020).

4.3.1 The database

The data collected during the study resulted in a database containing a summary of the reviewed literature. The database contains information on the material content of the six materials for the four building types in kg per m^2 UFA. In addition, the database contains the floor areas of each building type that we calculated from the TIMER info and the distribution over the different types of buildings. The results of the calculations are presented in the supplementary information with the original publication.

4.3.1.1 Material content

Table 4.2 depicts the values for the mean material contents across the four different dwelling types for six different construction materials at present. When calculating the material quantities, we did not distinguish between rural and urban areas assuming that the material intensities in the residential buildings in both areas are similar. More detailed information related to the different regions is presented in Appendix 4.

Steel, concrete and wood appear to be the materials most commonly included in studies on material intensities. For aluminium, copper and glass the number of data points is much lower.

The material intensities show high variability. This could be due to the variability in architecture and construction. However, some materials have a more standard use than others. Concrete, wood and steel are used for the structure of the house. Copper is used for wiring and piping, and sometimes ornamental. Glass is used for windows and sometimes, in high rise buildings, for surfaces of buildings. Aluminium is used for window frames and also, widely varying, as an ornamental material. We can, therefore, expect the data for aluminium and glass to show the highest variability.

The studies taken into consideration in this chapter show that concrete is the main material in terms of quantity used in the construction of houses (Abd Rashid et al. 2017; Asif et al. 2007; Cuéllar-Franca and Azapagic 2012; Ortiz-Rodríguez et al. 2010). Concrete intensity is high in all housing types (often > 1000 kg/m^2). The values in Table 4.2 show that steel is mainly used in apartments and high-rise buildings. Intensities in detached and row houses are much lower. Apartments and high-rise buildings use steel as a structural material, either in columns and beams as such, or as a part of reinforced concrete (Zhang et al. 2014; Mesta et al. 2019). The results for wood show a higher intensity for detached houses. We assume that these results are mostly due to the fact that the single-family houses presented in the database are mostly wood-based constructions (Pajchrowski et al. 2014; Oyarzo and Peuportier 2014). For copper, as well, detached and semi-detached houses show the highest density. This may be explained by the higher density in plumbing and wiring for these more spread-out housing types. Finally, the glass content in detached houses and high-rise buildings comes out higher compared to the quantities in the remaining dwelling types.

Table 4.2. *Mean values of the material content by housing type expressed in kg per m² (I_m). In the brackets, the number of data points is presented. They describe the material content in the 56 studies reviewed in our database. Some studies describe material content for multiple houses or case studies, thus leading to more than 56 data points in some cases.*

	Steel	Concrete	Wood	Copper	Aluminium	Glass
Detached Houses	35.63 (87)	846.33 (104)	53.07 (121)	1.73 (13)	3.56 (19)	2.68 (43)
Row Houses	32.89 (8)	1208.13 (11)	34.97 (10)	0.01 (4)	0.23 (1)	1.07 (1)
Apartment Buildings	97.36 (53)	955.92 (84)	37.17 (82)	0.31 (22)	1.94 (17)	6.35 (33)
High-rise Buildings	116.98 (30)	910.21 (56)	54.48 (36)	0.01 (1)	2.20 (6)	4.42 (25)

Notes: For region-specific details, please see the SI.

Table 4.2 also shows the number of data points (between brackets) from the 56 studies in our database, that are used to calculate the mean of the material content and the material stock. It is important to note that the data points do not correspond to the number of studies addressing certain material. They reflect the data on individual houses available in the database.

4.3.2 Stock

Based on the information from the previous section compiled in the database and the data delivered from the IMAGE-TIMER model the development of the housing and material stock (S_{ufa} and S_m) was calculated.

4.3.2.1 Housing stock

Figure 4.2 presents the housing stock development in square meters for the IMAGE regions according to TIMER for the period 1970 - 2050, distributed over the different housing types. The 26 regions are grouped in 3 different categories related to their pattern of development: fast-developing regions which include South American countries, Africa and Asia, steadily developed regions comprised of North-America, Europe, Oceania, Russia and the Middle East, and finally China and Japan. China and Japan are grouped based on the similarity of the projected development of their total housing stocks until 2050: these countries are the only ones with a stock that declines towards the end of that period.

Figure 4.2a represents the urban areas and indicates consistent growth throughout the modelled period. According to the projections, the growth is particularly rapid in the fast-developing regions. More surprising is the steady growth in the housing stock in developed regions. This phenomenon originates from the projections made by the SSP2 scenario assuming that the urban population will still increase, as will the UFA/cap, although slowly (van Vuuren et al. 2017). The fast growth of the in-use floor space in the fast-developing regions indicated the improvement in the living standards in these lower-income countries (Wang et al. 2017).

Figure 4.2b, illustrating the rural areas, shows different patterns. As one would expect the square meters for detached houses dominate. It is interesting to highlight that the housing stock of the steadily developed countries as well as of the China and Japan group is expected to decrease in the period after 2030. This phenomenon can be explained with the growing urbanisation and the trends related to the relocation of the population towards urban areas, including the suburbia (van Vuuren et al. 2017).

4.3.2.2 Material stock

By combining the housing stock in terms of floor space calculated for the period between 1970 and 2050 and the information on the material contents delivered from the database we were able to calculate the material stock. This section presents a few of the results that can be obtained from the material stock time series. Figure 4.3 presents the global material stock distributed between urban and rural areas in 2018 and 2050. Concrete dominates the total stock of materials, representing over 90% of the total weight. Furthermore, the model results show that the stock of materials in residential buildings is expected to almost double until 2050, and will be located increasingly in urban areas. In rural areas, the stock of materials is not expected to grow so much, and in some cases may even decline somewhat. Only for copper, the scenario results show an increase in rural areas. This result suggests an interpretation related to the structure of the housing stock: detached houses have a higher copper intensity than the high-rise and apartment buildings. It may also be a consequence of limited data availability. The data points for copper are scarce and the results based on a limited set of studies.

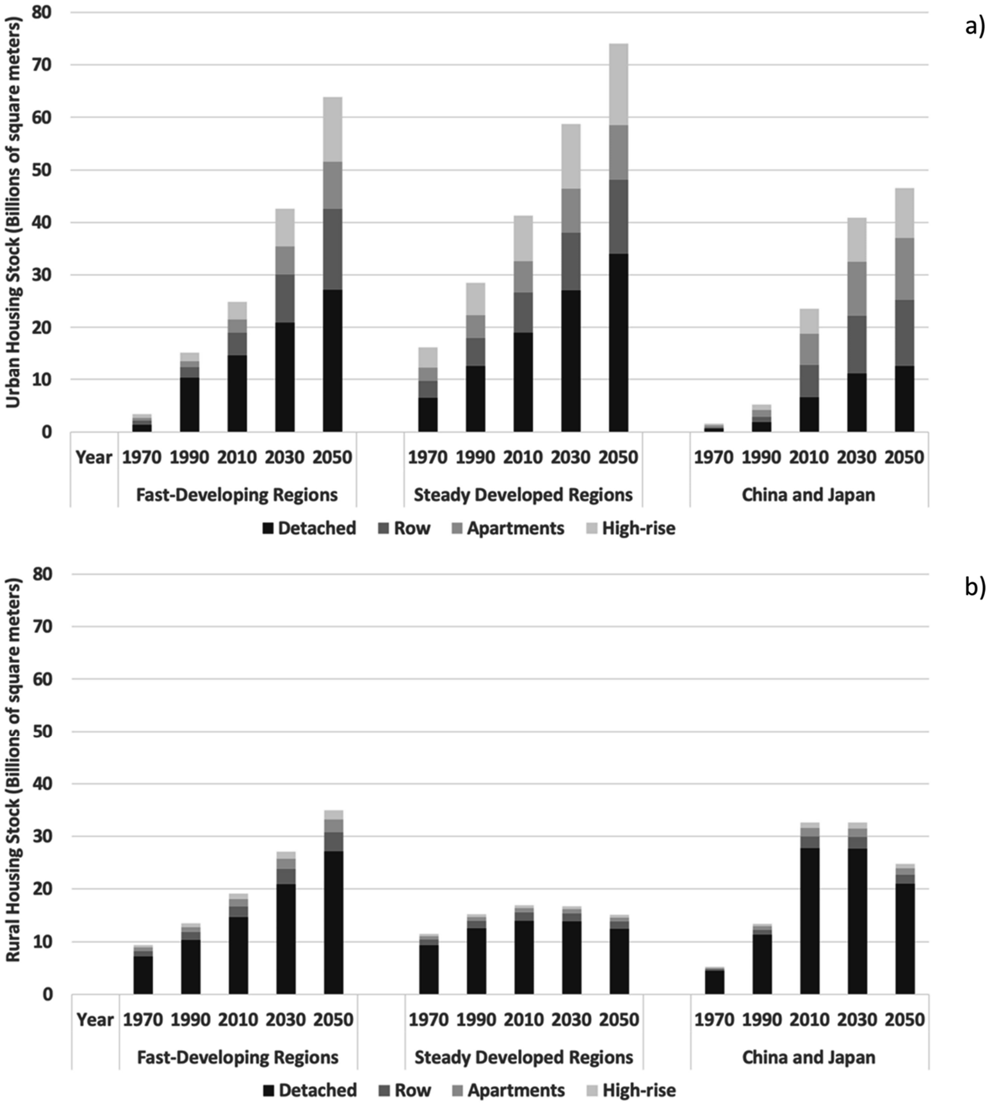

Figure 4.2. *Urban (a) and Rural (b) housing stock represented in square meters across four dwelling types and three regional categorisations. The graph on the top represents the urban areas while the bottom one depicts the rural areas. The countries representing the fast-developing regions are all South American countries, Africa and Asia, except China and Japan which are placed in a separate category, to show their distinct stock dynamics. The steadily developed regions consist of North-America, Europe, Australia, New Zeeland, Russia and the Middle East. The graph on the top illustrates the housing stock in urban areas whilst the bottom figure shows the stock in the rural areas.*

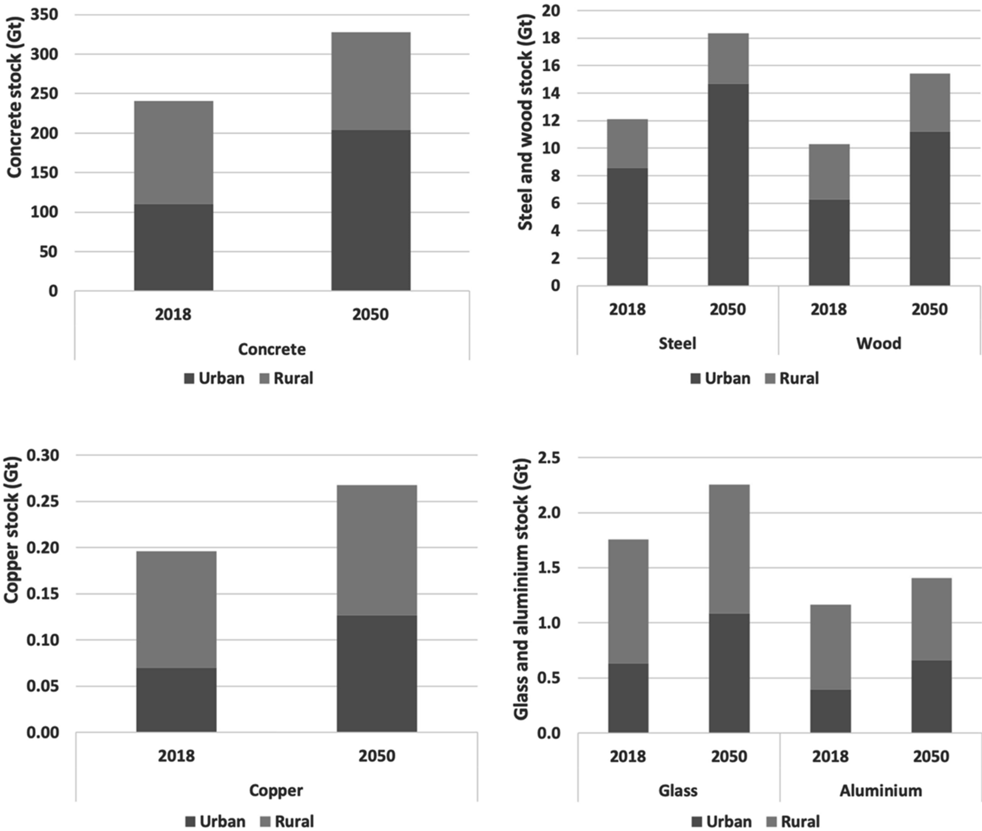

Figure 4.3. *Material stock in urban and rural areas on a global level. Current values and predictions for 2050, for concrete, steel, wood, copper, glass and aluminium.*

In general, the coverage of the database leads to different reliability of the results for different regions and different materials, and the results should, therefore, be used with caution. We elaborate on this issue in the discussion section.

Figure 4.4 illustrates the development of the steel stock as one material which plays an important role in the process of urbanisation. The information could be relevant for urban mining and usage as secondary material (Stephan and Athanassiadis 2017; Schebek et al. 2017). The results show the rapid development of China’s housing stock since 1980, and especially since 2000, and the concurrent great increase in the steel stock in residential buildings. After 2035 a saturation of the stock is visible and near mid-century, the growth of the steel stock in Chinese residential buildings is expected to cease. Still, model results indicate that a significant part of the global steel in-use stock can be found in China in 2050.

China is a country with a huge population showing rapid development. According to the SSP2 scenario, roughly 35% of the housing stock in square meters will be located in China in 2050, and the share is even higher for the steel-intensive high rise and apartment buildings. None of the other 26 areas shows a pattern like China. All have much slower growth, although for India and Africa an acceleration can be detected near the end of the model period. The stock development of rest of the studied materials is shown in the supplementary information with the original publication.

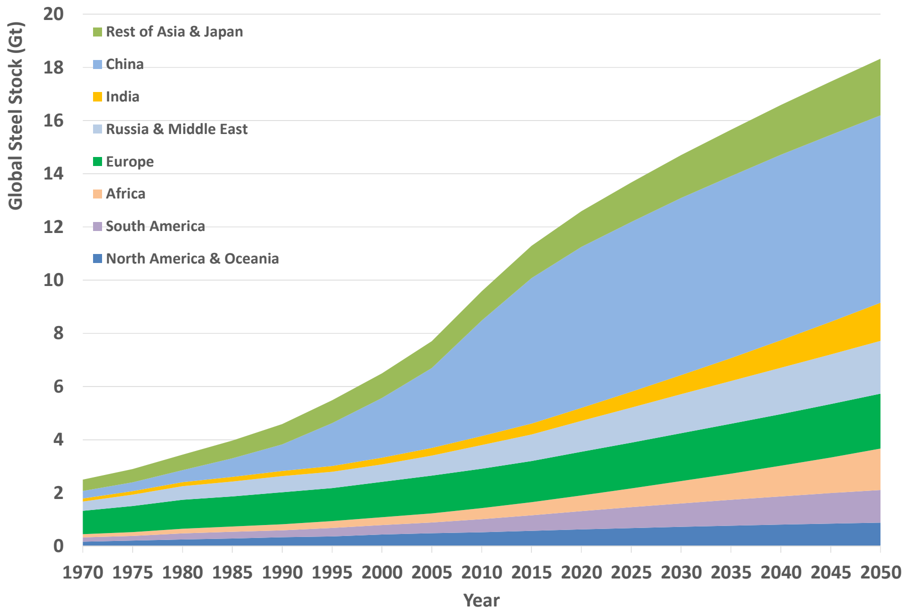

Figure 4.4. *Global stock of steel across ten regions for the period between 1970 and 2050.*

Figure 4.5 shows the development of the stock of five materials in China (left) and India (right). The results show a significant difference in the stock behaviour across the two countries. The graph depicting China illustrates the same trends as in Figure 4.4 – rapid growth from 2000 onward, and saturation or even decline of the stock for all materials near 2050. The graph representing India shows a rapid growth for all materials, which is not expected to slow down before mid-century. Please note the different scales of the y-axes of both figures.

4.3.3 Data uncertainty and sensitivity analysis

Figure 4.6 shows the distribution of the material intensity data by illustrating the 20th and 80th percentiles as well as the mean and the median value for each building type and material. If a study has more data points describing the same building type and material, we use the mean of the values within that study.

We chose to present the data distribution in percentiles. The percentiles allow us to display the number below which 20 % and 80 % of the values can be found. In Figure 4.6a, a higher range of the data set can be observed. The distance between the minimum and the maximum value in relation to the mean is large for each of the building types, which shows the diversity in the data and available construction methods. On the contrary, in Figure 4.6b the steel in detached and row houses depicts a smaller range of the data in the available studies.

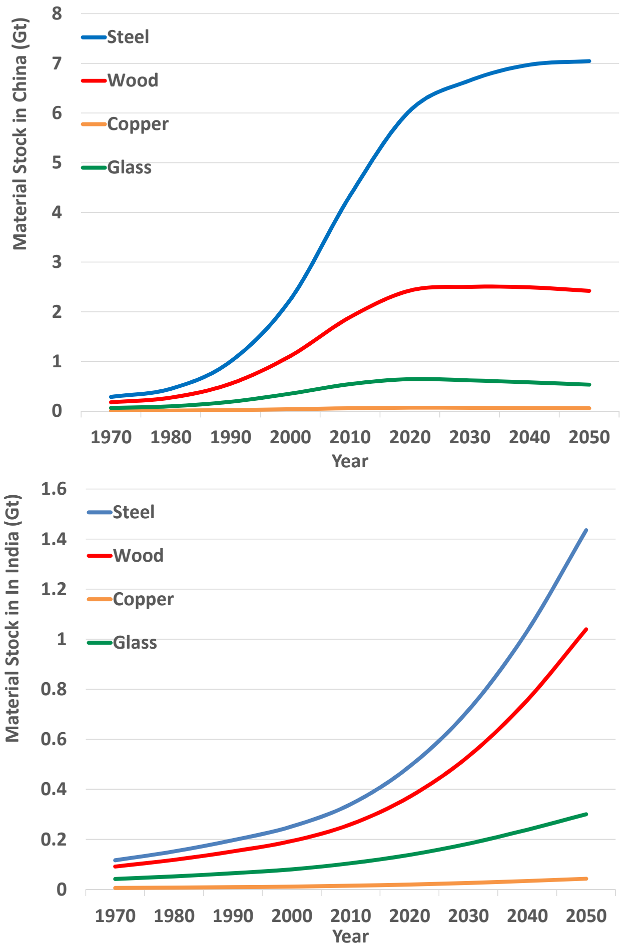

Figure 4.5. *Four materials in residential housing stock in China (top) and India (bottom)*

The material content per building type, the useful floor area per capita, and the population are the main drivers in the model described in the previous section. There is a certain degree of uncertainty related to the development of all three of these variables, therefore it is important to estimate the impact of these drivers on the model outcomes (Hong et al. 2016). The UFA/cap and the population forecasts are generated by the IMAGE model. Since these data are also used in other assessments, notably in the scenarios for climate change, we will not include those in our sensitivity analysis. Instead, we focus on the sensitivity of the outcomes for different estimates of the material content per square meter of UFA.

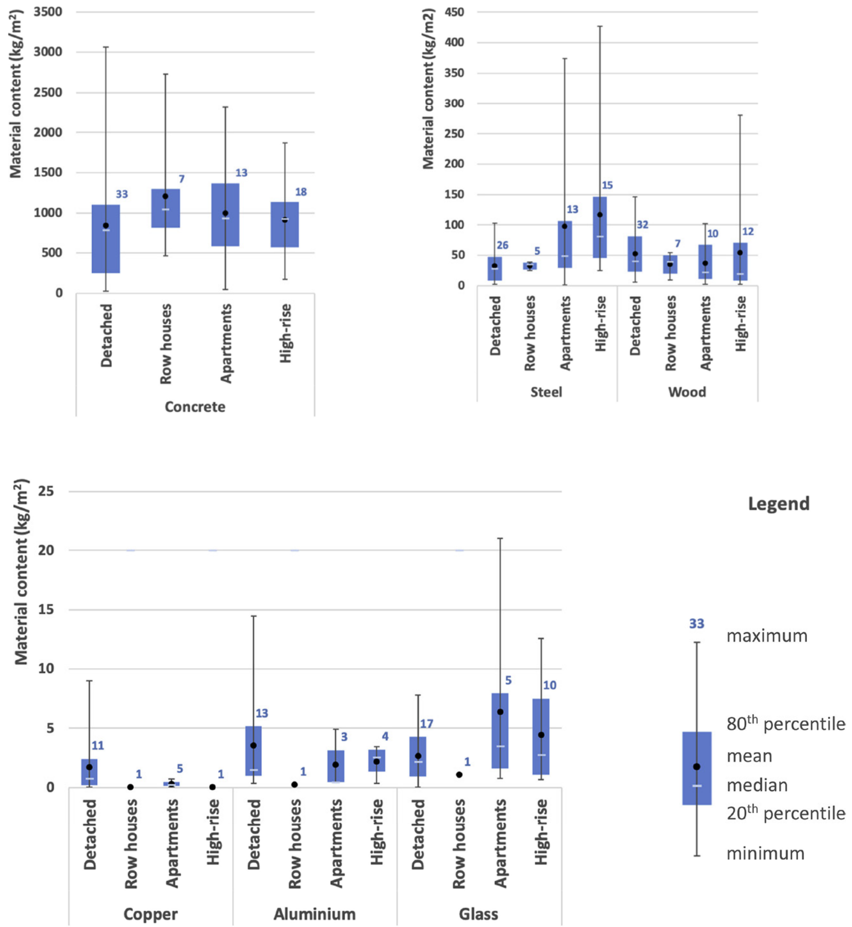

Figure 4.6. *Percentile distribution of the data in the material content database (in kg/m²). The graphs show the 20th and 80th percentile, the minimum and the maximum values as well as the mean and the median of all available studies. Indicated above each bar is the number of studies reporting on a particular material and building type. The graphs present the data distribution for concrete, for steel and wood and copper, aluminium and glass.*

Figure 4.6 shows the influence of changes in the material intensity parameter on the stock model. We show the 20 percentile, 80 percentile and the median material content values in addition to the mean value which we have been applying as a standard. The 20 and 80 percentile values provide a reasonable bandwidth for our results – based on the present state of knowledge, the "true" value will probably be in that range. The median could be used as an alternative for the mean value. Detailed results are presented in Appendix 4. Median, 20th percentile and 80th percentile refer to the database at a global level.

The 20th and 80th percentile values show a wide range, with a factor 4 difference between lowest and highest values. A remarkable finding is that both mean and median values are closer to the 20th percentile values than they are to the 80th percentile value. That would suggest that the high material content values from the database represent more a-typical buildings.

The sensitivity analysis shows a difference between the mean and median values: for most of the materials, the median values are lower than the mean. This, too, suggests some outliers on the high side of the spectrum. An argument could be made to use the median values instead of the mean. We decided not to do that – in a field where there is still so little information, we do not know whether the very high values are exceptional (to be excluded) or just part of the normal range (and therefore to be included). More research will hopefully clarify this point.

In all, we conclude that the database on material contents for doing such stock assessments is sufficient to arrive at order-of-magnitude credible values, but still is limited and could benefit from further expansion of data and details regarding regional differentiation and differentiation over the housing types. This is a challenge for future database building, to be taken up by researchers, but also by architects, construction companies and demolishers.

4.3.4 Material stock comparison with literature

The values for the Chinese in-use steel stock show very high values in comparison with the rest of the world regions. To check the reasonability of our estimates, we compared our results with previous steel stock estimations for China (Pauliuk et al. 2013a, 2013b; Hatayama et al. 2010). The results can be found in Appendix 4. We conclude from it that our estimates are, although not identical, still in the same order – if the difference would be relevant, our estimates appear to be on the low side.

4.4 Discussion and conclusion

In the above, we reviewed a collection of studies on material content of the residential built environment and, consequently, developed a database of the material intensities. We used this information together with the output of the IMAGE-TIMER model to generate data on the material stock of residential buildings at the global scale, for the period 1970 – 2050.

The database contains material content data per square meter of useful floor area of residential buildings for six materials, four housing types, and urban and rural areas, for the 26 IMAGE world regions. The database is still limited in the number of samples it includes. We have not been able to find data for all 26 IMAGE regions. However, we considered the database to be sufficient to calculate global mean values for each housing type. For those regions where we did not have sufficient data, we used these global means. In addition, we observed a large range in the material content data per housing type. One reason for that might be the large variety in types of buildings and materials within and between regions, that is insufficiently documented. Another reason might be the limited number of data points: as the number of studies is not that large, it may be that they do not combine to a representative sample.

We assessed the applicability of the material content database in a scenario context by generating stock developments over time of six major construction materials: concrete, wood, steel, aluminium, copper and glass using the SSP2 scenario as a background. Changes (mostly increases) of the material stocks in residential buildings originate from three types of developments such as specified in IMAGE-TIMER:

(1) changes (mostly growth) in population leading to a changed (mostly larger) requirement for residential buildings
(2) changes (mostly increase) in affluence resulting in a changed (larger) UFA per capita over time
(3) urbanisation leading to a different distribution over the four types of residential buildings.

The database in our view represents a good first start of data collection required for scenario analysis. It is, nevertheless, far from complete and has strong limitations we hope can be overcome in time.

(1) There is a notable difference between the per capita UFA data from TIMER, and the UFA/cap emerging from the material intensity database. An explanation may be that the TIMER data include very small houses (including shacks and shanties), which are not represented in the studies investigating material content or material intensities of residential buildings. This implies that the material stocks as calculated by us could be

an overestimation. Since we use the IMAGE-TIMER output for per capita floor space, this overestimation would not be the result of assuming too high values for the per capita floor area, but only of too high material intensity values.

(2) In general, developed countries are overrepresented in the material intensity database. This may not be a major problem for high rise buildings or apartment buildings, as these are not very different all over the world. For detached houses, which are generally much more traditional and differ greatly in their material composition throughout the world, the largest variations may be expected which may not be captured adequately in our database.

(3) The material intensities in the database are static. Although there is some evidence that material intensities in the built environment are subject to changes over time (Tanikawa and Hashimoto 2009; Kleemann et al. 2016; Heeren and Fishman 2019), we found insufficient data to enable including such changes in our model. Moreover, the data from IMAGE-TIMER refer to stocks and not flows, which means we have no information on the period in which the houses were actually built. We are thus presently unable to include developments in construction technologies and building design in our scenarios.

(4) The allocation of dwellings over the four housing types in urban and rural areas is static and relies on data for the present situation. Changes over time in this allocation have not been included in the scenario analysis.

All this implies that the uncertainties in the material intensities database are large. By making it available, we hope that results from future studies will be added, making it more suitable for answering further research questions related to resource scenario development and urban mining.

Despite these limitations, the results at the aggregate level presented above show that the database provides useful information and can be used in a scenario context. As a result of population increase, development and urbanisation, we see a considerable increase in the stock of residential buildings at a global level, with a concurrent increase in material stocks. For some materials, the growth of the stock appears to be larger than for others. The stock of steel, for example, is shown to rise by 50% by our calculations, while the stock of copper increases only with 25%. The highest growth worldwide occurs in apartment buildings and high-rise buildings in urban areas, indicating urbanisation as the main reason for this difference.

Our results show a difference in stock behaviour between the different regions. In developed countries, the stock is generally slowly rising. China dominates global developments in the coming decades by its rapidly rising stock, but this growth is expected to level off towards 2050. In regions such as India, South East Asia and Africa, the stock is starting to rise now and according to our assumptions will continue to do so, probably long after 2050. These regions may become dominant for global developments after 2050.

Given the abovementioned uncertainties and data gaps, we have to conclude that the database we present is open for improvement. Nevertheless, we think it could already now be used to estimate future stock developments, and could be used as a starting point to assess options for reducing the environmental impacts as well as the possibilities for life span increase, recycling and using secondary materials in construction. These stock developments are a very important input for estimates about the flows of construction materials: the demand for construction materials, and the generation of demolition waste. How stock dynamics can influence flows is explored in the following Chapter 5 (Deetman et al. 2020).

Such a stocks-and-flows database is very relevant input for global level assessments of policies on resource efficiency and circular economy. The size of the urban mine and what is coming out of it determines the potential for a circular economy. Having information on the different building types also allows for a better estimate of energy use in the built environment, which in turn is relevant to assess greenhouse gas emissions. Having information on the demand for materials enables assessing environmental impacts related to materials extraction and production, thereby providing a starting point for generating and assessing options to reduce these impacts.

So far, we have only included the SSP2 baseline scenario in our calculations. The same approach is applicable also for the other SSP scenarios. Especially when the projections on population and affluence differ, we expect the stocks of materials in the built environment to be different. The SSP scenarios may also provide a baseline to enrich with assumptions on resource efficiency or a circular economy, showing how policies in that direction may affect material demand. We hope to address these issues in future work. Having knowledge about the urban mine and the materials that will be available for secondary production allows assessing to what extent, and when, it will be possible to close cycles of those major construction materials. By the link to an IAM on climate change, it will thus become possible to assess the climate benefits (and drawbacks) of circular economy policies.

In conclusion, the results of the research show that, despite the rather limited information, we have been able to generate scenarios for the development of in-use stocks that make sense, and that can be used in a modelling environment that is relevant at a global level. The current study provides a foundation for the development of a more comprehensive material intensities database. By making the database available, we hope it will grow in future to allow for more detailed and more reliable assessments.

Acknowledgements

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Appendix

Additional information with regard to the analysis and the assumptions can be found in Appendix 4.

5.

Modelling global material stocks and flows for residential and service sector buildings towards 2050

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Note: a corrigendum to the article is provided in Appendix 5

Abstract

Residential buildings and service sector buildings have an important contribution to climate change, directly via energy use in these buildings and indirectly through construction activities and the production and disposal of buildings materials. In this chapter, we introduce a model that looks at total global building stock for 26 regions between 1970 and 2050 and calculates the floor space and building materials both in new buildings and in demolished buildings. For residential buildings, we build upon the work of Marinova et al. (2020), who used a building material database to come up with scenarios for materials in the residential building stock. This chapter adds two things. First, we introduce a new regression-based model for service building floor space, recognizing 4 different types of service-related buildings. Secondly, we use a dynamic stock model, based on lifetime distributions found in literature, to calculate the construction (inflow) and demolition (outflow) of building floor space for both residential and service-related purposes. We combine this with data from the building material database to come up with scenarios for the annual demand for construction materials worldwide as well as an estimation of the availability of waste materials after building demolition towards 2050. The model can thus be used to assess the potential for closing the material cycles in the construction sector, while distinguishing urban and rural areas explicitly. The results show that demand for construction materials will continue to increase in most regions, even in developed countries. Global demand for steel and cement for the building sector is estimated to be 769 Mt/yr and 11.9 Gt/yr respectively, by the end of the modelling period. This represents a respective growth of 31% and 14% compared to today. Drivers behind this are an expected growth of global residential building stock of about 50%, and a growth of about 150% in the building stock for services. Our model projects that by 2050, only 55% of construction-related demand for copper, wood and steel could potentially be covered by recycled building materials. For other materials the availability of scrap may be higher, reaching up to 71% of new demand in the case of aluminium. This means that in most regions urban mining cannot cover the growing demand for construction materials.

5.1 Introduction

The construction of buildings is the main driver for demand of bulk material such as steel (Pauliuk et al. 2013), cement (Cao et al. 2017) and aluminium (Liu et al. 2012). Assessing the development of the building stock over time can thus help to assess trends in demand of construction materials in the future. This is critical to understand impacts on material cycles and the possibility of urban mining (Krook and Baas 2013) and the circular economy (Ghisellini et al. 2016). In addition, because the production of construction materials is energy intensive (van Ruijven et al. 2016; Gutowski et al. 2013) this will help to assess future energy demand and consequential carbon emissions (Pauliuk and Müller 2014; Müller et al. 2013).

Existing literature on the future development of building stocks is often focused on the consequences for direct energy consumption (typically 20% of total end-use energy (Sartori et al. 2009; Kavgic et al. 2010; Vásquez et al. 2016). Studies that, in contrast, describe the materials used in the building construction often focus on a single country or region such as China (Cao et al. 2018; Huang et al. 2013; Hu et al. 2010) or within the Europe for example (Wiedenhofer et al. 2015; Sandberg et al. 2014). Some studies only address the historic development of in-use stocks (McMillan et al. 2010; Krausmann et al. 2017; Tanikawa et al. 2015), while the basis for studies dealing with future stock predictions varies from fixed average growth rates (Wiedenhofer et al. 2015), historic stock (Fishman et al. 2016) to population based growth, intensity of use curves (Hatayama et al. 2010) or by explicit modelling of lifestyle changes by modelling per capita floor space development (Müller 2006; Daioglou et al. 2012). Many of these different methodological approaches to modelling the stocks and flows of construction materials are summarized in a recent review by Augiseau and Barles (2017), who also identify other differences between studies such as the materials under investigation or the building categories covered (e.g. residential buildings, or a broader definition), again emphasizing that studies either have a regional or local focus, and at the global scale, often focus on one material only (Hatayama et al. 2010; Liu et al. 2012).

There is thus a need for a global description of the long-term development of materials in the building stock based on a more systematic coverage of regions and materials and a more explicit depiction of building categories, including non-residential buildings. However, the availability of literature on scenarios for non-residential building demand is scarcer than literature on residential buildings. Some studies model regional developments (Teh et al. 2017; Bressand et al. 2007; Coffey et al. 2009), but global scenario studies which discern non-residential buildings often lack the detail to be used in scenarios for material demand (Deng et al. 2012). The inferior coverage of non-residential buildings also translates to the data availability of material content in non-residential buildings. For example, the majority of data points in a recently published database for material intensity research is on residential buildings (Heeren and Fishman 2019).

This chapter documents a first attempt to achieve a more systematic coverage of material demand scenarios in buildings by building upon recent work by Marinova et al. (2020). They used the available model output from the IMAGE integrated assessment model (Stehfest et al. 2014) to develop a scenario for the stock of 6 building materials in 4 different residential building types, based on the physical demand for residential floor space (in square meters) towards 2050, which was originally described by Daioglou et al. (2012). While the original IMAGE model provided residential floorspace (stock) in both urban and rural areas, data on several regions was used to define the share of building types in these rural areas and urban areas. As such, four building types were distinguished, being detached houses, semi-detached houses, apartments and high-rise buildings. As the share of these building types in the total residential stock differs between urban and rural areas, the urbanization trend was used to drive the shift in the demand of residential building types. Where possible, the work by Marinova et al. (2020) then used material intensities (in kg/m^2 of net floor area) specific to the four different residential building types to come up with scenarios for building materials in the stock towards the year 2050.

In this chapter we use the developed model and database as described by Marinova et al. (2020) and add two things: 1) we define a model to derive the corresponding inflow and outflow of both the building stock (in m^2) and the construction materials in kgs. 2) We define a model describing the development of floor space demand in the service sector. These non-residential buildings comprise of three commercial building types and one category describing other (non-commercial) service-related applications. Similar to the approach for residential buildings we also calculate the corresponding material stocks and flows for service sector buildings. The resulting model has a global coverage, but also a high level of detail, looking at 26 regions (see Appendix 1). The model captures the development of urban and rural housing demand and describes four residential building types and another four service-related building types. The model also provides both stock and flow scenarios for a total of six construction materials (being steel, concrete, aluminium, glass, wood and copper). All this ensures that the model accounts for relevant dynamics such as urbanization trends, income saturation effects and shifts in building types, while providing a global and comprehensive overview of the development of construction material demand. The connection with the IMAGE model allows us to couple the model to existing scenarios such as the Shared Socio-economic Pathways (SSPs) (van Vuuren et al. 2017a). The model generates relevant output in a format that could easily be coupled to integrated assessment models to also calculate the indirect consequences of changes in energy demand.

For generating scenarios, we use the SSP2 elaboration of the IMAGE model as described by van Vuuren et al. (2017b) towards the year 2050. This scenario describes the potential future development in terms of median assumptions for population growth towards 9.2 Billion people globally by 2050 and GDP growth (of a factor 3.4 between 2010 and 2050).

By modelling the global material stocks and flows in buildings based on their explicit service in terms of per capita floor space (in m^2 per person) we hope to contribute to a better understanding of one of the main drivers of bulk material demand in the global sociometabolic system (Pauliuk and Hertwich 2015). In the results section, we will focus on the potential for closing the cycles of various building materials by 2050 from a global perspective. We do however present this work as an initial attempt, and are aware of its limitations as addressed in the Discussion section. We have documented and disclosed the assumptions, the data input, the model code as well as the detailed outcomes as much as possible in the Appendix 5, so that others should be able to build and improve upon our work.

5.2 Methodology

In the previous chapter, Marinova et al. (2020) described a method for modelling residential building stock and materials for 4 building categories. Here, we add two key features. First, we extend the model to also cover building materials in a selection of service-related buildings. Secondly, we added the explicit modelling of inflows and outflows of floor space as well as building materials by means of a dynamic stock model. We start by describing the model on buildings in the service sector in section 5.2.1 and continue with the description of Inflow and Outflow modelling of building materials. The entire model is implemented in Python, for which the model code is available through a link in Appendix 5.

5.2.1 Service sector buildings modelling

5.2.1.1 Demand for service sector floor space

In contrast to the residential floor space demand, the IMAGE integrated assessment model does not provide any data on service-related or other non-residential floor space. Therefore we developed our own demand projections for the floor space in service-related buildings using regression analysis on data from the commercially available Navigant Global Building Stock Database (Machinchick and Freas 2018). This Global Building Stock Database provides information on service floor space use at a country level basis for a time period from 2017 to 2026, for 231 countries, and for eight different building types related to services, which we grouped to four service building types for use in our model, being:

1) offices
2) retail, shops and warehouses
3) hotels & restaurants, and
4) other (a.o. educational buildings, hospitals, governmental buildings, but also buildings for assembly and public transportation)

Unfortunately, the building types used do not cover all non-residential buildings as no data was available for industrial or agricultural floor space. Moreover, due the extremely heterogeneous nature, modelling of industrial and agricultural buildings is very hard. Altogether, these buildings are excluded from our analysis.

A regression analysis was performed to estimate a relationship between the per capita service sector floor space demand and the Service Value Added (SVA) per capita at a global level. We used the data for the year 2017 to perform our regression, because this was the only year representing historical data. In doing so we derive a relationship between sectoral income (SVA in US$) per capita and service building stock (in terms of m^2) per capita. Next, we assume this relationship to be time-independent and use it to project the future development of service related floor space demand towards 2050, given the development of the population size and SVA in 26 regions according to the IMAGE model and the SSP scenarios. The data on the Gross Domestic Product (GDP, in US dollars at Purchasing Power Parity, PPP) per capita and the shares of the SVA were obtained for the year 2016 (the latest available year) from the United Nations statistics (UNData 2018a),(UNData 2018b). After the omission of outliers like small-island states (e.g. Tuvalu) and city-states (e.g. Singapore) and countries for which no SVA was available from the UN statistics, the regression was performed on 147 remaining data points corresponding to individual countries that together represent 97% of the total global population and 96% of the global GDP. In Appendix 5 we show the resulting regression fit to the data points.

Though we tested for the usefulness of several other models, we decided to use a Gompertz-type relationship, based on the superior R^2 values and because the use of a Gompertz curve is similar to the approach taken for residential buildings (Daioglou et al. 2012). The Gompertz curve used is defined by the following equation:

$$y = \alpha \cdot e^{-\beta \cdot e^{-\gamma x}}$$

Here *y* is the floor space demand for service sector buildings in square meter per capita, and *x* is the Service Value Added per capita in 2016-US$ per year for a particular country, in PPP. The coefficients α, β and γ are the three Gompertz parameters, which were estimated using a least squares optimization routine from the scipy package implemented in a python script (See Appendix 5). Because the α parameter describes the maximum value of the curve, it represents the value at which the per capita service-related floor space demand reaches saturation. We use a boundary condition for the regression by defining an upper limit for α, of 25.6 m^2 per capita. This value is the maximum value found in the current data. We chose to employ this boundary condition on α, because there is no historic evidence that its value could be higher. However, in the sensitivity analysis we explore the effect of choosing a higher value for α.

Initial regression based on an unweighted least squares optimization method yielded proper fits (R^2 = 0.86), but unsatisfactory model validation for the year 2017 (the resulting model was underestimating the total global stock according to the original data for 2017, because most countries with a large population size were situated above the fitted curve). Therefore, it was decided to model the total service floor space demand using a weighted (or generalized) least squares model, where the uncertainty σ was defined to be inversely proportional to the population size of a country. So a high population size would translate into a high certainty, thus a high importance in the regression, where we minimized the goodness-of-fit parameter, or the χ^2, according to Bevington and Robinson (2003):

$$\chi^2 = \sum_{i=1}^{147} \left\{ \frac{1}{\sigma_i^2} [y_i - y(x_i)]^2 \right\}$$

Though this method yields a lower R^2 (= 0.69; with weighting), it makes sure that the model is able to re-create the known global stock in 2017 more accurately compared to an unweighted regression model. The resulting parametrization for the Gompertz curve for the total service sector can be found in Table 5.1. For details on the exact definition of σ, please see appendix 5.

The modelled total service floor space resulting from the weighted regression was subsequently subdivided into floor space for the four service building types based on the relative contribution of these sectors at a given income level, based on their individually fitted curves (using weighting based on GDP per capita as a proxy for data reliability, see Appendix 5). Thus, leading to a total of five regression models. The parameter setting resulting from these five regression curves (one population weighted, four weighted by GDP per capita) can be found in Table 5.1, and the resulting relation between Service Value Added levels and service-related floor space demand can be seen in Figure 5.1.

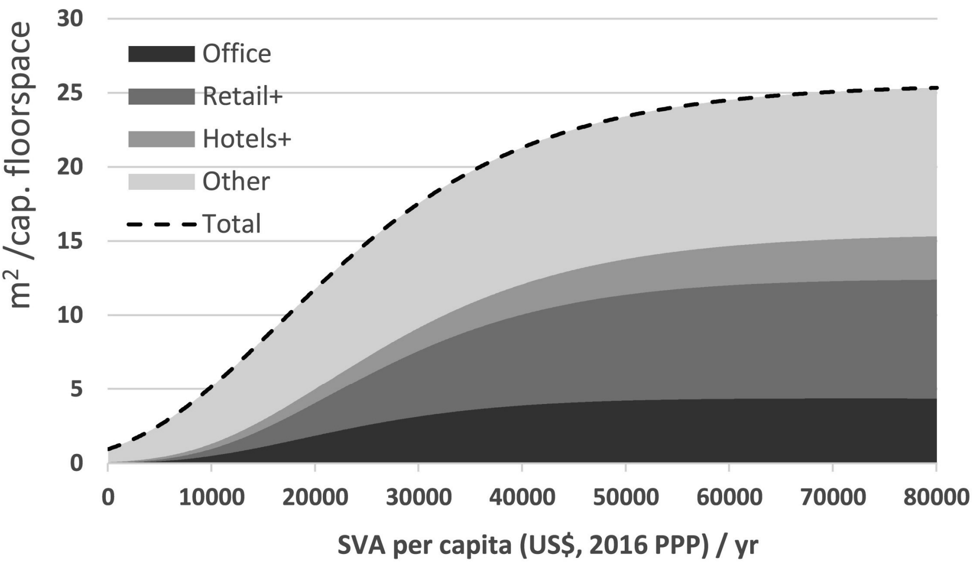

Figure 5.1. *Development of per capita service-related floor space stock at different levels of affluence (expressed as the per capita Service Value Added per year, in 2016 US dollars, at Purchasing Power Parity), as derived using a regression analysis as described (for more details, please see Appendix 5).*

Table 5.1. *Estimated parameters and coefficient of determination (R^2) of the Gompertz function used to derive a relationship between service floor space demand at different income levels. Note that only the parameters for the total service floor space define the absolute demand (dashed line in Figure 5.1), the parametrization for 4 service-related building types is only used to define the relative contributions.*

	α	β	γ	R^2	Comment
Offices	4.253	5.54	$6.95 * 10^{-5}$	0.80	Weighted by GDP/cap
Retail, Shops & Warehouses	8.010	6.524	$6.33 * 10^{-5}$	0.76	Weighted by GDP/cap
Hotels & Restaurants	3.083	4.527	$4.79 * 10^{-5}$	0.69	Weighted by GDP/cap
Other	9.980	2.652	$5.17 * 10^{-5}$	0.77	Weighted by GDP/cap
Services (total)	25.601	3.289	$7.22 * 10^{-5}$	0.69	Population weighted

For the year 2017 the model leads to a global floor space demand of about 38 billion m^2, of which 8% in hotels and restaurants, 13% from offices, 17% in retail & warehouses and the remainder in other service-related buildings.

It is important to note that the current service floor space resulting from the model is slightly lower (by about 9%) than the total stock in 2017 according to the Navigant Global Building Stock Database. A key reason for this is the difference in the country data used for deriving the model and the aggregated regional data in IMAGE (based on the SSP database and fractions for service value-added from the World Bank). Secondly, the regression is based only on a selection of countries, so a perfect historical calibration remains impossible. Finally, and perhaps most importantly, the model assumes that floor space per capita depends on SVA per capita only, ignoring other factors. Examples of such factors are cultural habits, climatic conditions and population density. Even though the resulting model is slightly underestimating the current stock, we feel that given an acceptable R^2 this global approach does allow for a useful estimation of the development towards the future, which is the main goal for this modelling exercise. We explore some options for alternative formulations of the regression model in the sensitivity analysis and we provide some reflections on future improvements regarding this issue in the Discussion section.

5.2.1.2. Materials in service sector buildings

The assumptions on the material demand for service sector buildings are simpler than those for the residential stock analysis by Marinova et al (2020). Because of a lack of data, the materials in service sector buildings are not defined regionally. Instead, a global average is used for the four service-related building types, in terms of kilograms per m^2 of net floor space (i.e. the material intensity). Similar to our approach for residential building stock scenarios, we assume a static material intensity. The recently published database on building material intensities by Heeren and Fishman (2019) provided a helpful starting point, but was supplemented with studies describing material intensities specific to the four service sector building types. It can be seen from Table 5.2 that the material content of retail & warehouse buildings is based on four sources (Reyna and Chester 2015; Schebek et al. 2017; Kellenberger et al. 2007; Gruhler and Deilmannl 2017), while the offices were modelled based the average numbers found in six office specific studies (Reyna and Chester 2015; Kashkooli et al. 2014; Kofoworola and Gheewala 2009; Oka et al. 1993; Kellenberger et al. 2007; Schebek et al. 2017).

Table 5.2. *material content assumptions (kg/m2) for the different service sector building types. See Appendix 5 for details.*

	Offices	Retail & Warehouses	Hotels & restaurants	Other
Based on	Average of offices & multi-storey buildings in (Oka et al. 1993; Kashkooli et al. 2014; Kofoworola and Gheewala 2009; Reyna and Chester 2015; Schebek et al. 2017; Kellenberger et al. 2007)'.	Average of multiple shop types described in (Reyna and Chester 2015; Schebek et al. 2017; Gruhler and Deilmannl 2017) and a hall-type building in (Kellenberger et al. 2007)	Average of a description of multiple hotels in (Reyna and Chester 2015; Rosselló-Batle et al. 2010; Gruhler and Deilmannl 2017)	Average of various educational & health care buildings in (Kumanayake et al. 2018; Reyna and Chester 2015; Gruhler and Deilmannl 2017; Marcellus-Zamora et al. 2016)
Represents	Offices	Shops, Retail & Warehouses	Hotels, Restaurants	Hospitals, Educational, Institutional, Transport, Public assembly & Others
Steel	115	78.5	84.4	101.9
Concrete	905.1	700.1	724.2	1029.1
Aluminium	4.8	2.4	4.4	5.8
Copper	3.9	2.3	3.5	3.4
Wood	6.7	11.2	18.5	25.5
Glass	6.5	5.9	3.9	14.5

For Hotels & Restaurants we found three studies describing the building materials required for a hotel (Reyna and Chester 2015; Rosselló-Batle et al. 2010; Gruhler and Deilmannl 2017). Finally, material use in other service sector buildings was based on four studies describing materials in educational and other institutional buildings (Kumanayake et al. 2018; Reyna and Chester 2015; Gruhler and Deilmannl 2017; Marcellus-Zamora et al. 2016).

The inferred relation between income-levels and service floor space demand (stock, in m^2/cap), together with the static set of building materials comprises the model for the service sector building material scenarios. Effectively the weight of materials in the service sector building stock for any IMAGE region at any time is given by the income level (US$/cap), which through the Gompertz curve, gives an average floor space demand (m^2/capita). This is multiplied by the population to get the total stock (in m^2), which is then multiplied by the material content (kg/m^2) to derive the development of construction materials in the building stock.

5.2.2 Inflow and outflow of building materials

5.2.2.1 Dynamic stock modelling: life-times

The combination of residential and service-related building stock as presented here, allows us to subsequently estimate building construction and building demolition activities (i.e. inflow & outflow of the building stock). This increases the relevance of the model output for policy questions related to the circular economy, in particular to assess whether construction materials could potentially be sourced from scrapped building materials. We applied a cohort-based dynamic stock model as developed by Pauliuk and Heeren (2018) with Weibull lifetime distributions to translate the scenarios on building stock into scenarios on the global inflow and outflow of building materials.

In order to simplify our initial model setup, we only account for the materials contained in the 'one-off' construction. So we do not take material losses into account, nor materials used for maintenance or building retrofits. Though this coverage would definitely be of interest, it remains outside the scope of this chapter, as it would require elaborate and dedicated efforts given the global scope of our model.

Similar to the building stock, the inflow & outflow of floor space is calculated on a square meter basis. We applied a cohort-based dynamic stock model, using a stock-driven approach, which implies that the stock prescribes the inflow as the sum of the stock addition plus the replacement of existing stock. Throughout the scenario period however, it happens occasionally in some regions that the drivers behind the stock are causing the building stock to shrink. Either due to a decline in population (e.g. for the former Soviet Union regions), or as a result of a decline in GDP (e.g. during the global economic crisis of 2008). In these cases, the stock driven model is required to balance the equation by immediately generating a large outflow. In realistic terms, this means that we do not account for vacant buildings. Even though we know that the share of vacant buildings can be significant. Typical values would be a 5% natural vacancy in urban areas (Zhang et al. 2018), but depending on market conditions, speculation could increase vacancy rates, like in China where vacancy rates are estimated to be over 20% of urban stock (Dericks et al. 2018).

For the building lifetimes we used values found in a literature review, which yielded 16 usable studies, which mostly identified a Weibull lifetime distribution. In correspondence with the resulting data, we chose to stick with this form of probability density function, but other options for modelling building lifetimes exist (Miatto et al. 2017), which were tested in the sensitivity analysis. Where possible we applied Weibull lifetime distributions specific to the building type and even the area. If this information was not available, we used one set of region specific Weibull parameters. If that was not available we used a global average lifetime distribution. However, for some regions we couldn't find lifetime distribution data, but we could find the mean lifetime. In these cases we used the global average shape parameter, but adjusted the scale parameter to correspond to the mean lifetime for that region. If no lifetime data for houses was available, we used a global average, corresponding to a mean lifetime of 60 years. For details of averaging distribution parameters, we refer to Appendix 5. Table 5.3 shows a summary of the final set of applied Weibull parameters of residential buildings, which defines the fraction of buildings demolished for any given year after construction (for details see Appendix 5). For the lifetime of service-related buildings we applied one global distribution according to the Weibull shape parameter of 1.44 and a scale parameter of 49.6, resulting in an average lifetime of 45 yr according to combined data from (Kapur et al. 2008; Daigo et al. 2007; Nomura et al. 2013). This is considerably lower than the lifetime of residential buildings in most regions, which has an effect on the material demand for service sector buildings as will be discussed in the following section.

***Table 5.3**. Summary of Weibull lifetime distribution parameters for residential buildings used in the dynamic stock modelling, and the resulting mean lifetimes.*

Region	shape	scale	mean lt (yr)	Sources
Japan	2.06	38.70	34	(Daigo et al. 2017)'(Nomura et al. 2013)
China	2.00	44.43	39	(Wang et al. 2015b)
Eastern Europe	2.50	87.35	78	(Novikova et al. 2018)
United States	4.16	85.19	77	(Olson 2011; Kapur et al. 2008; Hatayama et al. 2009)
Western Europe	2.95	70.82	63	(Heeren et al. 2015; Davis et al. 2007; Hatayama et al. 2009)
Canada	1.97	57.53	51	(Buyle et al. 2013; Murakami et al. 2010)
Mexico	1.97	63.17	56	(Murakami et al. 2010)'(OECD and Eurostat 2015)
Brazil	1.97	112.80	100	(Condeixa et al. 2017)
Rest of South America	1.97	68.24	60.5	(Olaya et al. 2017; Buyle et al. 2013; Murakami et al. 2010; OECD and Eurostat 2015)
Southeastern Asia	1.97	56.40	50	(Buyle et al. 2013)
Oceania	1.97	94.00	83	(Buyle et al. 2013; Stephan and Athanassiadis 2017)
Global Average	1.97	67.34	60	average of parameters from Japan, China, US & Europe

Additional assumptions had to be made on how the building stock developed before the starting point of the scenario period, which is the year 1971 in our case. Since we do not have data on the age-distributions (i.e. the share of the stock by age-cohort) of buildings in that year, we needed to extend the historic time series to derive the age-distribution of buildings based on historic inflow as described in Appendix 5.

5.3 Results

Here, we present results for residential and service-related building stock (Section 5.3.1), the resulting inflow and outflow of floorspace (Section 5.3.2) and the implications for material demand and recycling potential (Section 5.3.3).

5.3.1 Comparing residential buildings & service sector buildings

Figure 5.2 shows the resulting development of service sector building stock in the total number of square meters as compared to the (urban and rural) residential building stock, in eight regions, based on an average of recent history (2000-2015) and for the end of the scenario period (2035-2050). The service-related building stock will remain a small fraction of the entire building stock going up from about 16% now to a little over 23% of the total modelled stock globally, towards 2050. But it also shows that for some regions like Europe and North-America the service sector building stock substantially outweighs the rural residential building stock by the end of the scenario period, making it a relevant component of the building stock in absolute terms. Another reason why service-related building stock should not be overlooked is its growth rate. In fact, our model projects the growth of service-related building stock to be higher than the growth of residential building stock from a global perspective (between 2015 and 2050). This is in line with observations from literature (Deng et al. 2012) and examples from regular building surveys in the United States (IEA 2015, 2012).

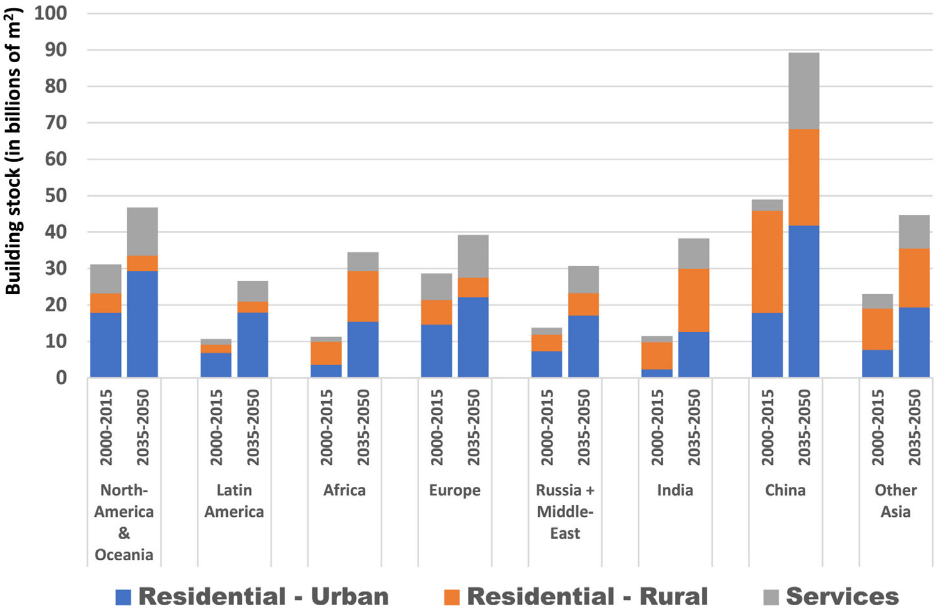

Figure 5.2. *Regional building stock development for residential & service sector buildings in billion square meters. Bars indicate the average stock in recent history (average of the 2000-2015 period) and by the end of the scenario period (average of the 2035-2050 period). For the per capita floor space demand, see Figure A5.9 in Appendix 5.*

Further detail on the share of service-related building types is shown in Figure 5.3. It shows that global stock of service sector building types will grow by about 150% towards 2050. Our model projections thus indicate that the building stock of services might expand more than twice as fast as the global residential building stock, which grows by roughly 50% over the same period. A closer look at the numbers behind Figure 5.3 shows that the floor space demand for offices and retail grows a bit faster than for the other service sector building types, as a consequence of the regression analysis (see Table A5.4 in Appendix 5).

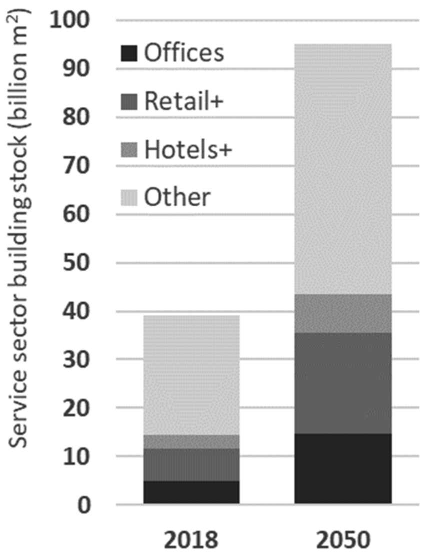

Figure 5.3. *Global stock of service sector buildings by building type in Billion square meters), current and by 2050.*

5.3.2 Results for building stock inflow and outflow

Figure 5.4 presents the results for the inflow and outflow of stock as derived using the dynamic stock model (the Figure shows 5-year moving average to smooth annual fluctuations). Interestingly, it is possible to distinguish three regional typologies. The first group contains regions with a steady growth in building stock like Europe, the US, Australia, but also the former Soviet- and Middle Eastern regions. In these regions, though the outflow of building floor space remains smaller than the inflow, the rate of building demolition slowly approaches the rate of the new construction leading to a slow stabilization. Secondly, in regions with a rapid economic development over the scenario period such as Latin America, Africa and Asian regions (Including India, but not China or Japan), the stock grows at an accelerated rate in the coming decades. This also means that the demand for construction of new buildings will remain much higher than the rate of demolition. Finally, two regions show a different result. Projections for China and Japan both show a stabilization and even a slight decrease in the total building stock towards the end of the scenario period. Towards 2050, this causes a decline in the demand for construction (inflow), while demolition activities (outflow) are increasing following a delayed response after a rapid historic expansion of the built environment. For China and Japan, the delay between inflow and outflow is smaller due to the application of lifetime distributions with a shorter mean lifetime (Table 5.3). As a result, these are the only two regions for which the outflow of building floor space approaches the volume of the inflow within the considered scenario period. These observations have very relevant implications with regard to the secondary material availability as we will see in the following section.

5.3.3 Material calculations (inflow-outflow)

The development of building stock, inflow and outflow shown in Section 5.3.2 translates into projections for material demand. To calculate these we used the database specifying the building materials requirement per square meter, for four different residential buildings (Marinova et al. 2020), together with the material content of the four service-related building types as described in Section 5.2.1. In presenting the results of the material calculations we focus on the ratio between the inflow and the outflow, which gives an indication of the recycling potential, or more specifically, the potential for closing material loops in pursuit of achieving a circular economy. While maintaining the regional typologies as identified in Section 5.3.2, Figure 5.5 shows the average ratio between material outflow and inflow based on the last 5 years of the scenario period (average of 2045-2050). Additionally, it specifies whether the material is used for or sourced from urban residential buildings, rural residential buildings or service-related buildings.

In general, Figure 5.5 shows how the strong differences in regional typologies for floor space demand (Figure 5.4) translate to distinct patterns in the material inflow and outflow as well. Towards 2050, the demand for new construction materials (in) will still strongly outweigh the amount of materials potentially available for recycling (out) in fast developing regions. In steady developed regions, however, the potential for closing the building material cycle will be larger, but it will not be possible yet to fully ‘close the loop’ even given a 100% end-of-life recycling rate. For Japan and China, the availability of some secondary building materials like concrete, glass and aluminium, should in theory be sufficient to fulfill the demand for construction purposes towards the end of the modelling period. The high material outflow in these regions, however, seem to be strongly related to the outflow of construction materials in rural areas.

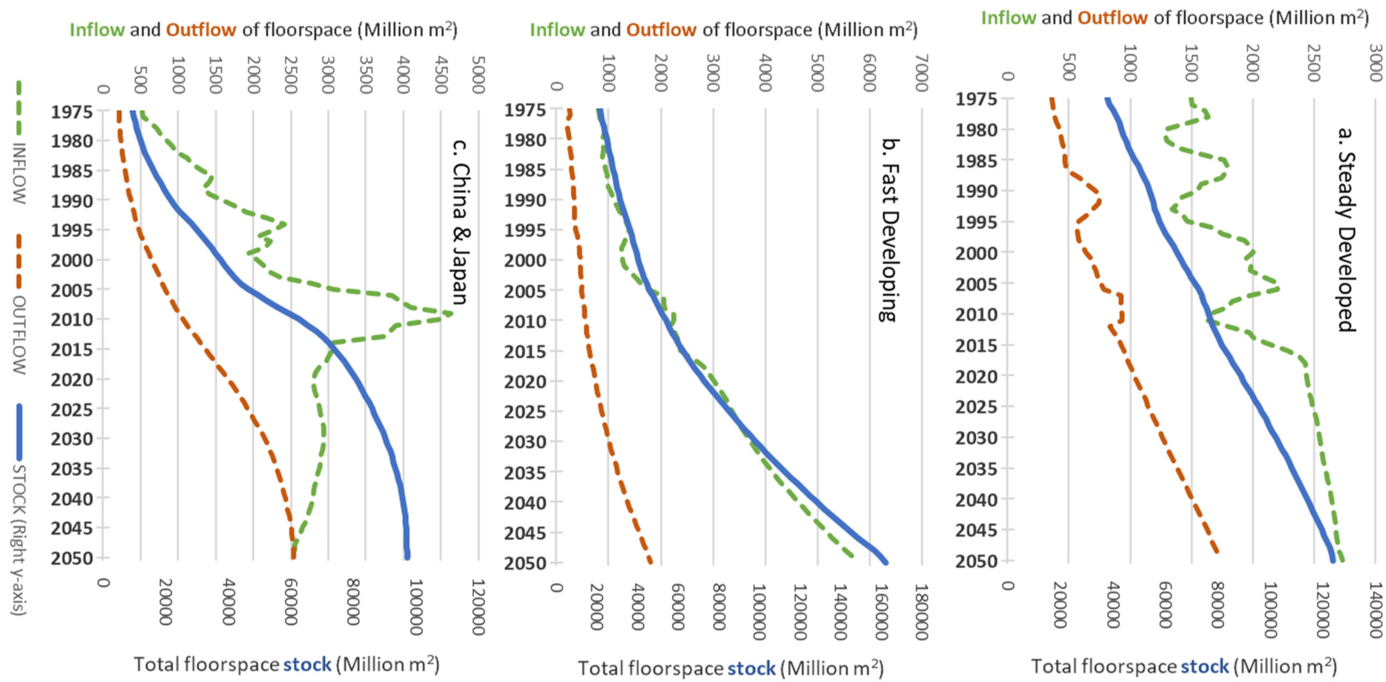

Figure 5.4. *Modelled development of (residential and service-related) building stock, inflow and outflow in Millions of square meters, for three regional typologies. Steady Developed regions (a) are: North-America, Europe, Australia, Former Soviet regions and the Middle East. Fast Developing regions (b) are: all Latin-American, African and Asian regions (except Japan & China (c)). The data represents a 5-year moving average of the model outcomes.*

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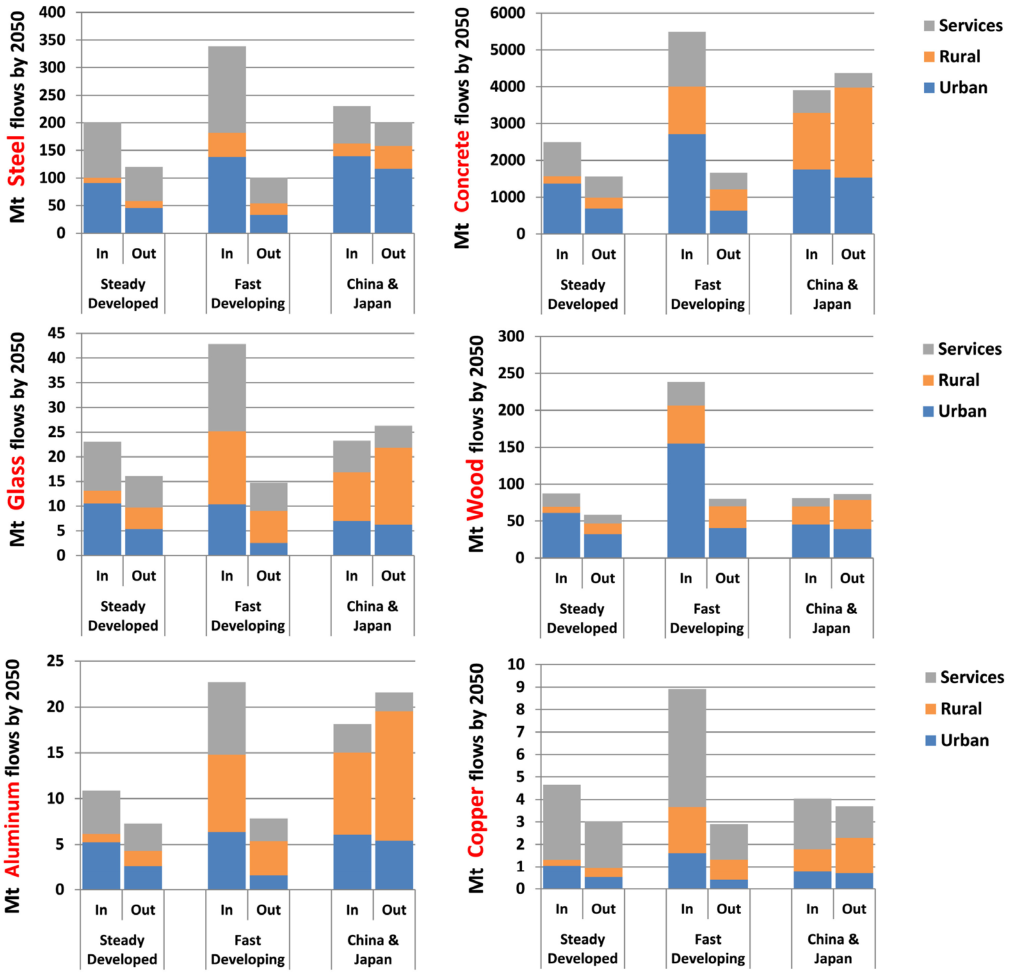

Figure 5.5. *Comparison of construction material requirements (In) and scrap generation from demolished buildings (Out) by the end of the scenario period (average of 2045-2050). We use the same regional grouping as in Figure 5.4. Urban and rural data indicates the materials sourced for and from residential buildings, in addition, the total material flows related to service sector buildings are shown in grey.*

So the ongoing urbanization trends that explain these model outcomes may be an argument to expand the focus from urban mining to also include rural mining for the coming decades. When we focus only on the urban residential fraction of the material flows, none of the presented regions show a potential for matching the demand of construction materials (inflow) entirely by using secondary supply (outflow), for any of the materials covered. Even though the model does not allocate service sector buildings to urban or rural areas specifically, we can safely assume that most of the service-related buildings would be built in urban areas. This would mean that service sector buildings aggravate the mismatch between secondary supply and demand for construction materials in urban areas.

Furthermore, our results show that by the end of the scenario period (2045-2050) the global annual demand for building materials increases to 769 Mt steel, 11.9 Gt concrete, 89 Mt glass, 52 Mt aluminium, 407 Mt wood and 18 Mt Copper. Compared to more recent years (2010-2015, not shown), this is an increase of 31% for steel, of 14% for concrete, of 24% for glass, of 24% for wood, of 5% for aluminium and of 58% for copper. The outflow of steel from demolished buildings in the 2045-2050 period (Figure 5.5), however, would only be equivalent to 55% of the annual steel demand in this period. Similarly, by the end of the modeling period, the outflow would only represent 64% of the sectoral demand for concrete, 71% of the sectoral aluminium demand, 55% of the sectoral wood demand, 64% of the glass demand and 55% of the copper demand. This discrepancy between outflow and inflow indicates that closing the loop for construction materials based on the urban mine alone seems highly unrealistic before the year 2050. Especially given the fact that only a fraction of the secondary materials could actually be re-used (Nautiyal et al. 2015; Duan et al. 2015; Martínez-Rocamora et al. 2016).

Another noteworthy outcome shown in Figure 5.5 is that buildings in the service sector play a more important role in the inflow and outflow of building materials, despite having a relatively small contribution to the stock (Figure 5.2). The reasons for this are threefold. First of all, according to the studies used in our database, the material content per square meter in service-related buildings is simply a bit larger than in residential buildings for some materials, such as for copper, steel and glass for example. Secondly, the average lifetime of service sector buildings is smaller, leading to a higher contribution to both inflow and outflow of materials. Finally, in our model the global building stock of services expands faster than the global residential stock, which also results in a large contribution to the inflow.

The results presented in this section are only a selection of the available model output. For further details on regional model outcomes, please see Appendix 5 and the Supplementary Data provided with the original publication. Furthermore, the presented outcomes are a result of various choices and assumptions both for the data and the modelling. The following section provides a comparison of our model outcomes to existing studies, followed by some reflection on the assumptions by means of a sensitivity analysis and a reflection on the opportunities for model improvement, to end with the conclusions.

5.4 Discussion and conclusions

5.4.1 Discussion

5.4.1.1 Comparison with existing literature

To get a feeling for the value and probability of our model outcomes we start this discussion by a comparison to existing studies. We can only make these comparisons sporadically, and only to get a rough comparison, since the methodologies and categorization of material use do not always correspond between studies. We start with a comparison of the development of building stock in terms of floor space (m^2), where we are able to compare with a study by Amecke et al. (2013), who model the floor space demand in China to be about 62 Billion m^2 (residential and services) by 2030, while our model suggests a total stock that is almost 35% higher. Simultaneously, Amecke et al. model the total building stock in the United States to amount to 35 Billion m^2 by 2030, while our model produces a figure that is 16% lower. On the one hand this indicates that our model could benefit from improving the regional representation and one should be careful when using the detailed regional outcomes without reflection. On the other hand, it also indicates that the few given points of comparison do not indicate a consistent over- or underestimation of the stock.

Comparison with the in-stock material estimates for buildings with existing studies is done at the level of the stock per capita for different regions and materials in Table 5.4. It shows that for steel and cement outcomes are comparable and in the range of existing studies. For Aluminium our model seems to produce slightly higher estimates for in-use construction-related stock. This is a direct result of the studies used to define the material content database (Marinova et al. 2020).

Table 5.4. *Comparing model outcomes for the material stock per capita with available existing studies.*

Material	Year	Region	Model outcome (ton/cap)	Other studies (ton/cap)	References studies
Cement	2010	Global	11.1	10	(Cao et al. 2017)
Cement	2010	EU	15.4	23	
Steel	2005	EU	3.42	1.3 to 3.5	(Hatayama et al. 2010) and (Müller et al. 2010)
Steel	2005	US	2.66	2 to 4	
Aluminium	2030	Global	0.27	0.20	Estimates derived from (Liu et al. 2012)
Aluminium	2010	Japan	0.20	0.11	

Though the comparison in Table 5.4 indicates that the model presented in this chapter is able to generate plausible outcomes for some materials and for some comparable regions, it does not mean that the detailed outcomes for every region and material will make sense. This is inevitable when compiling a model with a global scope like this. As indicated by Marinova et al. (2020) this is partly due to the sensitivity of our model to assumptions based on single study or data point, which is undesirable, but currently unsurmountable, given the data availability. We emphasize that the work presented here is an initial attempt at formulating a global model, and therefore provides plenty of sensitivities and opportunities for future improvements as discussed in the following sections.

5.4.1.2 Sensitivity analysis

To better understand the importance of some of the model assumptions to the outcomes we performed a sensitivity analysis. We defined four sensitivity variants, two of which were focused on changing the regression of service sector floorspace demand, one representing an alternative assumption on building lifetimes and one using an alternative set of material intensities based on the global mean values. The regression analysis on service sector floorspace demand was changed by allowing a higher value for alpha (representing the maximum per capita floorspace). In a second sensitivity variant the regression model based on a Gompertz function was replaced by an exponential decay function. Both alternative approaches to the regression did not lead to exceptional changes in the outcomes given that annual material demand for service sector buildings ended up only slightly lower (by 2%) or higher (by about 8%).

The implementation of normal lifetime distributions for both residential and service-related buildings, however, did have a larger effect on the outcomes by the end of the scenario period, leading to a decrease of annual material demand of 13% for service sector buildings, while decreasing material demand in residential buildings by up to 10%. These deviation are unsurprising, given that lifetime assumptions are known to greatly affect inflows and outflows in building stock models (Miatto et al. 2017).

Finally, the implementation of a different set of material intensities based on the global mean value did have a large effect on some materials. Annual glass and wood demand in service sector buildings decreased by 23% and 35% respectively, due to relatively high material intensity estimates for the category of ‘other’ service-related buildings in the default analysis. While relatively high regional material intensities in China caused a decrease in the annual demand for aluminium (by 18%) and concrete (by 20%) towards

2050, in the sensitivity variant. Thus emphasizing the importance of validating the assumptions before using the regional model outcomes. For a detailed description of the assumptions and outcomes of the sensitivity analysis, please see Appendix 5.

5.4.1.3 Model improvements

Future model improvements could be focused on including other non-residential buildings such as agricultural and industrial buildings and on a better understanding of regional dynamics. For example, implementing a regionally specific regression for the service-related floor space demand could improve regional results. Other potential improvements to the regression analysis could be made by performing a more elaborate multivariate analysis or multiple regression, to get a better understanding for other factors determining the service sector floor space demand. In general, the choice of a suitable regression model depends on the detail in the available data, but also on the scenario background. So the current model may not be suitable for use in scenarios other than the SSP2 (for additional reflection on the model specification, please see Appendix 5).

A better representation of stock dynamics may also be achieved by allowing a dynamic lifetime (assuming different lifetimes for buildings built in different years) as for example applied by Hu et al. (2010), an approach that could for example be used to represent the stock of monumental buildings more accurately. Another improvement could be aimed at more realistic lifetime estimates, by critical reconciliation of literature based lifetime estimates with building statistics (see Appendix 5 for an example). Furthermore, we would like to implement the option to account for material demand from maintenance and retrofitting, which is currently not possible. This could for example be done on the basis of lifetimes of partial building elements such as provided by Condeixa et al. (Condeixa et al. 2017). Another important improvement to make this study more relevant for practical policy making would be to translate the theoretical potential availability of scrapped building materials to a more realistic estimate for the actual recycling potential, given the practical collection and recycling practices. Finally, a suggestion for further work would be to implement this model in a global integrated assessment model such as IMAGE. This should contribute to a better understanding of interlinkages between material and energy demand, and would allow to assess the climate benefits of changing building technologies.

5.4.2 Conclusions

Based on the results of the current model, we are able to address the main objectives of this study. Our model shows that service sector floor space currently amounts to about 17% of the global building stock. We also show that the service sector building stock becomes more important when considering the inflow and outflow of building materials due to faster stock growth, shorter average lifetimes and higher material content for some materials like copper, glass and steel. This category of buildings is often overlooked or modelled as part of a single 'buildings' category. However, given the large contribution to the inflow and outflow of some building materials, this study emphasizes the importance of explicit modelling of non-residential buildings when developing scenarios for the future built environment.

Our model projects a global residential building stock (expressed in square meters) that grows by about 50% towards 2050 and it projects the global service-related building stock to grow by 150%. Based on the resulting ratio between inflow and outflow of building floor space we were able to identify three distinct regional typologies. Regions like China and Japan are projected to have a slight population decrease towards 2050, which translates to a stabilizing building stock. Additionally, the short lifetimes of residential buildings in these regions cause a quick increase in the outflow of building stock, which closely matches the required inflow well before 2050. This means that, for some materials, the maximum theoretical amount of scrapped building materials that would potentially be available for re-use or recycling matches the demand for new construction materials. Thus identifying opportunities for closing the loop for building materials according to the views of the circular economy. However, this cannot be achieved based on the urban mine alone. The ratio between inflow and outflow of urban building materials in China and Japan suggests that the demolition of rural housing might provide an even more important source for materials than the urban mine. Thus, suggesting that expanding the focus from urban mining to include rural mining might be worthwhile.

For all other regions (both steady developed and fast developing) the promise of a fully circular metabolism for construction materials seems highly unlikely before 2050. In steady developed countries the slow population growth, combined with a continued GDP growth, ensures a steady growth in the building stock towards 2050. Given the longer lifetimes of houses in these regions, this means that the outflow catches up only slowly with the stabilizing inflow, which means that the availability of scrapped building materials will not be enough to fully supply the demand for new construction materials before 2050. A conclusion that is only amplified for fast developing regions like India, Latin-America and Africa. There, the annual demand for construction materials will continue to grow rapidly, with the outflow lagging behind substantially. Globally, this means that the outflow of construction materials is insufficient to provide the sectoral demand for new materials by the end of the modelling period. By 2050, scrapped copper from buildings could provide only 55% of the copper demand in construction, while for aluminium up to to 71% of demand could be based on building scrap. As buildings are often the main contributor to the societal stocks of steel (Wang et al. 2015a) and concrete (Cao et al. 2017), they are an important driver of bulk material demand. This study thus identifies impressive challenges for achieving a global circular economy in the coming decades.

Acknowledgements

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Appendix

Supplementary Information, describing the model code, assumptions & data in additional detail is provided in Appendix 5.

6.

Projected material requirements for the global electricity infrastructure – generation, transmission and storage

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Abstract

We analyze how the global material stocks and flows related to the electricity sector may develop towards 2050. We focus on three electricity sub-systems, being generation, transmission and storage and present a model covering both bulk and critical materials such as steel, aluminium and neodymium. Results are based on the second Shared Socio-Economic Pathway scenario, with additional climate policy assumptions based on the IMAGE integrated assessment framework, in combination with dynamic stock modelling and an elaborate review of material intensities.

Results show a rapid growth in the demand for most materials in the electricity sector, as a consequence of increased electricity demand and a shift towards renewable electricity technologies, which have higher material intensities and drive the expansion of transmission infrastructure and electricity storage capacity. Under climate policy assumptions, the annual demand for most materials is expected to grow further towards 2050. For neodymium, the annual demand grows by a factor 4.4. Global demand for steel and aluminium in the electricity sector grows by a factor 2 in the baseline or 2.6 in the 2-degree climate policy scenario.

We show that the combination of rapid growth of capital stocks and long lifetimes of technologies leads to a mismatch between annual demand and the availability of secondary materials within the electricity sector. This may limit the sector to accomplish circular material flows, especially under climate policy assumptions. We also highlight the potential for electric vehicles to curb some of the material demand related to electricity storage through adoption of vehicle-to-grid services.

6.1 Introduction

Demand for electricity has been increasing rapidly worldwide, by over 4% per year in the 1990-2015 period (IEA 2019), and will likely continue to grow due to trends such as continued economic development (Steinbuks 2017), electrification (Blonsky et al. 2019) and climate change (van Ruijven et al. 2019). Consequentially, the amount of materials contained in the infrastructure required to generate and deliver the electricity to end-users is increasing as well. There are several reasons to explore the effect of increased electricity demand on the demand for materials. First of all, previous research has pointed out that material scarcity could be a limiting factor to the expansion of renewable energy systems (de Koning et al. 2018; Valero et al. 2018; Månberger and Stenqvist 2018; Harmsen et al. 2013; Elshkaki et al. 2018). Secondly, the material demand of infrastructural stock development could be relevant for energy demand and related carbon dioxide emissions (Müller et al. 2013; Pauliuk and Müller 2014; Baynes and Müller 2016). A better representation of materials in infrastructural stocks could therefore contribute to more realistic scenarios on the energy system, while at the same time improving the understanding of its environmental impacts (Södersten et al. 2018; Chen and Graedel 2015). Currently, however, very few models that are used to generate global emission scenarios capture such explicit linkages between material demand and industrial energy use (Pauliuk et al. 2017). A key reason is that it requires detailed insights in the demand for individual materials that contribute to the formation of capital stocks in economic sectors, for example in buildings and vehicles (Hertwich et al. 2020; Habib et al. 2020; Deetman et al. 2020). The electricity sector specifically, comprises of large infrastructural stocks, but its size and the implications of its growth on material demand have been poorly understood from a global perspective.

Existing literature has addressed the development of material demand in relation to the electricity sector, but often reported results using a regional focus (Elshkaki and Shen 2019; Li et al. 2020a), or a broadly defined end-use category (such as 'construction'), making it difficult to strictly distinguish materials used in the electricity sector alone (Wiedenhofer et al. 2019; Langkau and Tercero Espinoza 2018; Krausmann et al. 2017). Others have considered parts of the electricity sector such as only the electricity generation (Elshkaki and Graedel 2013; Deetman et al. 2018). Some studies also looked at the material use in the electricity sector using a life-cycle or a material footprint approach (Watari et al. 2019; Mostert et al. 2018; Kleijn et al. 2011; Hertwich et al. 2015; Luderer et al. 2019; Berrill et al. 2016) or with a narrow focus on reserve depletion (Capellán-Pérez et al. 2019; Jacobson and Delucchi 2011). Such studies are all valuable in highlighting the issues related to material demand in the electricity sector. However, they do not encompass a global perspective of all the physical infrastructure involved in providing electricity to consumers. In particular, developments towards higher shares of renewable electricity will require a combination of electricity storage and grid expansion to guarantee a reliable and affordable electricity supply (Laugs et al. 2020; Koskinen and Breyer 2016; Child et al. 2019).

Here, we address the knowledge gap by focusing on the materials used in the electricity sector, as defined by the infrastructure used to generate, transport and store electricity. We explore how the global material stocks and flows related to the electricity sector will develop, by introducing a model with a long-term perspective that provides comprehensive coverage of material stocks as well as the annual material flows related to the electricity sector towards 2050. The model covers bulk materials such as steel, concrete, aluminium, glass and copper, as well as some specific metals used in lower volumes, such as cobalt, neodymium and lead, but coverage of materials is often based on data availability and could be expanded in the future.

As a scenario background, we use a 'middle-of-the-road' scenario, i.e. the Shared Socioeconomic Pathway (SSP2) as implemented by the IMAGE integrated assessment framework (Stehfest et al. 2014; van Vuuren et al. 2017), which ensures that we consistently account for the regional development of important drivers such as population, affluence and electrification. We also look into the derived climate policy scenario consistent with the 2^{o}C Paris Climate target (UNFCCC. Conference of the Parties (COP) 2015). This scenario includes a rapid increase of renewable energy use. Our analysis requires an elaborate set of assumptions on material intensities, lifetimes and the future development of the electricity infrastructure, which are documented in Appendix 6 and the associated model code (available via Github). The transparent approach allows to support future model improvements and facilitates the integration of material-energy feedbacks in integrated assessment models such as IMAGE.

6.2 Method

This section describes the approach and the assumptions in the calculation of the materials used in the electricity infrastructure, i.e. 1) electricity generation capacity, 2) the electricity transmission grid and 3) the required electricity storage, as summarized in Figure 6.1. With regards to the electricity sector, we define the system boundaries of our model to only include the stationary infrastructure that strictly functions to reliably provide electricity to end-users. For storage technologies this means that pumped-hydro dams and other dedicated electricity storage technologies are accounted as part of the electricity sector, while electric cars and their batteries (though available as a form or storage) are not.

However, we do reflect upon the importance of electric vehicle batteries to support a renewable energy system in the discussion.

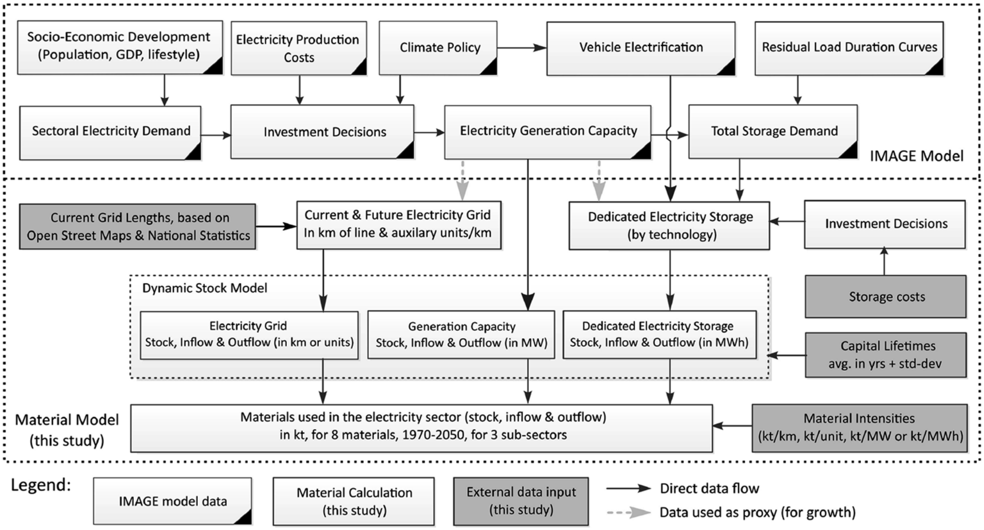

Figure 6.1. *Overview of the calculations. The top box indicates information within and from the IMAGE model. In the lower box, the calculations performed in this study are presented in black and external data input is indicated in the blue boxes.*

For each of the three parts of the electricity sector, we use a similar approach. The electricity grid, generation capacity and storage capacity are all described by an infrastructural stock model. They are driven by the actual demand. In the case of generation, this is provided by the IMAGE model, which accounts for trends in population, affluence and electrification. For the electricity grid and storage, we model the required capacity consistent with these IMAGE projections. Subsequently, new capacity is calculated by the difference between existing and required capacity, while depreciated capacity is determined using assumed technical lifetimes and a dynamic stock model (Pauliuk and Heeren 2019). The total capacity in stock, the newly installed capacity and the depreciated capacity is subsequently used to calculate the stock, the annual inflow and the annual outflow of materials by using a set of material intensity data, established through elaborate literature review. Below, we briefly describe the methods for each of the three infrastructural parts and subsequently discuss the key characteristics of the SSP2 scenarios used to generate the results.

6.2.1 Model description

6.2.1.1 Electricity generation capacity

In a previous study (Deetman et al. 2018), we presented a method to calculate the demand for metals in electricity generation technologies. The method used data on the material intensity for different metals expressed in kg per MW of installed generation capacity. Which were combined with the IMAGE model projections for the growth of installed generation capacity of 28 technologies, including those based on wind, solar, nuclear, hydro, biomass and various fossil power plants (with or without combined heat/power installations or carbon capture and storage capabilities). The method is summarized in equation 1 as follows:

$$GenMat_{flow,tech,reg,yr} = GenCap_{flow,tech,reg,yr} * MI_{tech} \quad (1)$$

Where, for any given year (yr), the material use in electricity generation (GenMat) in kg is a product of Material Intensity (MI) as expressed in kg/MW and the Generation Capacity (GenCap) expressed in MW. Flows are represented by inflow, outflow or stock, and a full list of the 26 regions (reg) and the 28 generation technologies (tech) can be found in the Appendix 1 & 6 respectively.

In this study, we use the same method, but we expand the list of materials covered by including several bulk materials, such as steel, aluminium and concrete and glass. We incorporated 27 studies in our review (Öhrlund 2012; Elshkaki and Graedel 2013; BBF Associates; Kundig 2011; Moss et al. 2011; Sullivan et al. 2011; Ehtiwesh et al. 2016; Crawford 2009; Dones et al. 2007a; Haapala and Prempreeda 2014; Bonou et al. 2016; Marimuthu and Kirubakaran 2013; Guezuraga et al. 2012; Habib 2015; Wilburn 2012; Energinet 2015; van Exter et al. 2018; Vici Ventus 2020; Flury and Frischknecht 2012; S&T2 consultants 2006; Albers et al. 1977; Dones 2007; Weitzel et al. 2012; Dones et al. 2007b; Singh et al. 2015; Jungbluth 2007; Faist-Emmenegger et al. 2007; Moss et al. 2013; Bauer 2007) to come up with the overview of material intensities (in ton/MW) as presented in Table A6.2 in Appendix 6. By default, these material intensities were assumed to remain constant over time, but the effects of foreseeable changes in material composition where analyzed as part of the sensitivity analysis. The material intensities were then applied to the stock and the in/out-flows of the generation capacity in the IMAGE elaboration of the SSP2 baseline and the SSP2 2-degree climate policy scenario. We then calculate the inflow and outflow using a stock-driven dynamic stock model (Pauliuk and Heeren 2019) and the individual lifetimes of the electricity generation technologies ranging from 25 years (solar PV & wind turbines) to 80 years (hydro dams), as elaborated in Appendix 6.

6.2.1.2 Current and future electricity grid

In short, the size of the transmission and distribution grid is calculated using an estimate of the current high-volage (HV) grid size and a growth factor based on the indexed growth of the installed generation capacity as in equation 2:

$$HVGrid_{reg,yr} = HVGrid_{reg,2016} * \frac{GenCap_{reg,yr}}{GenCap_{reg,2016}} \quad (2)$$

Where the in-use stock of High Voltage grid (HVGrid) is expressed in kilometers of transmission line and the generation capacity (GenCap) in MW as before. The grid size of lower voltage levels (Medium & Low voltage) is derived using a fixed ratio with the HV grid length. The material use is then calculated based on these line lengths, multiplied with voltage-specific material intensities (MI) for various sub-elements of the grid, such as lines & poles, and substations with their transformers, as follows:

$$HVGridMat_{reg,yr} = HVGrid_{reg,yr} * MI_{lines} + HVGrid_{reg,yr} * \frac{Units_{trns.\&\,sbst.}}{km} * MI_{trns.\&\,sbst.} \quad (3)$$

Where the HV line length (in km) is multiplied with the material intensity (MI) in kg/km of lines to get the materials in the lines, which is then summed with the materials in transformers and substations to yield the materials in the HV grid (HVGridMat) in kg. The stock of transformers and substations is expressed in units by multiplying the grid length (HVGrid) in km by the units per km based on literature (Harrison et al. 2010; Turconi et al. 2014). The material intensity (MI) for transformers and substations (trns. & sbst.) is thus expressed in kg/unit. The same equation is applied to get the materials in the medium- and low voltage levels, but with material intensities specific to the voltage level. Below, we elaborate on the current grid size calculation, followed by some more in-depth discussion on the assumed grid growth and the used material intensities.

We estimate the current size of the global electricity transmission and distribution network based on two sources. We use our own data based on the OpenStreetMap database for the year 2016, available from (OpenStreetMap contributors 2016) and a second dataset for the year 2019 based on (Arderne et al. 2020). We used Geographic Information System (GIS) software to extract the available grid-related infrastructural elements, such as electricity poles and transmission lines, to determine the length (in kms) of the High Voltage grid for each of the IMAGE model regions. Where possible, we correct and compare these findings with available national statistics as can be found in Table A6.4 in Appendix 6.

Subsequently we assume a fixed ratio between High Voltage lines and lower voltage distribution such as Medium Voltage (MV, 1-130 kV) and Low Voltage (LV, <1 kV) distribution. If no national data is available, we use a ratio of 2.85 km of MV network per km of HV lines and assume 17.4 km of LV distribution network per km of HV transmission lines, based on the sources detailed in Table A6.5 in Appendix 6. A further distinction is made between the fraction of the network that is underground versus the part of the network that is aboveground. Based on data from Eurelectric (Eurelectric 2013) as elaborated in Figure A6.2 Appendix 6. This leads to a total global electricity line length of 3 million km HV line, 10 million km MV line and 51 million km LV distribution line in 2016.

To derive the development of the stock of grid infrastructure towards 2050, we apply the indexed growth of the installed electricity generation capacity over the same period, according to the IMAGE-TIMER SSP2 scenario (van Vuuren et al. 2017) as indicated in equation 2. We feel that this is currently acceptable as a pragmatic approach given that there is no research or database describing the grid length and transmission capacity over time at the global level. This approach captures the most important drivers for network expansion, given that the IMAGE model accounts for a rising peak capacity as the average load drops in a renewable electricity scenario. By expanding the transmission network according to the growth in the generation capacity, we account for at least some of the additional demand for grid infrastructure in a system with high variability in the supply (Child et al. 2019). Additionally, the sensitivity analysis deals with alternative assumptions on the growth of the grid.

In order to assess the relevant stock dynamics, we applied a lifetime based dynamic stock model in python (Pauliuk and Heeren 2018) to calculate the inflow and the outflow as a result of the given infrastructural stock. Here, we used average lifetimes of 30 years for transformers and 40 years for all other elements (lines, stations), based on (Harrison et al. 2010; Turconi et al. 2014), in combination with a standard deviation based on (Balzer and Schorn 2015).

To complete the assessment of material requirements for electricity transmission and distribution, we calculate the requirements for auxiliary grid elements such as transformers and transformer sub-stations on a per km basis, based on detailed life cycle assessment studies (Jorge et al. 2012) on Great Britain (Harrison et al. 2010) and Denmark (Turconi et al. 2014) as given in Tables A6.6-9 in Appendix 6. Finally, we apply the material intensities to derive the materials contained in the global grid infrastructure. An example of the material intensities for transmission and distribution lines is given in Table 6.1.

6.2.1.3 Electricity Storage Capacity

For the estimation of materials required in electricity storage, we use the total amount of storage required according to the IMAGE model (see Figure 6.1). This is calculated using regionally specific residual load duration curves (RLDCs) as described by (Ueckerdt et al. 2017) and implemented into the IMAGE model as described by de Boer et al (de Boer and van Vuuren 2017). Using this method, ensures an optimal deployment of electricity storage capacity, given the changing levels of penetration of wind and solar energy as variable renewable energy sources. As wind and solar energy have different intermittency profiles, the specific combination of wind and solar shares results in a different demand for storage as elaborated in Figure A6.4 in Appendix 6.

Table 6.1. *Material Intensities on High, Medium and Low Voltage network lines (ton/km) based on* (Jorge et al. 2012; Turconi et al. 2014; Harrison et al. 2010)*, for details on the composition of auxiliary grid elements (transformers and substations), please see Appendix 6.*

	High Voltage		Medium Voltage		Low Voltage	
	Over-head	Under ground	Over-head	Under-ground	Over-head	Under-ground
Steel	52.3	-	0.80	-	-	0.18
Aluminium	12.9	-	-	0.82	0.98	0.53
Concrete	209.1	17.5	-	-	-	-
Copper	-	11.7	1.49	0.66	-	-
Glass	1.1	-	-	-	-	-
Lead	-	14.1	-	-	-	-

Given the total demand for electricity storage capacity over time, we apply a tiered approach to determine which technologies will be deployed to supply the actual storage capacity (please see the sensitivity analysis for alternative assumptions):

1) First, pumped hydro storage will be deployed according to the projections from (Rogner and Troja 2018)
2) Then, vehicle-to-grid (V2G) capacity is used, based on regional electric vehicle availability
3) Finally, dedicated (stationary) electricity storage capacity is built, using various technologies

Given that pumped hydro is the cheapest form of electricity storage (IRENA 2017), we simply assume that this is always deployed first and will therefore supply a considerable part of the required electricity storage capacity. However, the potential for deployment of pumped hydro storage is very region and site-specific (Carneiro et al. 2019), which is why we used the projections on availability of pumped hydro-storage capacity based on (Rogner and Troja 2018). Though these projections provide data only for a few regions and only until 2030, we used a regional disaggregation and assumed a continued growth of pumped-hydro storage capacity in accordance with the regular hydropower availability in the IMAGE model.

The second tier of storage capacity is the battery capacity of idle electric vehicles that is (partially) available to provide grid backup & stability through discharging from vehicle-to-grid (V2G). Though the concept of vehicle-to-grid is currently technically feasible (Lauinger et al. 2017), it is not yet a mainstream practice for most electric vehicle owners, due to barriers such as battery degradation or charger communication protocols (Noel et al. 2019). We assume that beyond 2025, provided the right incentives (Jian et al. 2018), battery electric cars will start to be available as a means for electricity storage, growing to large scale adoption towards 2040. In our model we assume that only privately owned cars are available for V2G, and that only a percentage of the battery capacity is available. The number of privately owned electric vehicles (plugin or full electric) is derived from a previous study (Deetman et al. 2018) and we assume a partial availability of 5% of the battery capacity of plugin-hybrid electric vehicles and 10% availability of the larger battery capacity in full electric vehicles. The total available battery capacity per car changes over time, as we assume that due to falling prices and an increase in energy density, the limiting factor to the battery capacity will be the weight of the battery pack in the vehicle. We use currently available car models for 2019-2020 to derive a current average battery capacity and use a fixed battery weight assumption, leading to an EV battery capacity that grows from about 60 kWh now, to roughly 120 kWh by 2040; see Appendix 6 for an elaboration.

The final tier of so called ‘dedicated’ (i.e. stationary) electricity storage technologies is the remainder between the storage demand and the available supply from pumped hydro storage and electric vehicles (tier 1 & 2).

To find the relevant technologies for dedicated (stationary) electricity storage capacity we elaborate a market-share model based on price and storage performance indicators for 17 electricity storage technologies, including various battery-types as well as mechanical storage technologies. The assumptions on the performance of storage technologies for dedicated electricity storage are based on an elaborate review of 23 studies (Majeau-Bettez et al. 2011; Wikipedia 2019; IRENA 2017; Batteryuniversity.com 2019a; Berg and Zackrisson 2019; Xu et al. 2017; Yang et al. 2014; Gür 2018; Van den Bossche et al. 2010; Rydh 1999; Batteryuniversity.com 2019b; Li et al. 2016; Patel 2016; Deng et al. 2017; Yu et al. 2019; Albertus et al. 2018; Collins and BloombergNEF 2019; Gerssen-Gondelach and Faaij 2012; Zackrisson et al. 2016; Tan et al. 2017; Zhu et al. 2016; Gallagher et al. 2014; Luo et al. 2015; Gardiner 2014), which were summarized in a table with indicators on energy density, cycle-life, efficiency and price, as given in Appendix 6 (Table A6.13).

Subsequently, a review of the material composition for each of the 17 storage technologies was based on 15 additional studies (Majeau-Bettez et al. 2011; Cusenza et al. 2019; Nelson et al. 2019; Dakota Lithium 2019; Olofsson and Romare 2013; Chen et al. 2015; Rydh 1999; Sullivan and Gaines 2010; Van den Bossche et al. 2010; Deng et al. 2017; Zackrisson et al. 2016; Axpo 2018; Eller et al. 2018; Liu and Chen 2015; Azo Materials 2020; Werfel et al. 2008; Moss et al. 2013) and is summarized in an overview of the material composition as given in weight percentages in Table A6.14 in Appendix 6. By default, the material composition (in wt%) of battery technologies is assumed to be static, but the energy density of storage technologies was assumed to change between 2018 and 2030, mostly based on projected changes according to (IRENA 2017). As a consequence, the weight per kWh of storage capacity will go down over time, and the material demand per unit of storage capacity will drop accordingly. In the sensitivity analysis we also explore the effects of a changing material composition of some battery types. With regards, to costs, we apply a decline in the storage costs (in US$/kWh) based on the projections by (IRENA 2017). Even after 2030, we assume a continued decline in the costs towards 2050, be it with a lower annual cost decline than before. We use the development of the storage costs to determine the market share of the newly installed storage capacity, by means of a multi-nominal logit function:

$$MS_{tj} = \frac{e^{-\lambda C_{tj}}}{\sum_{k=1}^{J} {}^{-\lambda C_{tk}}} \qquad \text{for } j=1,\ldots,J \qquad (4)$$

Where the market share of a technology *j* (MS_{tj}) is determined by its cost C_{tj} (in US$ per kWh delivered back to the grid), the costs of other technologies C_{tk} , and the multi-nominal logit parameter λ, which is calibrated against historic values according to the International Energy Agency (IEA 2017), see Appendix 6 for details. Figure 6.2 shows the resulting market shares of grouped electricity storage technologies.

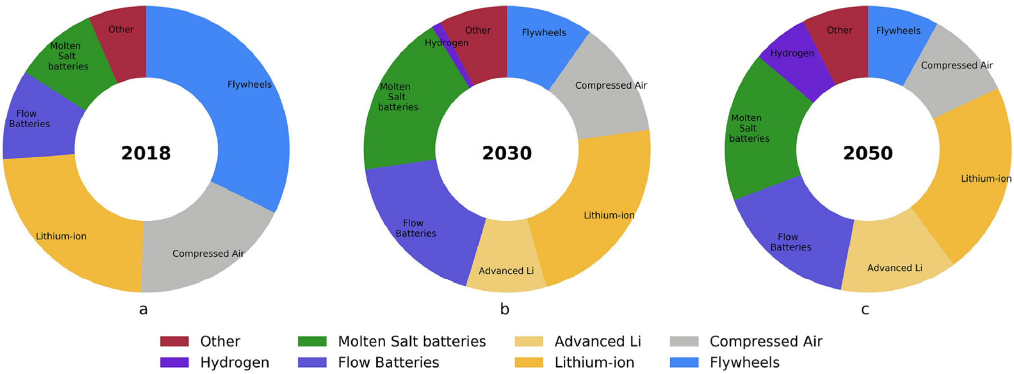

Figure 6.2a-c. *Assumed development of market shares for dedicated electricity storage technologies.*

6.2.2. Scenario assumptions

The model as described above can be applied with different scenario settings by changing the IMAGE data on generation capacity and electricity storage. We present results for the second shared socio-economic pathway (SSP2). The SSP2 scenario is commonly referred to as a middle-of-the-road scenario when it come to the development of population (towards 9.2 Billion people by 2050) as well as affluence (growing by a factor 3.4 between 2010 and 2050) (O'Neill et al. 2017; Riahi et al. 2017). In the results section we show outcomes for the material use in the electricity sector for the SSP2 baseline as well as the SSP2 2-degree scenario, which accounts for decarbonization efforts to limit global warming below 2-degrees above pre-industrial levels. Figure 6.3 shows the development of the drivers for the material model for the SSP2 Baseline and the 2-degree scenario. Here, total global generation capacity and total electricity storage are derived from the IMAGE model (see Figure 6.1). The development of the global grid and the disaggregation of electricity storage categories (also shown in Figure 6.3) are calculated in this study.

Figure 6.3a shows that the total electricity generation capacity in the SSP2 Baseline is expected to grow beyond 10 TW by 2050. A number that is expected to be slightly lower under climate policy assumptions of the SSP2 2-degree scenario, as a consequence of lower electricity demand due to strong energy efficiency measures. Given that we assume transmission growth to be in line with generation capacity, this influences the development of the transmission grid in a similar way as can be seen from panel 6.3c, however, in the following section we explore the effects of alternative assumptions on the expansion of transmission lines as part of the sensitivity analysis.

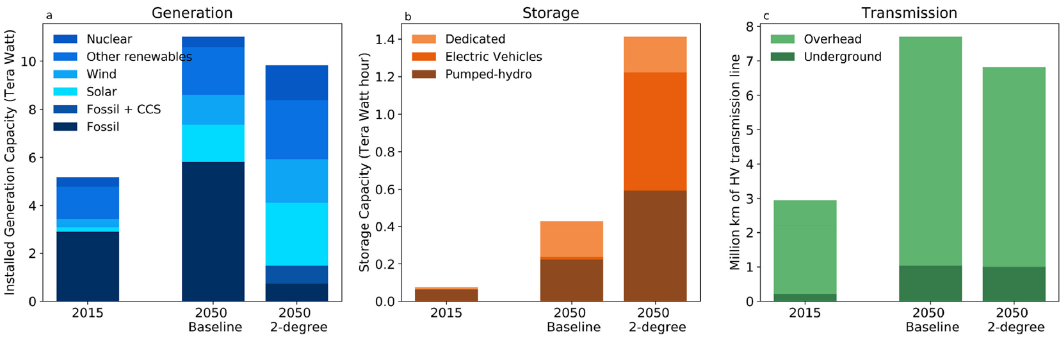

Figure 6.3a-c. *Global infrastructural components in the electricity sector, in the SSP2 Baseline and 2-degree scenario. Panel a) Generation Capacity in TW, b) Storage capacity in TWh c) High-Voltage Transmission line length in km. For regional details on the model drivers (generation & storage) please see Figure A6.3 and A6.8 in Appendix 6.*

The middle panel, Figure 6.3b, shows that the storage capacity is expected to grow, especially in the 2-degree scenario, but the availability of pumped hydro storage and battery capacity from electric vehicles would be nearly sufficient to provide the required storage capacity. As a result of our tiered modelling, we foresee a surplus storage capacity in electric vehicles in many regions if Vehicle-to-Grid technology becomes available, as elaborated in Figure A6.7 of Appendix 6. However, we do explore the effects of alternative assumptions on storage deployment, as part of the sensitivity analysis, in the following section.

6.2.3. Sensitivity analysis

The assumptions underlying the described model and the used scenarios encompass inherent uncertainty about possible developments into the future. To assess the sensitivity of the model outcomes to some of these assumptions we perform a sensitivity analysis by using three sets of alternative assumptions (i.e. three sensitivity variants) with regard to the development of storage, grid expansion and material efficiency. More information on the sensitivity analysis can be found in Appendix 6.

First, we define a 'high storage' sensitivity variant, in which we double the demand for storage towards 2050 (originally defined by the IMAGE model), while we halve the availability of storage in electric vehicles. Furthermore, the pumped hydro storage capacity does not grow beyond 2030, and of the remaining storage demand (after PHS) 50% is deployed as dedicated storage, loosely based on reflections by (Child et al. 2019; Laugs et al. 2020). Effectively, this means that we discard the tiered approach for storage deployment in this somewhat pessimistic sensitivity variant.

In the second sensitivity variant on 'alternative grid' developments we adjust the assumptions on the growth of the high-voltage (HV) grid to make the model more sensitive to the penetration of variable renewable energy sources (solar and wind). This is based on views in the literature that expanding HV transmission capacity could be a way to improve reliability as well as costs of electricity supply in regions with high levels of solar and wind (Koskinen and Breyer 2016; Laugs et al. 2020; Child et al. 2019; Berrill et al. 2016). Practically this means that we double the demand for grid lines in relation to generation capacity from solar and wind, while lowering the growth of the HV grid in relation to the other (baseload) generation technologies.

The third sensitivity variant aims to explore the effects of foreseeable changes in material content of some of the technologies used by adjusting the material intensities (up or down) towards 2050. In this 'dynamic material intensity' variant, we explore the effects on material use as a consequence of the following changes: 1) reducing cobalt content to zero in selected lithium-batteries, based on (Li et al. 2020b), 2) increasing the copper content of underground HV transmission lines by 13% to represent a possible increase in the adoption of high voltage direct current (HVDC) transmission, after (Chatzivasileiadis et al. 2013), 3) implementing an annual material efficiency improvement of 1% for steel and aluminium used in generation capacity based on wind and solar.

6.3 Results

The model presented in the Method section allows us to explore the amounts of different materials in stocks as well as inflow and waste flows for the electricity system as a whole; comprising of the electricity generation capacity, the transmission grid as well as electricity storage applications. In this section, we discuss the results for three selected materials, being steel, aluminium and neodymium. However, the full range of results on all eight materials is available in the Supplementary Information provided with the original publication, which covers both the SSP2 baseline as well as a 2-degree climate policy scenario.

Figure 6.4 shows the resulting global in-use stock of steel, aluminium and neodymium in the grid, the generation capacity and in electricity storage applications, under the SSP2 Baseline. It shows a steady increase of materials in stock for each of the three sub-sections of the electricity sector. However, the relative contribution of elements to the stock varies for the materials shown. Steel and aluminium use in the electricity grid is in the same order of magnitude, but the substations are responsible for a large fraction of the aluminium use, while transformers require more steel. In the electricity generation, the use for steel is widespread in all technologies, while the aluminium stock is projected to be dominated by solar PV applications and neodymium is mostly found in windmills.

Finally, the use of steel and aluminium in electricity storage applications is of much less importance in absolute terms, but here the Pumped Hydro dominates the steel stocks, while aluminium and neodymium stocks are dominated by mechanical storage like compressed air and flywheel technologies (where neodymium is used in permanent magnets).

The materials stocks contained in generation capacity displayed in Figure 6.4 and 6.5 continue to expand, even under the climate policy assumptions of the 2-degree scenario, despite lower installed capacities (see Figure 6.3a). This can be explained by the higher material intensities of renewable energy technologies. For example, the (global average) steel intensity of electricity generation would increase from 65 tons of steel per MW of generation capacity in 2015 to 101 tons of steel per MW of generation capacity (in-use, or stock) by 2050 under the 2-degree scenario. The material intensity of the generation capacity is expected to go up towards 2050 for most materials, however a few materials will have a lower material intensity per MW by 2050, as can be seen in Appendix 6 (Table A6.3).

Corresponding to the growth of total stocks, Figure 6.5 also details the resulting total annual inflow and outflow of steel, aluminium and neodymium at the global level. Here, the inflow relates to the total annual demand for these materials in the electricity sector, and the outflow indicates the corresponding availability of scrap materials resulting from decommissioned infrastructure.

As a consequence of the projected expansion of electricity infrastructure, the annual outflow of steel, aluminium and neodymium for the electricity sector will not be enough to cover the sectoral raw material demand through recycling alone. In fact, the mismatch between annual inflow & outflow towards the year 2050 indicates a serious challenge for establishing a circular economy when it comes to the electricity infrastructure.

Furthermore, the challenge of closing material cycles seems to be amplified under climate policy conditions of the SSP2 2-degree scenario, which causes an initial drop in annual material demand as a consequence of lower electricity demand due to energy efficiency measures, but subsequently leads to higher annual material demand due to the expansion of storage and generation capacity towards 2050. For steel specifically, the annual outflow in the 2-degree scenario increases at first, as a consequence of early retirement of fossil-based generation capacity. However, this development is offset by the expansion of renewable generation capacity, with higher material intensities, towards 2050. Though these results are highly dependent on scenario dynamics and assumptions on timing, the climate policy scenario seems to worsen the perspectives on circular material flows in the electricity sector by 2050, because it increases the annual material demand, while lowering the availability of scrap materials in the same period. Detailed results for all materials are shown in Table 6.2 as well as in Appendix 6.

Table 6.2 shows the total global stock, inflows and outflows of materials in the electricity sector for recent years, compared to the same indicators by the end of the scenario period, for both the SSP2 baseline and a 2-degree climate policy scenario. It shows that the stock as well as the annual demand for materials used in the electricity infrastructure is expected to rise between now and 2050 and that despite a slightly smaller stock in the 2-degree scenario, the continued expansion of renewable electricity generation likely adds to the annual material demand for most materials.

Table 6.2 also shows that the ratio between outflow and inflow of materials indicates that a relative shortage of secondary materials to fulfill the new demand for materials in the electricity sector continues to exist towards 2050 as a consequence of continued growth of the electricity demand, and a corresponding expansion of both grid infrastructure as well as generation and storage capacity. For most materials, the 2-degree scenario increases this gap towards a more circular use of materials in the electricity sector.

In order to get a feeling for the magnitude of the annual material demand of the electricity sector compared to other sectors, we compare these results to the current production (CP) globally of materials, based on (USGS 2017; Butler and Hooper 2019; Morimoto et al. 2019).

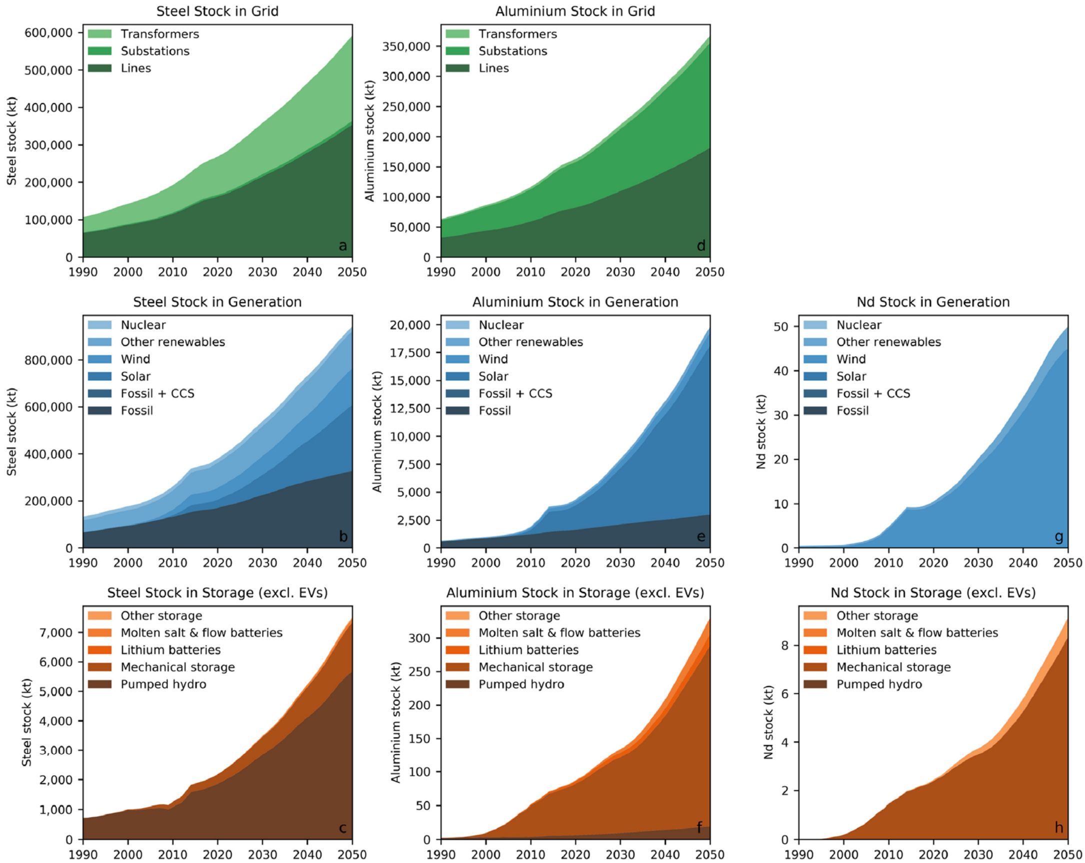

Figure 6.4a-h. *Steel, aluminium and neodymium (Nd) stock in the electricity sector between 1990 and 2050, in kt. The panel shows the SSP2 Baseline scenario results regarding the stock of Steel (left, a-c) and Aluminium (middle, d-f) and Neodymium (right, g-h) in the three sub sectors of the electricity sector, being: generation capacity (top), the transmission grid (middle) and electricity storage (bottom). Mind that the materials required for storage in electric vehicles are not displayed here because they are not strictly part of the electricity sector. The plateau in the material stocks for generation capacity around the year 2015 has to do with the IMAGE model adjusting to historic over-capacity. Panels for other materials and for the 2-degrees climate policy scenario are available in the supplementary information provided with the original publication.*

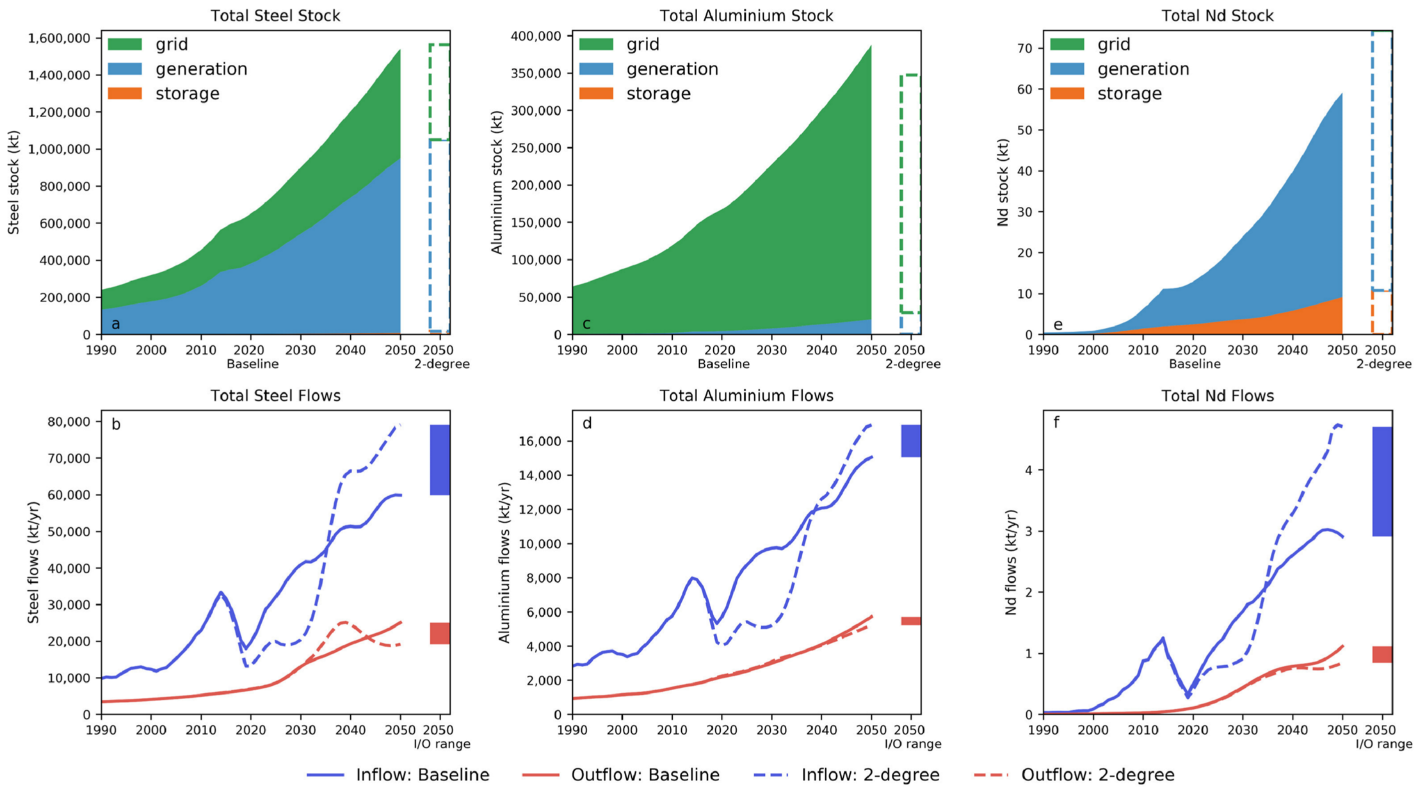

Figure 6.5a-f. *Total steel, aluminium and neodymium stocks (a,c,e) in the electricity sector and the corresponding material flows (b,d,f) in the SSP2 Baseline and the SSP2 2-degree scenario. Top panels display the stock in the SSP2 baseline as a stacked area chart and compare it to the size of the stock in the SSP2 2-degree scenario by 2050 (dashed bars). Lower panels display the inflow and the outflow of the materials under the SSP2 baseline (solid) and 2-degree (dashed) scenario. The range of the resulting inflow and outflow by 2050 is indicated by the blue and red bars respectively. Similar to Figure 6.4, the plateau in the material stocks for generation capacity around the year 2015 is a consequence of the IMAGE model adjusting to historic over-capacity, which also explains the drop in inflow for both the SSP2 baseline and the 2-degree scenario.*

This shows that the annual material demand (inflow) of the electricity sector is generally small compared to the current total global production for materials such as concrete, steel and glass, but for other materials such as copper and aluminium the electricity sector represents a considerable fraction of the total global demand. As the annual demand of the sector is expected to increase, so does the relevance with respect to the current production. Our estimates in Table 6.2 show that in a 2-degree scenario, by 2050 the electricity sector would represent up to 34% of the current global aluminium production and up to 28% of the current global copper production.

We find that by 2050, the annual copper demand in the electricity sector could exceed the copper involved in the construction of houses (Deetman et al. 2020). Even the speed at which the electricity sector expands may be larger than the growth in construction of housing (see Figure A6.11 in Appendix 6). So while the electricity sector is by no means the only cause for an increase in the global material demand (OECD 2019), it may play an increasingly important role in the demand for some materials such as copper and aluminium.

These outcomes are in line with other studies that provide projections on the material demand in the electricity sector, such as (Watari et al. 2019) who project a 2 to 9 fold increase in the demand for minerals associated with the electricity sector. Nevertheless, these outcomes are highly dependent on the timing of capital expansion. Our findings indicate the importance of developing suitable waste management practices for large infrastructural capital in the electricity sector. Our model results indicate a substantial rise in infrastructural waste flows is expected, and the expansion of the electricity sector could lead to an increased dependence on virgin raw materials. The combination of rapid growth of the capital stock and relatively long lifetimes (25-40 yr.) of technologies used in the electricity sector could lead to a mismatch between annual demand (inflow) for materials and the availability of secondary materials (scrap, or outflow) within the sector. The delay between increased material demand during stock expansion and the availability of scrap, decades later, would limit the potential for the sector to accomplish a circular flow of materials before 2050.

A general picture that emerges from these findings is that it depends on the material whether the electricity sector plays an important role in the global demand. However, mainly as a consequence of the use in the electricity transmission, the demand for copper and aluminium is considerable in comparison with other large demand categories such as residential buildings. Furthermore, the demand for most materials in the electricity sector is expected to grow rapidly, especially when accounting for the additional demand for materials under climate policy assumptions in the SSP2 2-degree scenario.

Table 6.2. *An overview of the stocks, inflows and outflows of materials in the electricity sector in 2015 and 2050, under the SSP2 baseline and the 2-degree climate policy scenario* (van Vuuren et al. 2017)*. Because inflow and outflow are volatile, the value indicated with 2015 is based on an average of the last historical model years (2010-2015) and the 2050 numbers are based on the average of the last years in the scenario period (2045-2050). The ratio column shows the outflow over inflow ratio and indicates the maximum percentage of the inflow that could be covered by the outflow of materials in the same year (when 100% of scrap would be recycled, without losses). The CP column indicates the inflow in the electricity sector as a percentage of total global current production according to* (USGS 2017; Butler and Hooper 2019; Morimoto et al. 2019).

	2015					2050 Baseline					2050 2-degree				
	Stock	Inflow	Outfl.	O/I	CP	Stock	Inflow	Outfl.	O/I	CP	Stock	Inflow	Outfl.	O/I	CP
	Mt	kt/yr	kt/yr	%	%	Mt	kt/yr	kt/yr	%	%	Mt	kt/yr	kt/yr	%	%
Steel	521	28,787	5,608	19%	1.8%	1,456	58,546	23,288	40%	3.8%	1,413	75,130	19,133	25%	4.8%
Aluminium	132	7,029	1,676	24%	14.7%	365	14,427	5,270	37%	30%	319	16,095	4,924	31%	34%
Concrete	4,772	184,782	31,173	17%	.69%	9,199	207,895	100,068	48%	.77%	8,396	227,571	85,347	38%	.85%
Glass	3	209	35	17%	.3%	23	1,257	255	20%	2%	41	2,662	263	10%	4%
Cu	38	2,086	571	27%	11.9%	98	4,256	1,828	43%	24%	91	4,934	1,611	33%	28%
Nd	0.009	1.0	0.04	3%	5.4%	0.055	3	1	32%	16%	0.064	4.4	0.8	18%	24%
Co	0.19	8	2.1	25%	7.9%	0.44	14	7	49%	13%	0.11	3.7	3.9	104%	3.4%
Pb	2.5	109	34	31%	2.1%	12.6	588	118	20%	11%	11.5	718	116	16%	15%

Even when total demand for electricity is expected to go down as a consequence of additional energy efficiency measures in a 2-degree scenario, the material intensity of renewable energy technologies leads to an increased demand for most materials used in electricity generation compared to the baseline. For more details on the outcomes of individual materials, and the full range of results for both the SSP 2 Baseline and the 2-degree scenario, please see the Supplementary Information provided with the original publication.

6.3.1 Results of the sensitivity analysis

Alternative model assumptions on the development of storage, grid expansion and material intensities as described in Section 6.2.3 only have a mild effect on the model outcomes for materials contained in the stock. The largest increase of in-use stocks is found for cobalt in the 'high storage' variant (+9%), while the largest decrease is found for steel (-7.7%) as a consequence of assuming a 'dynamic material intensity'. However, the effect of the three sensitivity variants on inflow indicators seems larger, in particular when implemented in a 2-degree scenario. This suggests that our model outcomes, especially results on annual material flows, are more uncertain for scenarios with rapid change and should therefore be interpreted with caution.

Though our model does not account for materials in vehicle batteries as these are not strictly part of the electricity sector, the sensitivity analysis does provide some insights into the importance of vehicle-to-grid services. The lower availability of storage capacity from pumped-hydro and battery electric vehicles in the 'high storage' sensitivity variant leads to an increased deployment of dedicated storage, which in turn leads to larger in-use stocks of materials by a factor 2.1 (for steel & copper) to 5.2 (for cobalt) compared to the default 2-degree scenario (See Table A6.16 in Appendix 6). This is higher than the expected increase from doubling the storage demand alone, and indicates that the availability of vehicle-to-grid storage capacity could help reduce the demand for materials in the electricity sector.

6.4 Discussion & conclusions

6.4.1 Discussion and model improvements

The key question of this chapter is how the global material stocks and flows related to the electricity sector will develop towards 2050. The model developed here is able to address this question, by showing the global stocks and flows of several materials related to the growing demand for electricity. These outcomes are relevant to a broader understanding of the societal metabolism (Pauliuk and Hertwich 2015) and its implications for curbing emission and attaining a more circular economy (Ghisellini et al. 2016). The model includes a number of key assumptions. Below we discuss the effect of these assumptions and how to possibly improve the model further.

First of all, we use our model in conjunction with outcomes of the IMAGE/TIMER model for the SSP2 baseline and 2-degree climate policy scenario. These scenarios prescribe the developments regarding the use of renewable electricity as well as the adoption of electric vehicles, for example. The outcomes of our model on resulting material stocks and annual demand are only valid in the context of this scenario selection. It would be interesting to explore the material implications of other scenarios with a higher penetration of renewable electricity and electric vehicles.

Secondly, we think that our work could benefit from an improved formulation of the development of the demand for transmission capacity of the electricity grid over time. Though we apply a set of alternative assumptions on grid expansion in a sensitivity analysis, ideally, our assumptions should be compared to scenarios from a spatially-explicit global transmission model, which unfortunately is not available at this time.

Thirdly, we should emphasize that our model assumes fixed material intensities for grid elements and generation technologies, by default. Even though our model accounts for a change in energy density of storage technologies, and the effects of some foreseeable changes in material composition are explores in the sensitivity analysis, we are unable to account for all relevant developments in the material composition of technologies. It would therefore be interesting to improve these assumptions in a future study, which may also expand the coverage of materials.

Finally, an integration of this type of work into integrated assessment models could be used to define an explicit feedback loop between material and energy demand, thus improving the modelling of long term emission scenarios (Pauliuk et al. 2017).

6.4.2 Conclusions

On the basis of the results is possible to derive several key conclusions.

The electricity sector will likely be responsible for a large increase in annual material demand towards 2050. Using the IMAGE/TIMER implementation of the SSP2 scenario and a scenario consistent with the Paris Agreement, we show that material demand for generation, transmission and storage is expected to increase. Most notably, we show that the electricity sector contributes substantially to the annual demand for materials such as aluminium and copper. While annual demand for steel and aluminium in the electricity sector is expected to roughly double in the SSP2 baseline, the aluminium demand in the 2-

degree scenario grows from 7 Mt in 2015 to around 16 Mt by 2050, and steel demand is expected to go up from 29 Mt in 2015 to 75 Mt by 2050. For Neodymium a growth factor of about 3 is found in the baseline, increasing to 4.4 in the 2-degree scenario. Copper demand grows from about 2 Mt now, to about 5 Mt by 2050. This means that by the end of the scenario period, the annual demand for copper and aluminium in the electricity sector may reach about 28% to 34% of the current annual global production (respectively).

The combination of rapid growth of the capital stock and relatively long lifetimes of technologies used in the electricity sector comprises a challenge to reaching a more circular economy. Given that the annual demand (inflow) of most analyzed materials will continue to surpass the availability of secondary materials (outflow) within the sector.

Climate policy could influence material demand in the electricity sector in different ways. In the analyzed scenarios the additional climate policies cause a higher annual energy efficiency improvement, which consequently requires a lower installed capacity of electricity generation technologies by 2050. In our study this leads to a lower amount of materials in infrastructural stock of the grid, but for the generation it still results in a larger stock as a consequence of higher material intensities of renewable generation technologies. In terms of annual material demand, climate policy seems to make it more difficult to reach circular material flows in the electricity sector by 2050.

6.4.3 Policy implications

While the electricity sector is by no means the only contributor to an increase in the global material demand in the coming decades, the expected rate of growth in the infrastructure required to generate, transmit and store electricity could mean it will be increasingly important in the demand for materials towards the year 2050. To mitigate some of the environmental impacts related to the production of these materials, regional policies could be aimed at adequate deployment of recycling capacity and stimulating material efficiency. Our analysis shows that material use in renewable energy systems is not only interesting from the perspective of the often-highlighted critical raw materials in storage applications. The demand for bulk materials in the infrastructure for the transmission and generation of electricity should also be accounted for in scenarios looking at the development of future energy systems. Higher material intensities for renewable generation technologies, and the required expansion of transmission and storage capacity in a renewable energy system imply a higher annual demand for most considered materials under climate policy ambitions. This seems to present an apparent trade-off between ambitions related to climate policy and circular economy policy, given that the long lifetimes of capital stock and the additional increase of the material demand resulting from a renewable energy system will make it more challenging (if not impossible) to achieve circular material flows in the electricity sector before 2050. However, this work does not encompassingly assess the material use implications of electrification in other sectors, which would be required to confirm such a trade-off. Nevertheless, the deployment of additional infrastructure in the electricity sector could ultimately enable the reliable production of low-carbon electricity at low costs. The enticement of this perspective could justify policies aimed at optimal timing of the deployment of transmission capacity, dedicated storage & vehicle-to-grid services, in order to limit the impacts of additional material demand from the electricity sector as much as possible.

Practically, our analysis highlights the potential of electric vehicles to provide electricity storage capacity to balance supply and demand on the grid. Though the concept of bidirectional charging or vehicle-to-grid (V2G) services is not yet applied on a large scale, it provides a promising opportunity to avoid demand of materials that would otherwise be required to install dedicated electricity storage towards 2050. Our analysis presents an optimistic picture in the sense that it assumes the availability of pumped-hydro storage as well as a slow adoption of storage in electric vehicles after 2025. Under these conditions, climate policy seems to provide a synergetic solution to its own problem as the additional demand for electricity storage could be fulfilled with a simultaneously growing battery capacity of the increased electric car fleet, in line with the SSP2 2-degree scenario. The increase in material demand under less favorable assumptions on storage demand in the sensitivity analysis emphasizes the importance of stimulating and governing the effective deployment of synergistic technologies such as vehicle-to-grid storage in a renewable energy system over the coming years.

Acknowledgements

Our model uses the open sousrce python Dynamic Stock Model as developed by Stefan Pauliuk and described by Pauliuk and Heeren (2019).

Appendix

More information regarding details of the analysis and assumptions made in this chapter are available in Appendix 6.

7.

A baseline scenario for material use in vehicles

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This chapter has not been published, but is added to provide perspective and is used in the synthesis, Chapter 8.

Abstract

In order to estimate the future contribution of vehicles to global material use, we present a model that translates a given demand for freight and passenger transport into the in-use vehicle stocks, both in terms of number of vehicles as well as their weight and material composition. Subsequently, we apply vehicle lifetimes in combination cohort-specific dynamic stock modelling to come up with the corresponding annual material flows related to vehicle production and decommissioning. We use the IMAGE model elaboration of the second Shared Socio-economic Pathway scenario to present the baseline developments of global vehicle-related material stocks and flows, without assuming additional climate action or material efficiency strategies.

Results show that, given current trends, global vehicle stocks as well as their corresponding annual demand for materials are likely to roughly double between now and the year 2050, mostly as a consequence of passenger car use. The inflow of materials required for vehicle production will continue to be larger than the corresponding outflow of decommissioned vehicles, thus presenting a challenge for achieving fully circular material flows in the transport sector, both with regards to bulk materials in vehicle bodies as well as for critical raw materials used in batteries for electric cars, buses and trucks. However, we also identify some regions for which in-use stocks of specific vehicles will shift from being a net sink to a source of materials, as a consequence of stabilizing population and saturating vehicle stocks. The presented model can thus be used to dynamically assess the global role of materials in vehicles and could complement existing transport models to better capture the synergies and trade-offs of climate and resource-oriented policies.

7.1 Introduction

The demand for transportation, be it of passengers or freight, causes about a quarter of global greenhouse gas emissions (Zhang and Fujimori 2020). Efforts to reduce the climate impacts of transport activities are currently being developed and deployed worldwide (Creutzig 2016; Zhang and Fujimori 2020). While the focus of many of these efforts has been primarily on the energy use through improvement of energy efficiency (Keith et al. 2019; Yeh et al. 2017), the use of alternative fuels (Edelenbosch et al. 2017) or new drivetrains in vehicles (Gómez Vilchez and Jochem 2020; Lombardi et al. 2020), some studies have drawn attention to possible trade-offs with respect to vehicle material use (Busch et al. 2014; Deetman et al. 2018; de Koning et al. 2018; Watari et al. 2019; Hertwich et al. 2019), and the related environmental impacts (Van der Voet et al. 2019; Watari et al. 2021).

While various studies have focused on the possible role of vehicles in driving the future demand for critical raw materials (Jones et al. 2020; Månberger and Stenqvist 2018), the current importance of bulk material use in vehicles, has previously been addressed using tools like Material Flow Analysis and Economy Wide Material Flow Accounting. Indicating that at the global level, the production of vehicles is responsible for about 13% of annual global steel demand (Cullen et al. 2012; IEA 2020), 8% of annual copper demand (Yoshimura and Matsuno 2018) and about 20-26% of annual aluminium demand (Cullen and Allwood 2013; Jones et al. 2020; Liu et al. 2012).

Such global overview studies, however, often lack the level of detail required to distinguish the role of different transport modes or vehicle technologies in driving the annual material demand. Even though these are essential and dynamic determinants of the development of vehicle related environmental impacts (Kaack et al. 2018; Cuenot et al. 2012; van Vuuren et al. 2017a; Mittal et al. 2017). Some exceptions exist, such as a recent study by the International Resource Panel (Hertwich et al. 2020) and some relevant regional analyses (Wang et al. 2015; Giljum et al. 2016; Liu et al. 2020) or studies addressing only one vehicle type (Habib et al. 2020). These show that the integration of a detailed material perspective in transport models is required in order to get a more comprehensive understanding of the future role of materials in a rapidly changing transport sector worldwide, which would enable the consistent and simultaneous assessment of policy objectives related to both climate change and the circular economy (Pauliuk et al. 2017).

This study aims to take a first step, and adds to the existing knowledge on material use in vehicles by developing a comprehensive model that generates long-term insights in the global material stocks as well as the corresponding material in- & outflows related to all vehicles, both passenger & freight, based on readily available international scenarios from the shared socio-economic pathways (Riahi et al. 2017). The model covers both bulk and critical material use in a range of vehicles and drivetrains, so that results are relevant with respect to material scarcity analysis as well as with respect to identifying the impacts of vehicle production, both now and into the future.

The analysis in this chapter is limited to a so-called baseline in the sense that it does not address fleet changes due to additional climate policy efforts, nor does it implement increasing material efficiencies or circular economy strategies related to vehicles. While the simultaneous assessment of climate and resource oriented policies would ultimately be the purpose of the developed model, we think that a description of the basic assumptions and relevant ongoing developments in the transport sector could contribute to a valuable understanding of the global importance of materials in vehicles.

7.2 Methodology

We use existing IMAGE model output for the Shared Socio-Economic Pathways as a starting point for our analysis and model development, because of their global coverage as well as their consistent narratives with a long term perspective (Riahi et al. 2017). For the purpose of this study, and similar to the approach in other chapters, we choose to work with the SSP2 baseline as it resembles a so called ‘middle of the road’ scenario without dramatic deviations from observed trends in the projections for population, affluence and lifestyles (van Vuuren et al. 2017b). Though it may be possible and worthwhile to explore the implications of other SSP baseline scenarios or their climate policy variants, the purpose of this chapter is to explore and document the basic model on material use in vehicles based on the IMAGE model output. More details regarding the narrative of the SPS2 scenario can be found in Appendix 1.

7.2.2 Number of vehicles and their weight in stock

The IMAGE model provides the global demand of passenger kilometers and tonne-kilometers and their modal split based on a model developed by (Girod et al. 2012); shown in Figure 7.1 are the model outcomes for the SSP2 baseline scenario as elaborated in (van Vuuren et al. 2017b). This demand for transportation is translated into the number of vehicles, by type, that were required to fulfill this service. To do so, we apply average capacity, load factors and mileage per vehicle type as detailed in Table 7.1. The vehicle weights indicated in the same table are subsequently used to derive the total weight of the in-use vehicle fleet, by vehicle type. These weights refer to the vehicle body including wheels and drivetrain, the weight and the composition of batteries used in electric vehicles is accounted separately in Section 7.3.

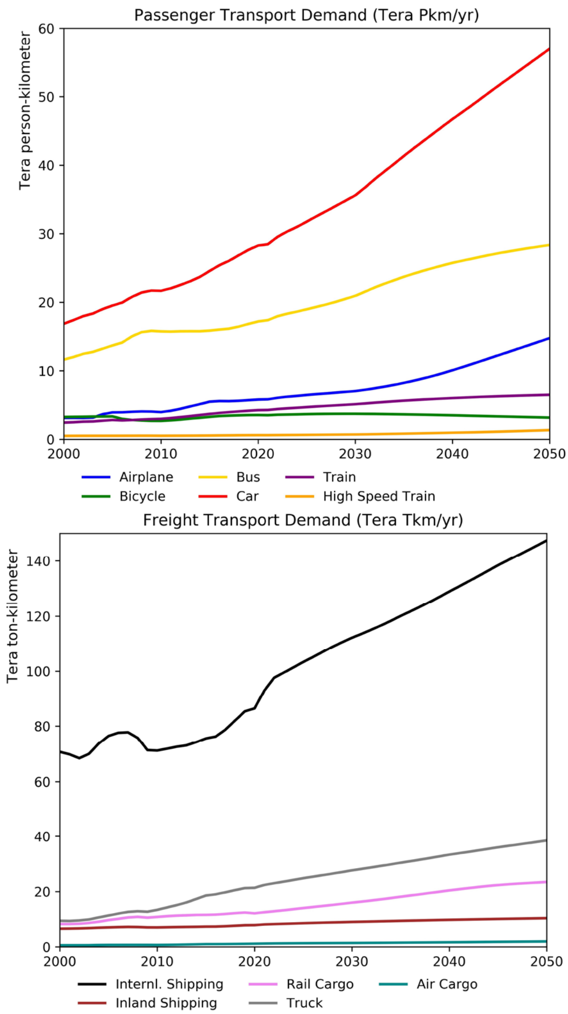

Figure 7.1. *Passenger & Freight Transport Demand in (Tera Pkm or Tkm) in the IMAGE model SSP2 scenario (2020).*

Table 7.1. *(page 138) Summary of the assumptions on current loads, mileage and body weights of vehicles. *mileage & load factor for cars & buses shown here are an average of the regional mileage applied based on the indicated sources, car weight is an average of different drivetrain types applied based on* (Hawkins et al. 2013)*, so (plugin-) electric vehicles have heavier bodies.** While the load factor for trucks is set to 100% because the indicated capacity represents average load, given by* (IEA 2017)*, the load factor for passenger trains is assumed to be 100% as a global average between relatively low occupancy rates typically reported in European studies and high occupancy rates in regions like India and China as reported by* (IEA 2019)*. *** The indicated capacities for international shipping are for 2018, the model applies dynamic assumptions between 2005-2018 based on* (Equasis; UNCTAD 2005)*.*

Passenger Vehicle	Type	Mileage (km/yr)	capacity (persons)	Load factor (%)	Empty weight (kg)	sources
Airplane		2,133,500	206	82%	60,558	(Airliners.net 2020; Airbus 2020, 2019; Boeing 2020b)
Train	Regular	138,500	400	100%**	252,000	(Connor 2011; Railfaneurope.net 2020; NS 2020; Messmer and Frischknecht 2016a; Spielmann et al. 2007; IEA 2019)
	High Speed	393,300	472	69%	424,000	(UNECE 2017; Doomernik 2015)
Bus	Regular	51,000*	57	43%	14855	(Huo et al. 2012; Schoemaker 2007; Ford 2019a; IVECO 2010; Mercedes-Benz 2020, 2018; ISUZU 2020; BYD 2019; Energy 2018; ABA Foundation 2016; Federal Highway Administration 2010; Kuhnimhof et al. 2017; CBS 2019; Statistics Norway 2020; Hill et al. 2015; Goel et al. 2015; Domingo et al. 2015; Oanh and Van 2015; UITP 2017; Adra et al. 2004; U S Department of Transportation 2019; Özdemir et al. 2015; Zheng et al. 2014; Liu et al. 2019; Yan and Crookes 2009; Singh et al. 2017; ADB 2018; Federal Highway Administration 2020)
	Midi	57,300*	23		7324	
Bicycle		2,400	1	100%	17.2	(Chang et al. 2012; Bonilla-Alicea et al. 2020; Leuenberger and Frischknecht 2010)
Car		14,200*	4	45%*	1500*	(Deetman et al. 2018; Girod et al. 2012; Hawkins et al. 2013)
Freight Vehicle	**Type**	**Mileage (km/yr)**	**capacity (tonnes)**	**Load factor (%)**	**Empty Weight (kg)**	**sources**
Airplane		2,133,504	61	49%	95843	(Casanova et al. 2017; Airliners.net 2020)
Rail		67,484	4,165	45%	1,764,500	(Railway Association of Canada 2018; Messmer and Frischknecht 2016a; Furtado 2013; Dick et al. 2019; IRG-rail 2013; Bureau of Transportation Statistics 2017)
Truck	Light Commercial	13,000	0.74	100%**	1,728	(IEA 2017; Tu et al. 2014; Ligterink 2016)
	Medium	37,000	7.95		8,229	
	Heavy	52,000	14		15,947	
Shipping	Inland	26,677	1,250	71%	322,000	Estimates based on (Bačkalov et al. 2014; Spielmann et al. 2007; Maraš 2008; CCNR 2020)
Inter-national shipping	Small	27,000	375***		77,625	(Equasis; UNCTAD 2005; Spielmann et al. 2007; Kristensen 2013)
	Medium		8,215***		1,306,200	
	Large	100,000	53,051***	65%	7,639,300	
	Very Large	145,000	147,805***	50%	19,510,300	

The transport demand is described by the SSP2 baseline scenario, as displayed in Figure 7.1, and is the result of trends in both population and GDP of 26 regions, combined with assumptions on converging travel time budget (TTB) and travel money budget (TMB) as detailed in (Girod et al. 2012). Passenger transport demand, expressed in person kilometers, continues to be dominated by travel by car, while the majority of freight movement, expressed in ton kilometers, is provided through international shipping. The stock of vehicles required to fulfill the given demand on an annual basis is consequently determined using the vehicle specific mileage, capacity and load factor as detailed in Table 7.1.

Some exceptions are made with respect to the calculation of in-use stocks of vehicles for cargo planes, buses, trucks and international ships. The number of cargo planes is halved given that about 45% of air cargo is moved in the surplus cargo space of passenger aircrafts (Boeing 2020a; Airports Council International 2019). While the IMAGE model discerns different vehicle drivetrains, it only distinguishes one bus size and two sizes of trucks (heavy and medium), our analysis expands the coverage of vehicle sizes by adding a smaller midi-bus and a Light Commercial Vehicle (LCV) truck with a Gross Vehicle Weight below 3.5t. We do so, to capture the higher material intensity per ton-kilometer or per person-kilometer for smaller vehicles. Practically, we maintain the total IMAGE transport demand but assign 6% of bus travel to midi-buses based on data in Table 7.1 & (UITP 2019) and we assign 4% of the Tkms by truck to Light Commercial Vehicles, based on (IEA 2017). Finally, we disaggregate the total demand for international shipping to small, medium, large and very large vessels based on sources shown in Table 7.1 and we account for the known development of fleet and ship capacities between 2005 and 2018 based on (Equasis; UNCTAD 2005) as shown in the Appendix 7. Capturing these dynamics in shipping fleet and vessel sizes is important to address the increasing material efficiency of freight transport by increasingly larger ships.

7.2.3 Vehicle fleet validation

Where possible we compare model outcomes to available estimates of current vehicle fleet sizes based on literature as shown in Table 7.2. The basis for comparison here is the total number of vehicles in use. It can be seen that, in general, the model performs better for passenger vehicles than for freight vehicles, when comparing to literature estimates. We'll elaborate on some of the observed model mismatch below.

The model mismatch may be caused by various sources, such as the originally modelled demand for transportation (in pkms/yr or tkms/yr) which is known to be highly uncertain (Yeh et al. 2017), by the assumptions in translating annual demand to the number of vehicles in-use, or by the lack of reliable global statistics on vehicle stocks. While at a first glance, the comparison may seem to suggest considerable model inaccuracies or even systematic underestimation of vehicle stocks, in most of the cases where the model deviates more than 10% from the available literature sources, the high deviation could be explained by the transport demand (in pkm/tkm, see Figure 7.1) as provided by the IMAGE model. For example, the used travel demand by passenger airplanes is exactly 33% lower in 2018 as reported by (IATA 2019) and, similarly, the person kilometers traveled by bus according to the IMAGE model are higher than reported by (ITF 2019), possibly explaining the higher results in terms of vehicle count.

The same holds for most freight vehicles, where the model predicts about 4 times more cargo planes, but this is driven by the IMAGE data, which prescribes about 4 times as much Tkms shipped by air than reported by (IATA 2019). Similarly, the used estimates of Tkm demand by trucks and international ships are about 30% lower than reported in (IEA 2017) and (UNCTAD 2019), thus explaining the majority of the mismatch in the number of vehicles. While this does not mean that the calculated number of vehicles, or the subsequent material calculations, are undisputable, it seems to suggest that generally, there is a large uncertainty when it comes to travel and transport demand at the global level.

While it is currently beyond the scope of the analysis in this chapter to resolve all these uncertainties, we develop a model that accounts for the number of vehicles and their composing materials based on the available information, while acknowledging that further validation and consolidation of global vehicle fleet statistics, both with regard to annual demand, the total number of vehicles, or details regarding average mileage, capacity and load, would be valuable to improve the model. We will elaborate on these and other possible model improvements in the discussion section.

7.2.4 Material in Vehicle Bodies

Given the total number of vehicles and their weight, we derive relevant material fractions based on the vehicle composition shown in Figure 7.2, which was derived from 20 studies, detailed in Table A7.1 in Appendix 7. Here, we consider the materials in the vehicle body, the wheels, as well as the drivetrain. The figure shows a variable material composition with a high fraction of steel in cars as well as in heavy vehicles such as buses, trains, ships and trucks. Aluminium seems to be more commonly used in passenger vehicles than in freight vehicles, with the exception of cargo planes.

***Table 7.2.** Validation of current global stock estimates (nr. of vehicles in use). In case multiple sources are used, the year of comparison is an average. * For some vehicles, the comparison is based only on selected regions (here, the numbers do not indicate global totals), e.g. inland shipping is compared only for the sum of Europe, China, the US and Russia. In addition, an overview of regional data and other assumptions regarding trains is given in Appendix 7.*

Passenger Vehicle	Year of compa-rison	Current model (SSP2 new)	Literature estimates	model devia-tion	Literature Sources
Airplanes	2017	15,481	23,000	-33%	(Airbus 2019; Mazareanu 2019; Morris 2017; Boeing 2018)
Trains*	2017	50,870	54,852	-7%	(IEA 2019; Railway Association of Canada 2018; National Bureau of Statistics of China 2021; Lawrence et al. 2019; Bureau of Transportation Statistics 2019; National Transit Database 2019; Rail Freight Forward 2020; Eurostat 2020; Deutsche Bahn 2019; NS 2018; Trenitalia 2018; Department for Transport 2018; JR East 2017; UIC 2018)
High Speed Trains	2019	4,697	4,959	-5%	(UIC 2020)
Buses	2016	12,000,000	10,400,000	15%	(SCI Verkehr 2017)
Bicycles	2014	1.37 Billion	1 to 2 Billion	-9%	Estimate based on (Sibilski 2016) sales in (Mason et al. 2015)
Cars	2016	1.02 Billion	1.1 Billion	-7%	Adjusted from (Yeh et al. 2017; Li and Chen 2019)
Freight Vehicle	**Year of compa-rison**	**Current model (SSP2 new)**	**Literature estimates**	**model devia-tion**	**Literature Sources**
Airplanes	2017	8,051	1,920	319%	(Airbus 2019; Mazareanu 2019; Morris 2017; Boeing 2018)
Trains*	2016	74,560	83,566	-11%	(IEA 2019; Railway Association of Canada 2018; National Bureau of Statistics of China 2021; Lawrence et al. 2019; Bureau of Transportation Statistics 2019; National Transit Database 2019; Rail Freight Forward 2020; Eurostat 2020; Deutsche Bahn 2019; NS 2018; Trenitalia 2018; Department for Transport 2018; Murray 2014; EBRD 2016)
Trucks	2015	108,000,000	186,000,000	-42%	(IEA 2017)
Internatio-nal ships	2018	52,900	76,000	-30%	(Equasis 2019; IHS Maritime & Trade 2019)
Inland ships*	2015	147,400	222,000	-34%	(Rail Freight Forward 2020; Wong 2019; Buzby 2018; Klyavin 2010)

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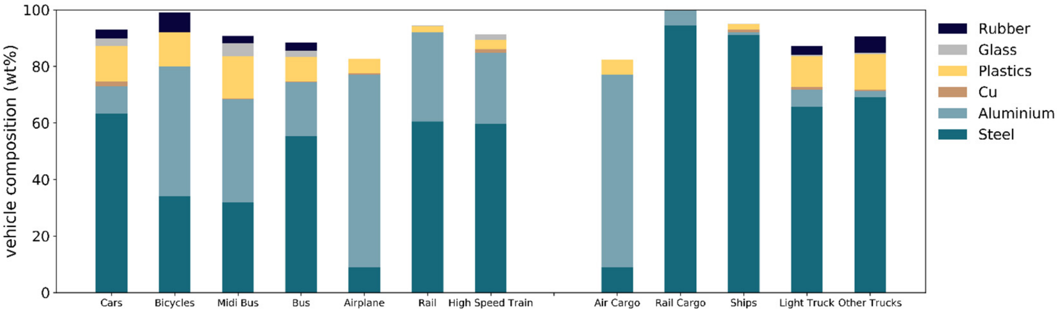

Figure 7.2. *Vehicle material composition (wt%). Average values as applied in the calculations, based on a literature review (see Table A7.1 for details).*

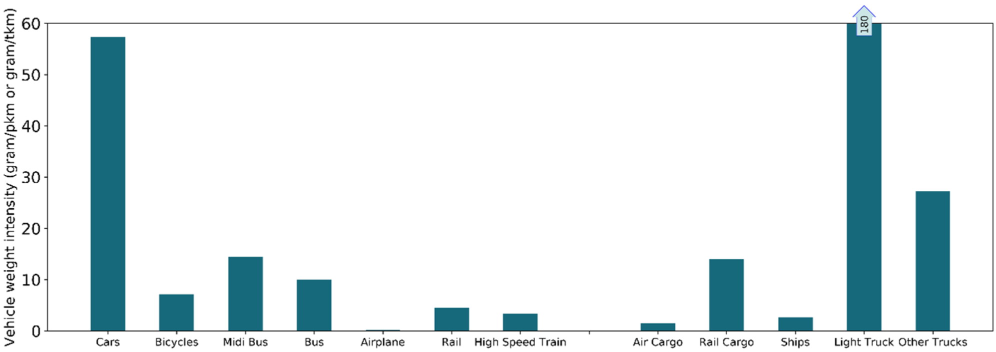

Figure 7.3. *Weight of the current in-use stock, by vehicle, required to provide 1 ton-km or 1 person-km on a yearly basis. The data represents an aggregate indicator of the total weight of vehicles in-use (stock) over the total person-kilometers (for passenger transport) or ton-kilometers (for freight) provided in a year (2018 is used as a basis).*

Figure 7.3 shows the variation in material requirements by vehicle type in order to fulfill the same transport service, either for passenger travel (pkms) or movement of freight (tkms). It shows that travel by car is rather material intensive, while bicycles, trains and especially airplanes require relatively small amounts of materials per pkm to operate. The latter is not surprising, given that airplanes need to fly, but it does not mean that air travel is environmentally friendly, just that airplanes are lighter. However, an overview like presented in Figure 7.3 can be used to identify possible trade-offs between climate-oriented transport policies and material demand. For example, switching from air travel to any other vehicle may have an overall benefit on emissions and the environment (Dobruszkes 2011), but it would present an often overlooked trade off in terms of material efficiency. Alternatively, stimulating a switch from car ownership to more cycling will not only address the impacts of fuel combustion, but also lead to a lower demand for materials.

In freight transport, the range of in-use vehicle stocks per tkm delivered on a yearly basis is lowest for ships and air cargo, but the vehicle weight intensity of light commercial trucks is a factor 5 higher than any other freight vehicle. While this is mostly a consequence of the used assumptions on cargo capacity and annual mileage (Table 7.1) this indicates that even if trucks become fully emission free (e.g. electrified), additional environmental benefits could be attained from optimized logistics and ride planning.

7.2.5 Materials in vehicle batteries

7.2.5.1 Battery weights

The IMAGE SSP2 scenario elaboration assumes the use of batteries in (partially) electric cars, buses and trucks. Given that the number and the share of (plugin/hybrid) electric vehicles is known, we apply a given battery weight per vehicle to derive the total use of batteries in vehicles over time. The default assumptions with regard to battery weight are shown in Table 7.3 below.

Combining the vehicle stock (in number of vehicles) detailed in section 7.1.2 with the weight of batteries in different vehicle types as shown in Table 7.3 gives the total weight of batteries in use. The following sections will elaborate how this was further used to derive the related material use.

Table 7.3. *Battery weight by vehicle (in kg). These represent the assumptions on current battery weights. Battery weights for Hybrid Electric trucks & buses are highlighted with an *, and are derived using a PHEV to HEV ratio based on passenger cars.*

Vehicle	Variant	HEV	PHEV	BEV	Trolley	Sources
Bus	**Regular**	96.9*	194	1256	118	(Ebusco 2020; US Department of Transportation 2017; Gallo et al. 2014)
	Midi	38*	76	546	-	(Gallo et al. 2014; Gao et al. 2017; Volvo 2020)
Truck	**Light Commercial**	27.6*	55.2	254	-	(Pelletier et al. 2014; California Air Resources Board 2015; Gnann et al. 2013; Ford 2019b)
	Medium	41.9*	84	540	-	(den Boer et al. 2013; Ippoliti and Tomić 2019)
	Heavy	69.1*	138.4	901.6	-	(Pelletier et al. 2014; Scania 2020; DAF 2020; den Boer et al. 2013; Gallo 2016; Bisschop et al. 2019; National Research Council 2012)
Car	**Electric**	20.8	44.8	240	-	(Deetman et al. 2021; Nelson et al. 2019)

7.2.5.2 Battery markets & materials

Given the beforementioned assumptions on the total weight of batteries we used additional assumptions on the share of the weight (wt%) of batteries used in new vehicles to find the total weight by battery type. To do so, we combined historic data on mobile battery market shares from (Li et al. 2018) with a moving average of cost-based scenario outcomes from (Deetman et al. 2021), leading to a market development as shown in Figure 7.4a. This market share is input to the material model and battery markets are assumed to be a homogeneous global market, so it is applied to all regions in the material calculations. The relatively large role of Nickel Metal-Hydride batteries in early years is due to their application predominantly in HEVs and PHEVs as well as their relatively low energy density.

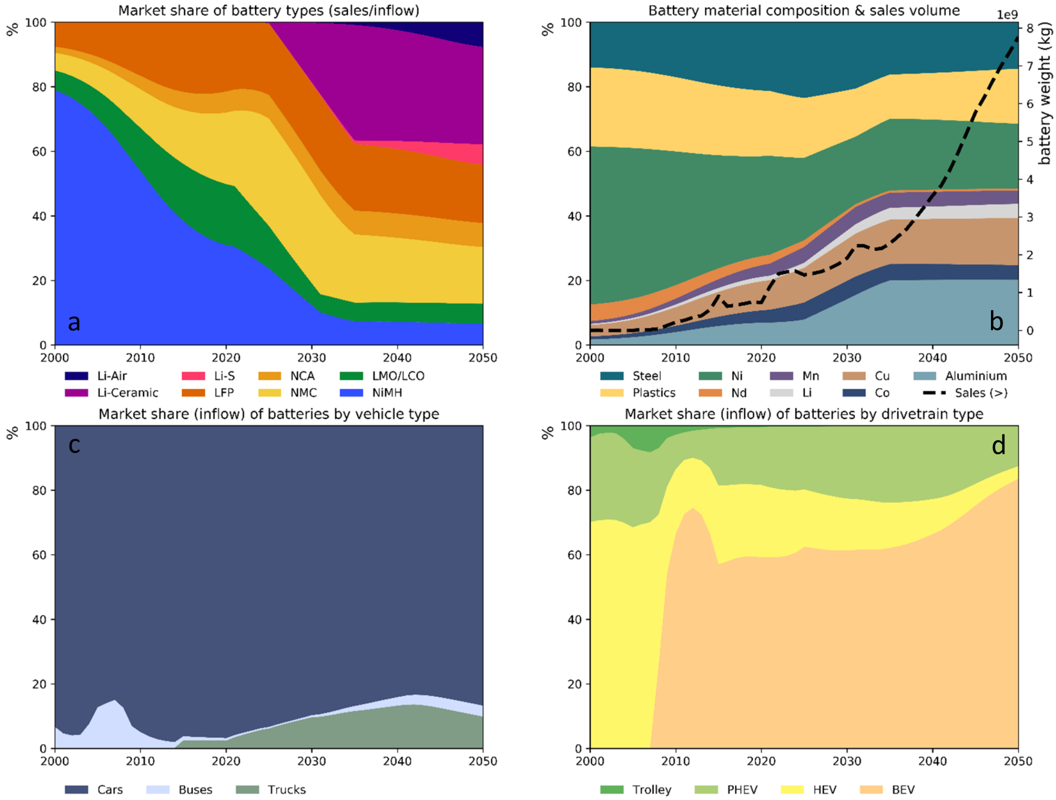

Figure 7.4a-d. *Assumptions on EV Battery markets, by battery type, material composition, vehicle, drivetrain & demand for newly purchased electric vehicles. The market share and material composition in panel a&b are based on a price-driven market model for mobile battery technologies as described in* (Deetman et al. 2021) *in combination with data from* (Li et al. 2018). *This market share is applied globally, thus assuming a global battery market.*

The total battery deployment, the battery market shares together with the material composition of each battery type based on (Deetman et al. 2021) leads to a particular share of the materials used in new batteries as shown in Figure 7.4b. Figure 7.4c-d shows the importance of different vehicles and drivetrains to the global sales, indicating that battery electric passenger cars will dominate global markets in the years to come.

7.2.4 Vehicle lifetimes and dynamic stock modelling

Given the size of the vehicle stock, we applied a dynamic stock model as described by (Pauliuk and Heeren 2018) and available from (Pauliuk and Heeren 2019). This methodology is used to derive the annual vehicle inflow (sales) as well as the size of the annual outflow (decommissioning), corresponding to the stock as detailed in Section 7.2.2. Assumptions on vehicle lifetimes and their lifetime distributions are described in Table 7.4. Next to the mean vehicle lifetime assumptions, Table 7.4 also details the assumptions on the lifetime distributions and the first year of operation. The latter is needed, because we apply a stock-driven dynamic stock model, so it is important to detail the assumptions of the historic development of vehicle stocks before the initial year of the IMAGE scenarios (being 1971), because they affect the calculated inflow & outflow throughout the scenario period.

7.3 Results

The results, both in terms of total global stock and the corresponding annual material demand & scrap flows, are shown in Figure 7.5a-d. It shows that passenger cars are by far the most notable contributors to material stocks, representing about 56% of a total of roughly 5 Gt of material stocks in vehicles worldwide. Not surprisingly, steel is the most important material composing all vehicles, and while material composition of vehicles is assumed to be constant under default model setting, Figure 7.5b shows a slight increase in the relative importance of copper in the stock of vehicles towards 2050 as a consequence of a shift from internal combustion cars to battery electric cars as well as a shift from regular trains to high-speed-trains, both of which use a higher amount of copper than their 'traditional' alternative (See Table A7.1). Figure 7.5c-d also show that the relative importance of different vehicle types in global material stocks depends on the material of interest. Where trucks and ships use relatively little aluminium in comparison to steel, the use of aluminium in buses, trains and even bicycles shows up as more pronounced.

With respect to material flows related to vehicles (dashed lines), the model predicts the annual demand of steel going into vehicle production to grow from about 158 Mt/yr now to about 294 Mt/yr by 2050.

Table 7.4. *Lifetime assumptions. * Standard deviation is expressed as a fraction of the mean lifetime. ** The standard deviation for vehicles other than Light trucks, buses and airplanes is assumed to be the average of these three categories. *** For passenger cars we applied a Weibull lifetime distribution with a shape parameter of 2.01 and a scale parameter of 16.02. **** The first year of operation of cars and bicycles is not necessarily historically accurate, but an assumption in the analysis.*

Vehicle	Type	Mean lifetime (yrs)	Standard dev.*	1st year of operation	Sources for lifetimes (and 1st year of operation)
Airplanes	Passenger	20	0.281	1940	(IATA 2016; Howe et al. 2013; Lopes 2010; IATA 2018) (Capoccitti et al. 2010)
	Freight	21			
Buses	Regular	13	0.322	1895	(Nordelöf et al. 2019; Law et al. 2011; Laver et al. 2007) (Daimler 2008)
	Midi				
Trucks	Light Commercial	14	0.196	1896	(Yang et al. 2018; Law et al. 2011; Sen et al. 2017; Dun et al. 2015) (Daimler 2006)
	Medium & Heavy	8	0.266**		
Trains	Passenger	35		1825	(Stripple and Uppenberg 2010; Nahlik et al. 2015; Yue et al. 2015) (Fava-Verde 2018)
	Freight	38			
	High Speed (pass.)	30		1971	
Ships	Maritime	26		1807	(Dinu and Ilie 2015; Chatzinikolaou and Ventikos 2015; Messmer and Frischknecht 2016b; Fan et al. 2018) (Woods 2009)
	Inland	40			
Bicycle	standard	10		1900****	(Bonilla-Alicea et al. 2020; Luo et al. 2019)
Cars	Passenger	14	***		(Deetman et al. 2018) as in Chapter 3

For aluminium the annual inflow grows from about 21 Mt/yr now to about 44 Mt/yr by the end of the scenario period. These outcomes for historic material demand are at least roughly in line with the studies referred to in the introduction (128 Mt/yr of steel in 2007, compared to 139 Mt/yr according to (Cullen et al. 2012), and 16.5 Mt/yr of aluminium, compared to 12 Mt/yr according to (Cullen and Allwood 2013)).

In addition, Figure 7.5 shows a continuing mismatch between inflow of material into vehicle stocks and the delayed outflow of materials from those in-use vehicle fleets. While this seems to suggest that for both aluminium and steel, even perfect vehicle recycling would only generate enough material to provide roughly 77% of the material demand for new vehicles, this finding is highly dependent on the regional developments. In some regions the demand for transport through specific vehicle types such as buses reaches saturation as an effect of both population dynamics as well as modal shift. This has consequences on whether the in-use vehicle stocks act as a net source or sink for materials in different world regions as can be seen in Figure 7.6.

While Figure 7.6 is based on only a selection of passenger vehicles, thus only representing a small fraction of the total steel flows related to vehicles, it shows that by the end of the scenario period in specific regions, such as China and Japan, the in-use stocks of some vehicles are starting to become a net source of steel, meaning that the annual outflow exceeds the required annual inflow. These dynamics are dependent on development of population, GDP and modal shifts, but they indicate a fundamental shift in resource flows at stock saturation, which we can only start to observe within the scenario period, but may become more common after 2050. At the global level, the vehicle fleet will continue to absorb a large volume of materials, but this signal provides a perspective for urban mining and a more circular economy in some regions beyond the scenario period.

With respect to batteries in electric vehicles, however, this shift to a net material outflow is not yet observed before 2050, as can be seen from Figure 7.7. Even in regions with stabilizing population such as China and Japan, the continued growth of per capita GDP leads to a continuing rise in the demand for cars, with a simultaneously increasing role for battery electric vehicles. This is the reason that the batteries in newly purchased (hybrid, plugin and fully) electric vehicles will increasingly outweigh the outflow of end-of-life batteries from decommissioned vehicles. Thus, presenting an increasing challenge in closing the material cycles from vehicle batteries before 2050. Figure 7.7 also shows that the penetration of electric transport is slower in developing regions as a consequence of high initial investment prices for (partially) electric vehicles.

In contrast to findings for other vehicles as shown in Figure 7.6, this leads the ‘Steady Developed’ regions such as (a.o) the US and Europe to dominate the annual demand of materials used in electric vehicle batteries (see Figure 7.4b for the individual materials), according to the SSP2 baseline scenario used.

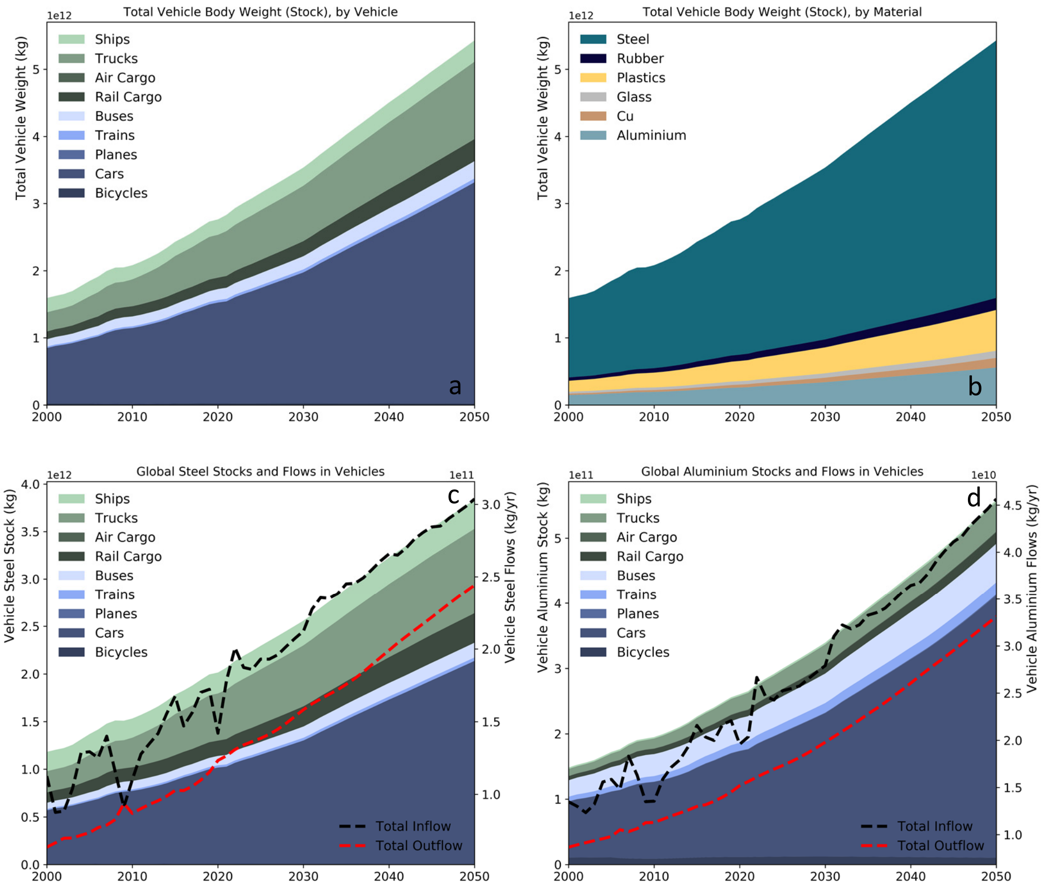

Figure 7.5a-d. *Global Material Stocks and Flows in Vehicles. Top panels show the weight of the stocks, either by vehicle type (a) or by material (b). Lower panels show the size of the stocks and in/out flows for steel (c) and aluminium (d).*

7.4 Discussion & conclusions

The model and the analysis presented in this chapter deal with the expected development of material use in vehicles towards 2050, under baseline assumptions. We used available projections of transport demand from the IMAGE model elaboration of the SSP2 scenario to come up with an estimate of materials in several passenger- and freight vehicles over time. A translation from annual transport demand expressed in person-kilometers or ton-kilometers to the total number of vehicles was made using indicators on vehicle mileage, capacity and load factor, while the material use was determined using vehicle specific weight and composition data, all based on an extensive review of available literature. This approach thus accounts for the heavier vehicle bodies of electric cars compared to combustion-based cars.

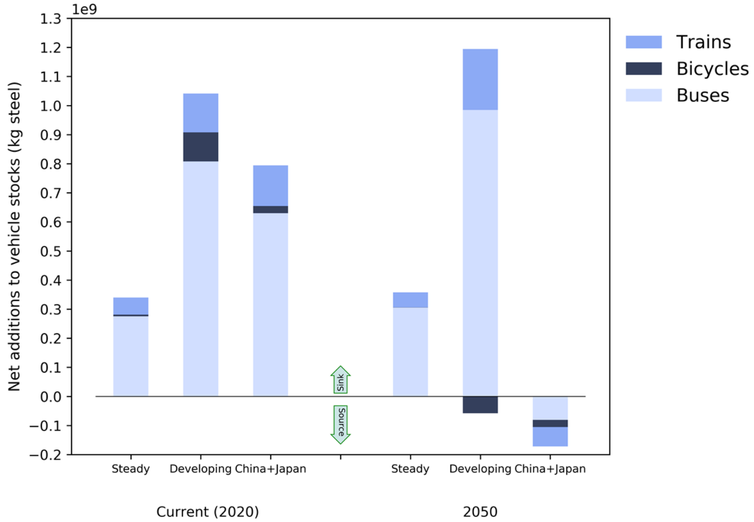

Figure 7.6. *Net additions to stocks of buses, trains & bicycles, as a source or a sink of steel in three global regions. The regional aggregation used assigns the following regions as 'Steady' (based on population growth projections): North-America, Europe, Ukraine, Russia, Middle East & Australia. 'Developing' regions have a higher population growth and are defined as the remaining regions minus China and Japan.*

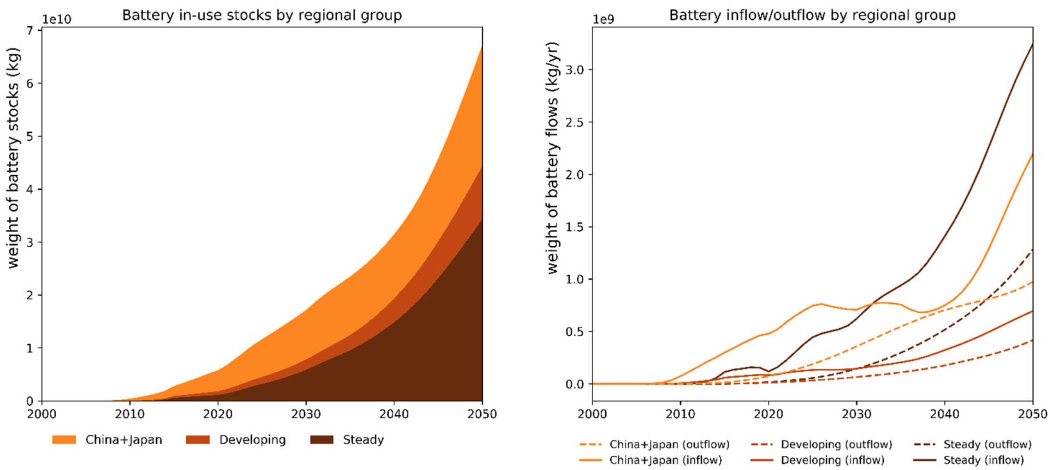

Figure 7.7. *Total weight of the battery stock, inflow and outflow by aggregated world regions. Regional aggregation is the same as detailed with Figure 7.6.*

The results show that a continued growth in transport demand will lead to a substantial expansion of in-use vehicle stocks, leading to roughly a doubling of the stock weight to more than 5 Gt as well as a doubling of the annual demand of materials used in vehicle production. Cars continue to dominate the total weight of the in-use vehicle stock, with steel being the most important material by weight. While vehicles other than cars are sometimes omitted in studies on material stocks, we show that they compose a relevant fraction of the total vehicle weight, at about 44 wt% of the modelled stock.

Given that stocks are growing and that the lifetime of most vehicles exceeds 10yr we observe a lag between the demand for materials in vehicle production and the availability of secondary raw materials from scrapped vehicles at the global level. This mismatch is also observed in battery electric vehicles and highlights a fundamental challenge to reaching a fully circular flow of both bulk and critical raw materials any time before 2050. Some exceptions exist, however, for example for buses, bicycles and trains in regions where stock saturation is observed as a consequence of stabilizing or declining population size and simultaneous modal shift, such as China and Japan. Here, targeted waste management may be required to make optimal use of vehicle stocks that will likely turn from a net sink into a source of materials before the year 2050. In general, we expect such shifts, where vehicle in-use stocks become a net source of recyclable materials, to happen more often beyond 2050.

We present our analysis as an initial attempt to provide a complementary material perspective to the often energy-oriented scenario models on the transport sector, but also highlight some possible model improvements. Starting with the imperfect match between the modelled number of vehicles and values found in general literature; while we find that most of the model deviation could be explained by the used scenario indicators on global transport demand, which are generally highly uncertain, it would be valuable to explore the effect of more realistic assumptions on vehicle mileage, capacity and load factors. Possibly even accounting for their change over time. Secondly, the model presented here does not account for actual recycling rates. Even though recycling rates for materials from vehicles such as cars can be quite high (Andersson et al. 2017), it would be worth to expand the model based on realistic assumptions regarding recycling. Finally, we feel that some perspectives beyond mere 'baseline' assumptions could provide more policy relevant insights with respect to the role of climate policies or material efficiency strategies in curbing the environmental impacts of vehicles and the transport sector as a whole. This could entail the assessment of an entirely different transport demand scenario, or the inclusion of dynamic assumptions regarding load factors, weights and material composition, for example.

Irrespective of these suggested improvements, we feel that the current model provides some valuable insights. First of all, it allows us to assess the future role of vehicles in the global material demand, with details on the contribution of regions, vehicle types, batteries and drivetrains. Secondly, it identified the role of particular in-use vehicle stocks as a potential source for materials towards 2050, this realization can help define synergistic resource policies. Finally, when combined with climate or energy models, our model could be used to highlighting often-overlooked trade-offs between climate & material efficiency policies. Given the increasing efforts to decarbonize the global transport system, the materials required for vehicle production will likely play an increasing role in the remaining environmental impacts related to transportation towards 2050. We hope that the model presented here could provide a platform to account for climate and resource impacts simultaneously.

Acknowledgements

We would like to acknowledge the work of Stefan Pauliuk and Niko Heeren (Pauliuk and Heeren 2019), who provided the open-source python module that was used for the cohort-based dynamic stock calculations.

Appendix

Appendix 7 provides more details with regard to vehicles material composition. Additional details, including future model corrections and updates will be reported in the online model repository available via www.github.com/spdeetman/VEMA.

8.

Synthesis

Before commencing the discussions and conclusion to this research, this synthesis chapter first presents an overview of the results from the chapters on specific material end-use categories, being buildings, the electricity sector and vehicles as detailed in Chapter 4, 5, 6 and 7.

The main purpose of this overview is to explore the relative importance of these material end-uses in global stocks as well as their relative contribution to annual material demand at the global level. Figure 8.1 shows these indicators for steel, aluminium and copper under the SSP2 scenario assumptions, given that each of these materials is used in in both the electricity sector, in buildings as well as in vehicles.

The overview presented in Figure 8.1 shows the stock of materials on the left side and the annual demand on the right side. While the stocks are typically dominated by construction materials used in buildings, vehicles play a more important role in defining the annual demand for materials. This is a consequence of the shorter lifetimes for vehicles (typically about 20 yrs, compared to 60 years or more for buildings), which dictates a larger annual demand to replenish existing vehicle stocks. For aluminium specifically, this means that by 2050 the use in new vehicles will likely be larger than the use in new buildings.

In the models detailed in Chapter 4, 5, 6 and 7 the growth in demand for materials is mainly determined by the demand for vehicles, buildings and electricity infrastructure as derived from the second Shared Socio Economic Pathway scenario (SSP2), provided by the IMAGE model (Stehfest et al. 2014). In turn, these drivers are derived from the demand for services such as transportation, floorspace or electricity and the corresponding in-use stocks required to fulfill those services on an annual basis. Figure 8.2b shows the indexed growth of the relevant in-use stocks, showing that the model drivers follow different growth trajectories.

In the results for the SSP2 baseline as presented in the overview Figure 8.1, fixed material intensities were applied to specific product sub-types (e.g. specific vehicle types, building types or electricity generation technologies), so that the material composition changes only as a consequence of shifting demand for product sub-types. For vehicles this is a consequence of both modal shift as well as the introduction of new drivetrains such as for electric vehicles. For buildings this is for example driven by shifting demand from detached and semi-detached buildings to a higher demand for apartments and high-rise buildings, in line with global urbanization trends. In the electricity sector this shift is mainly driven by the choice of generation technologies. Together, the growth and the shift in demand of products determines the expected global material use over the scenario period, as can for example be observed for copper use in vehicles, which grows faster than the steel use in vehicles as a consequence of switching to electric drivetrains, which contain more copper.

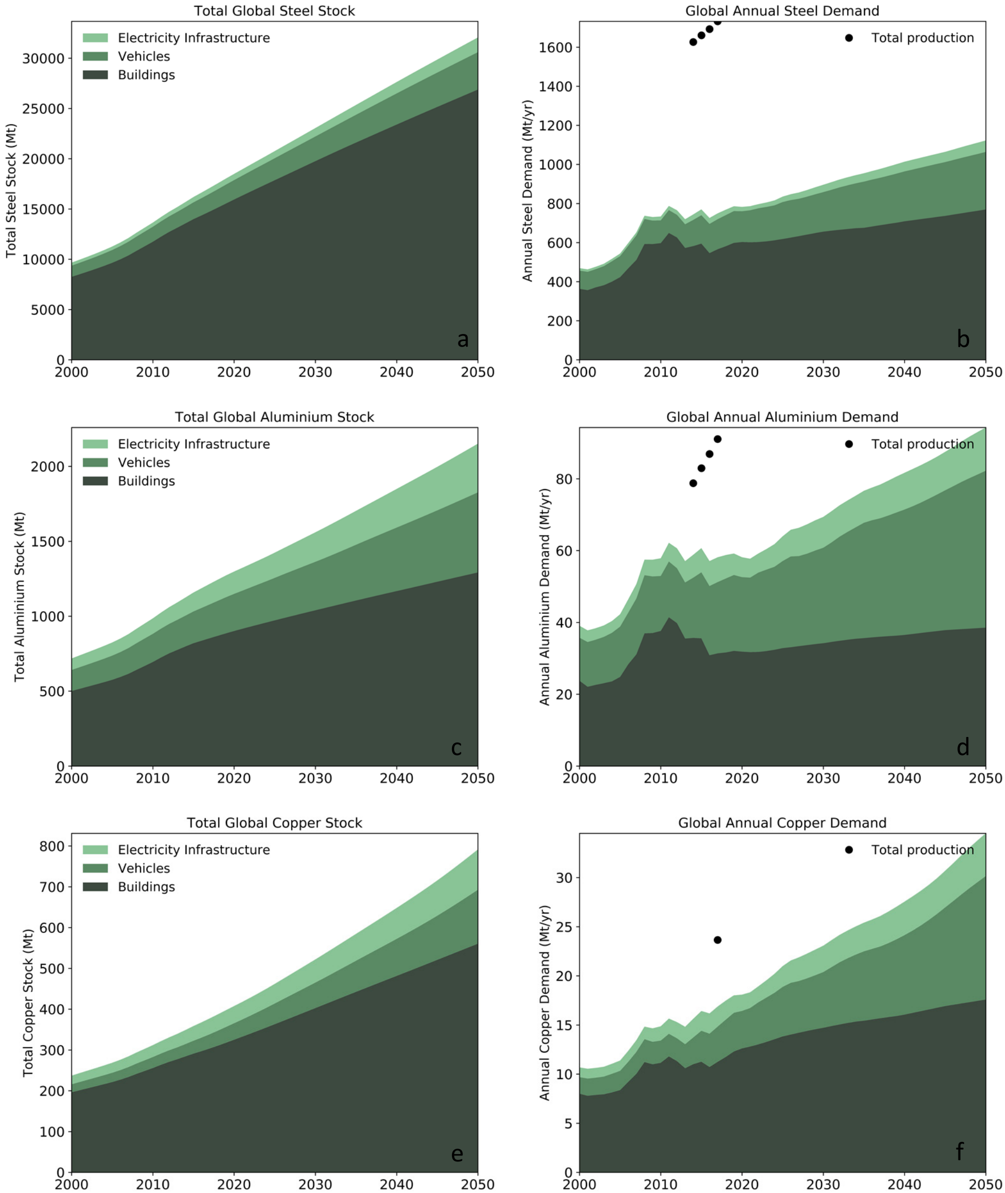

Figure 8.1a-f. *Overview of results on stocks and annual demand for steel, aluminium and copper in buildings, vehicles and in the electricity sector towards 2050 under the SSP2 baseline scenario. The dots in the plots on the right show the current total global annual production of materials based on (International Copper Study Group 2020; World Steel Association 2020; International Aluminium Institute 2017), representing the sum of virgin- and secondary material demand, thus showing the relevance of other end-uses (not covered in this research).*

The total demand of the three end-use categories therefore grows differently for individual materials, with the modelled steel demand expected to grow by 45% between now (2015-2020) and the end of the scenario period (2045-2050). For aluminium this growth is expected to be about 56% and for copper it is even larger at 94%.

Figure 8.2a shows how the size of the population, one of the main drivers behind material demand, develops in different regions and how this leads to the development of stocks for different end-use applications. Population growth explains some of the global growth in stocks, but it is not the only driver. The growth in stocks is expected to be larger than the maximum growth in population, suggesting that per capita stocks are simultaneously increasing; an observation often attributed to the growth in per capita affluence (GDP, measured in Purchasing Power Parity). This means that stocks may continue to grow even in regions where population is expected to stabilize or decline during the scenario period.

While the growth in population and the resulting in-use stocks of typical end-uses displayed in Figure 8.2 are driving a large share of the global annual material demand, the dots in Figure 8.1 indicate that a considerable fraction of current annual material demand is still missing from the analysis presented in this thesis. This is in line with existing estimates of global end-use for each of these materials. Below follows a discussion on the analogies with available global material flow studies and some reflections on the most important other end-uses for each of the three metals in the overview.

For steel, Cullen et al. (2012) estimate that about a third of the global annual production is applied in buildings; which is in line with our results (ca. 34% compared to the black dots in Figure 8.1b). For vehicles, Cullen et al. estimate about 13% of the produced steel is applied in vehicles, while our results show somewhat lower steel use in vehicles representing 9% of global demand. For electricity infrastructure, the comparison with the study by Cullen et al. cannot be made directly, but an estimate of the size of other end-use categories (not covered in this research) is about 52% of total demand based on Cullen et al. and about 55% based on our model results in relation to current production estimates. Of those remaining end-uses, other infrastructure (such as bridges, railways, sewage systems etc.) are the most important end-use category, followed by machinery/equipment and other goods (including appliances and non-stock-forming applications such as in packaging).

For aluminium, the comparison to another paper by Cullen and Allwood (2013) is useful. Cullen et al. indicate that in 2007 the use of aluminium in buildings was about 22%, whereas our results for the year 2017 indicate that buildings represent a somewhat larger fraction of the total use at 39% of current production levels. While that may appear as a mismatch, estimates by the International Aluminium Institute (2017) indicate that the share of construction in aluminium end-use has indeed increased from about 25% in 2007 to slightly over 40% around 2017.

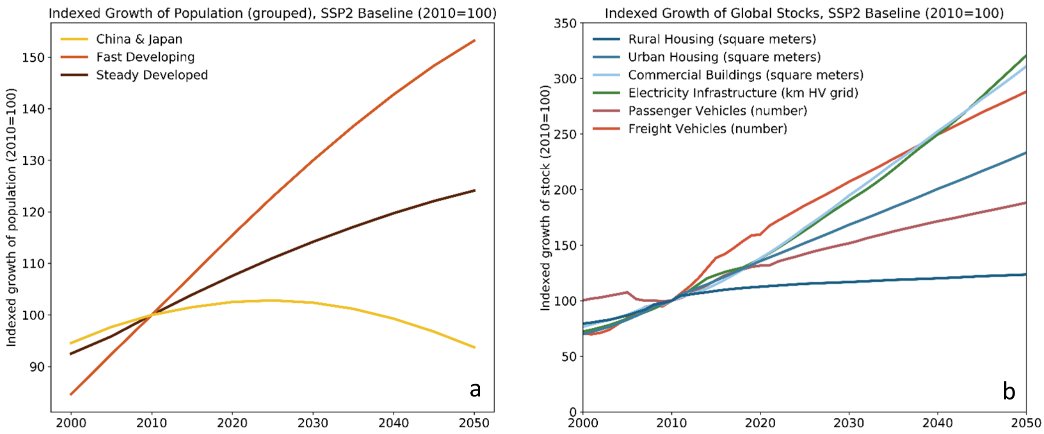

Figure 8.2a-b. *Indexed development of global population (a) based on* (KC et al. 2017)*; and indexed development of in-use stocks as drivers of material demand (b) based on the IMAGE model elaboration of the SSP2 Baseline* (van Vuuren et al. 2017) *and calculations in chapters 4 to 7. The regional aggregation used in panel a is similar to the one used in Chapter 5 and 7 (see Figure 7.6).*

For vehicles and the electricity sector, our results are more in line with Cullen et al, who state that ca. 26% of aluminium was used in vehicles in 2007, while Figure 8.1 indicates this to be about 22% in recent years (2014-2017). The electricity sector accounts for about 8-9% of aluminium demand in both analyses. This means that other end-uses account for the remainder or about 30% of total annual demand, mostly consisting of use in packaging and industrial equipment.

For copper, the results in Figure 8.1 suggest that about 48% of all copper produced is used in buildings by 2017, while a global copper flow analysis by Glösser et al. (2013) suggest it to be about 37% in 2010. Here, additional insights from end-use analysis by the International Copper Association points to possible over-estimation of the importance of buildings and construction in global annual copper use in our results as their data for 2019 indicates that about 28% of copper ends up in buildings (International Copper Association 2020). Our estimates for the contribution of vehicles and the electricity sector to total copper demand are more in line with these two studies, ranging from 12-15% for vehicles and about 9-13% for the electricity sector. This means that of the roughly 30% (possibly more if we assume that the results from Chapter 5 overestimate the copper use in buildings) of copper demand for which we do not model demand, most is used in consumer appliances and equipment followed by industrial applications such as machinery.

So, while the results presented in this overview may not correspond perfectly with previously available literature for all material end-uses, most of them can be reasonably validated against historic data and literature estimates. In addition to the historic alignment, our results are also in accordance with global material demand growth rates observed in forward-looking scenarios as reviewed by Watari et al. (2021). Though the sectoral coverage within this thesis is not encompassing, the resulting growth in the annual demand of the three modelled end-uses combined is well within the range of total annual demand growth found in scenario studies as compiled by Watari et al. (2021), who show a growth in annual demand towards 2050 for steel, copper and aluminium in every available scenario. However, for those materials, the resulting annual demand growth by 2050 found in this thesis is roughly midway between the mean and the minimum values as reported in the review by Watari et al., suggesting that the growth in annual demand reported in this thesis might be on the low side of the spectrum of available scenario studies. Whether this is due to the partial coverage of specific sectors, the service-demand assumptions in the IMAGE model, or the fundamental difference in methods is a question for further research.

The method used to produce the results in this thesis is mostly based on a combination of saturation of per-capita in-use stock estimates, dynamic modelling of product lifetimes and product composition data, and is fundamentally different from material flow studies that are often based on annual production statistics. The correspondence of the outcomes, at least well within the order of magnitude, both from an historical and a forward-looking perspective, is an indicator of robustness and could be encouraging to a broader use of such efforts to make more sensible forecasts and get a better understanding of material flows at the global level.

This overview also shows that the models presented in Chapters 2 through 7 capture some of the relevant dynamics and trends regarding global material demand. Using indicators from an Integrated Assessment Model (IAM) such as the IMAGE model as drivers of the material demand scenarios, enabled to account for the effects of mega-trends such as urbanization, electrification and globalization. Additional technological detail - such as information on specific transport modes and specific vehicle drivetrains, a plethora of electricity generation technologies as well as the newly introduced distinction of specific building types - enables the distinction of specific technologies as relevant drivers of changing material demand.

Figure 8.3 shows two additional perspectives for the same selection of materials as in Figure 8.1. First, it shows the difference between inflow (i.e. annual material demand) and outflow (i.e. end-of-life waste flow) at the global level, with some additional details about the origin of wastes, which shows a similar pattern as the inflow, be it, with a considerable delay. This delay, caused by long lifetimes of buildings, infrastructure and vehicles, also explains why the global waste generation will continue to be lower than the required annual inflow towards 2050, thus causing a continued demand for virgin raw material inputs, even if all waste could be recycled without losses. This leads to a ‘circularity gap’, defined here as the mismatch between the annual inflow and outflow[1]. Even with perfect recycling of all available scrap, by the end of the SSP2 baseline scenario 40% of the steel inflow would still have to come from virgin raw materials. For aluminium and copper, this gap is about 34% and 46% respectively.

Secondly, the regional details in the right-side panels in Figure 8.3 show that the timing and the size of the gap between inflow and outflow is highly dependent on the regional demographic developments. The development of population growth in the three regional groups is given in Figure 8.2a. While this regional aggregation used may seems somewhat subjective, it is based on comparable demographic growth projections and can therefore be used to explain some of the regional differences in the resulting material demand- and waste dynamics. A stabilizing, or even declining, population before 2050 in regions like China and Japan seem to be a key precursor in narrowing the 'circularity gap'[1]. In contrast, a continued growth in population in the group of fast developing regions causes a widening of the mismatch between inflow and outflow. Nevertheless, a stabilizing population does not necessarily translate into a stabilizing material demand due to other drivers such as affluence, which often leads to higher per-capita demand, or due to structural and technological shifts in end-use sectors. Examples of the latter are urbanization, modal shift, a renewable energy transition or a switch to electric vehicles.

The prospect of saturation of per capita in-use stocks combined with a stabilization of population seem to be a prerequisite in halting the growth in annual material demand, which is key to enabling a fully circular economy. In light of the Sustainable Development Goals (SDGs) as addressed in the introduction, this is indeed a challenge as the services provided by material stocks contribute to the infrastructure and well-being that are key to achieving the basic level of affluence and shared prosperity that everyone is entitled to, especially in developing regions where in-use stocks will therefore continue to expand at a rapid rate. This thesis shows that achieving a fully circular economy at the global level before 2050 is therefore hard, if not impossible. However, what goes in must come out. The same stock dynamics that dictate a continued reliance on virgin raw material inputs towards 2050 also dictate that in the second half of the century there will likely be a shift towards higher availability of secondary resources. The type of modelling presented in this thesis could help identify opportunities and the optimal timing to increase waste-management capacities or the global redistribution of materials.

[1] Mind that this definition of a 'circularity gap' is different from the definition used by others such as by www.circularity-gap.world, who use a measure of the *'cycled materials as part of the total material inputs'*, or the definition used by Aguilar-Hernandez et al. (2019), who define the circularity gap as the total generated waste (incl. stock depletion) minus the recovered waste.

In short, this synthesis shows the coverage of material end-use categories presented in this research and indicates that global stocks of buildings, vehicles and electricity infrastructure are expected to continue to grow towards 2050. Together, they account for just below half of the annual demand for steel, and about 70% of materials like aluminium and copper. While stocks are often dominated by buildings, production of vehicles is responsible for a relatively large share of annual material demand, due to their shorter lifetimes. In general, product lifetimes are a key determinant in material demand scenarios, and they dictate a delay between annual demand and end-of-life waste generation that presents an obstacle to reaching a fully circular economy before 2050 at the global level. Regionally, however, there are large differences with respect to such a 'circularity gap'. Regions that are expected to have a stabilizing or even declining population are potentially the first places where the availability of scrap starts to catch up with the annual demand, providing an opportunity to limit the need for virgin raw material inputs and the corresponding environmental impacts beyond the year 2050. These results shed a light on the increasingly important global challenge of providing the resources required for a prosperous society in a sustainable way. This synthesis also indicates how the scope of the presented modelling efforts could be expanded by covering more material-end use or even more years into the future. These and other model improvements and suggestions for further research will be addressed in the discussion in the following chapter.

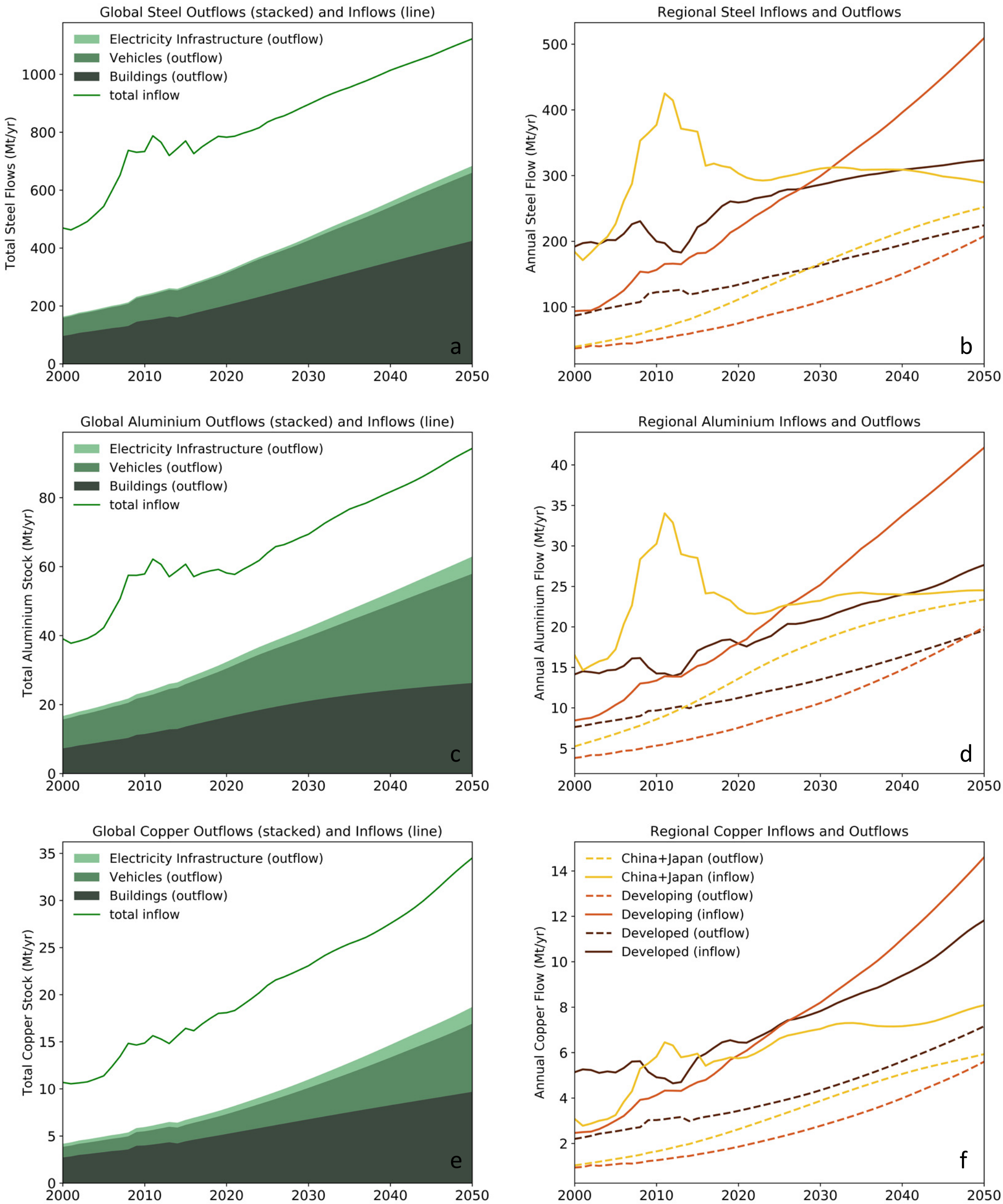

Figure 8.3a-f. *Overview of global and regional results on inflow and outflow of steel, aluminium and copper. The global total inflow (line in the left-side panels) is similar to the sum of the right-side panels in Figure 8.1. Regional grouping in the right-side panels is the same as used in Chapter 5 & 7 (see Figure 7.6).*

9.

Discussion

9.1. Model improvements

With respect to the modelling exercises presented in this thesis, a number of improvements can be made to enhance both the robustness as well as the relevance of the material demand scenarios. Beyond the expansion of coverage of material end-uses, which will be discussed as suggestions for future research in Section 9.5, the models presented in the previous chapters could benefit from an additional estimate of material use for maintenance of vehicles, infrastructure and buildings, thus expanding the current approach of assuming a one-off purchase by accounting for material inputs during the lifetime of products. Though this may typically involve smaller material volumes than those in new products, it would complement the current model coverage and provide a more realistic representation of overall material demand. Additionally, it would allow for a better representation of the environmental trade-offs of interventions aimed at life-time extension of these products, given that that would likely require more maintenance.

Other model improvements could be aimed at a more realistic representation of product compositions. While the model on building materials applies regional material intensities, the chapters on the electricity sector and vehicles do not. The underlying assumption of a global market for vehicles and electrical lines and equipment could be tested and improved where needed. The same holds for the assumptions on the development of product composition over time. With the exception of some of the sensitivity analyses, the current model assumes a constant material composition over time. This may not be realistic in the long-term, so the models presented here could be improved by accounting for changing material compositions, first of all to account for ongoing trends and material efficiency improvements, and secondly in order to assess the potential of (circular economy) policies oriented at a more radical improvement in material efficiency in a scenario that departs from such baseline assumptions.

The way product lifetime estimates are used in the presented models could also be improved. In particular the effects of changing lifetimes, either as a consequence of technological developments or circular economy policies, could be incorporated more explicitly, in order to capture the importance of product longevity and the effect of lifetime extension on material demand. This would go hand-in-hand with the expansion of modelling to account for circular economy policies and interventions more broadly. An effort that should eventually contribute to assessing climate and resource related issues in one consistent dynamic modelling framework.

The main reason that these adjustments are not widely incorporated in the current analysis is that this requires data that is currently often unavailable. Even the current product compositions and lifetimes used were hard to come by and could benefit from additional substantiation. While the models used are technically ready to implement changing lifetime and material compositions, and could be adjusted to account for maintenance material use, the data availability and uncertainty regarding future product developments was a limiting factor. The following section elaborates on such data issues in the current model in some more detail.

9.2. Reflections on data issues and uncertainty

9.2.1 Reflections on model inputs

A key characteristic of the presented analysis is that it builds upon the available information in the IMAGE model and the available elaboration of a set of scenarios called the Shared Socio-Economic Pathways (van Vuuren et al. 2017). This ensures that the drivers of the material demand projections are based on a consistent storyline and an encompassing scenario framework that is recognized and used in various international research fields. In this way our results consistently account for changes in drivers of material demand such as the development of population and affluence, but they also capture learning effects on the prices of new technologies, resource and capacity constraints in deployment of technologies, effects of (climate) policies and the feedback of climate on demand for services such as electricity and cooling. In addition, the SSP scenarios used throughout Chapters 3-7 also provide a consistent perspective on the implications of climate policies. Extending these scenarios with an explicit material dimension would allow to eventually assess the interaction between climate policies and circular economy policies and to map the potential trade-offs between the Sustainable Development Goals.

Nevertheless, this also means that, for now, the results on material use are dependent on the output of another model, thus adopting the issues and limitations related to Integrated Assessment Models in general, and the SSP scenarios specifically. Beyond an inherent uncertainty about the future, these include a somewhat limited regional detail, as well as a reliance on historic data on prices, and on historically calibrated relations between income and per-capita demand for products and services. Though emission scenarios are regularly updated, a calibration grafted on such historic data and trends, might introduce a certain level of inertia to system-wide changes, which could lead to overly pessimistic outcomes in the baseline with regard to, for example, climate impacts (Hausfather and Peters 2020). In a similar way, these limitations may affect the outcomes in terms of material requirements. Given that we use mostly constant material intensities, the presented results could be seen as a ‘material efficiency baseline’, which should be expanded to incorporate relevant material efficiency trends to capture a more realistic and optimistic future.

9.2.2 Reflections on data on in-use stocks

In-use stocks of materials are key in this work as they fulfill an existing demand for a service through physical products or infrastructure. Nevertheless, the availability of data on in-use stocks from official sources is surprisingly limited. National statistical offices tend to report mostly on annual indicators such as expenditure (e.g. on vehicle purchases), trade (e.g. imports of wood) and use (e.g. fossil fuel consumption) all of which are flow-based information. Sporadically, a country may have official accounts of in-use stocks for buildings (e.g. the Dutch BAG (Kadaster 2020)) or cars (e.g. the United States vehicle fleet (Bureau of Transportation Statistics 2021)), but coverage and the level of detail reported differs across countries, making it difficult to compile and compare data. A global database on in-use stocks of key products an infrastructure would make this type of research much easier, because it could be used to calibrate the underlying model relations between per capita stocks and per capita affluence, but also to compare model outcomes more easily. Such a global database on in-use stocks, however, would require countries to collect and report data on in-use stocks more systematically first.

9.2.3 Reflections on product composition data

The method used throughout this research has proven useful, but admittedly time consuming. Specifically, the dependence on product content estimates required a comprehensive review of detailed product information that is often not readily available in existing databases. Occasionally, however, the use of patents, so-called product environmental passports or Life Cycle Inventories (LCI) such as the Ecoinvent database were useful in providing a reference point.

The issue with LCI databases was that additional interpretation was often required to derive an actual product content from inputs describing the production or even material requirements during maintenance, thus introducing additional uncertainty. On the other hand, the LCI databases could allow to derive an estimate of material use in the maintenance of products, which was omitted in the current model. Product environmental passports, on the other hand, often did not provide suitable detail to account for critical materials used in minute quantities.

The problem with each of these data sets, as well as any of the additional sources used to estimate product contents, is that they provide data for a single product or a single year.

This introduces a dependency on data that can be (or become) outdated, which becomes problematic when it's the only available data point describing a product.

One way to avoid these pitfalls when developing the type of material demand scenarios as presented here is to continuously review and expand the data sets on product compositions. While this is time consuming, it could benefit the field of environmental assessment in multiple ways. A growing product composition data set may at some point be used to derive trends over multiple years, thus substantiating assumptions on changing material composition as mentioned in section 9.1. More generally, however, better data on the materials used in products could lead to a much better and broader appreciation of supply chain complexity and a true understanding of the material basis of society. The work presented in this thesis aims to make a humble contribution to that purpose by reporting a comprehensive set of product content estimates throughout the chapters and appendices.

9.2.4. Reflections on product lifetime data

Similar to the use of product composition data, product lifetimes were also derived from sparsely available sources. In particular, the dependence on product lifetime distributions made it difficult, because this data is not always available. A pragmatic approach was chosen, in which the product lifetime distribution was occasionally estimated based on specific mean lifetimes, which is much easier to find in literature, and an approximation of the distribution of failure was based on comparable products. This should ideally be improved through expansive review of product lifetime estimates, possibly accounting for regional lifetime assumptions, similar to the presented approach for buildings, in the future.

An additional source of uncertainty here is the definition of lifetimes for products. Many studies based on life-cycle assessment are not explicit as to whether they report on a product's intended lifetime (the foreseeable lifetime during the design), a products technical lifetime, or its economic lifetime. Each of these definitions may differ substantially from more realistic lifetime estimates for real-life use cases.

In Chapter 5, such discrepancy between reported and realistic lifetimes was observed in the age structure of the European building stock, which could only be reproduced using about double the lifetime reported in literature. Given that dynamic stock modelling is dependent and highly sensitive to such lifetime assumptions these should be checked and applied carefully in material use scenarios.

Finally, the use of stylized lifetime distributions, in our case described by the probability density functions of the Weibull distribution or the Normal distribution, excludes the possibility of products remaining in-use for much longer than average. Even though the 'tailed' Weibull distribution allows a fraction of a cohort to remain in stock for a considerable time, this method does not account for true antiquity of monumental buildings or old-timer cars for example. The use of alternative lifetime distributions or explicit accounting of multiple retrofits, second hand products or product quality classes could improve the representation of a reality in which product quality often dictates the extent of their lifetime.

9.3. Implications of dynamic stock models on the timing of a circular economy

The results of dynamic stock models provide a perspective on the size as well as the timing of inflow (annual demand) and the outflow (waste generation) of materials worldwide. This information is indispensable in circular economy research. Our analysis indicates large challenges in achieving a truly circular global economy before 2050, simply because the global demand of materials used in construction, infrastructure and vehicles will likely continue to grow, thus requiring continued inputs of virgin raw materials. Even if waste flows could be fully recycled, long product lifetimes limit the availability of scrap and secondary materials.

So, while it may be a sobering message to temper expectations of a fully circular economy anytime within the first half of the century, this does not mean that current policy efforts are in vain. First of all, because circular economy interventions contribute to closing the circularity gap by increasing resource efficiency (Aguilar-Hernandez et al. 2019). Secondly, because even if circular economy interventions, such as lifetime extension, closing supply chains, resource efficiency and better waste management, do not achieve a fully circular economy, they can have beneficial effects on other environmental objectives such as limiting global warming and reducing water and land use for example (Donati et al. 2020). While our results indicate some occasional trade-offs between climate policy and circularity through higher demand for electricity infrastructure or heavier vehicles for example, that does not mean that these are mutually exclusive policy objectives. Typically, demand reduction strategies perform synergistically for both the climate and the circular economy, thus presenting a likely ‘no-regret’ option towards a more sustainable future in many regions of the world. However, that does not mean that demand reduction strategies should be blindly promoted everywhere; in light of the Sustainable Development Goals the development of infrastructure and other in-use material stocks as a physical basis of wellbeing may simply be a pre-requisite to achieving decent living standards (Rao and Min 2018) as well as the goal of shared prosperity. The region-specific material demand development scenarios presented in this thesis, in combination with a certain level of inevitability to the continued build-up of indispensable material stocks suggests that currently, demand reduction strategies would be most sensible in high-income regions.

Unmistakably, our results also show that continued and long-term investment in waste management and recycling capacity are required as well as sensible in all regions. Given the continued rise in inflow of bulk materials into long-standing societal stocks, waste flows will continue to rise far beyond 2050. The presented results can potentially be used to assess optimal long-term investment strategies, both for the extractive industry and the waste management sector.

As discussed throughout the various chapters, population dynamics dictate that some regions and products will reach a turning point where stocks are stabilizing or even start to decline. Our analysis shows signs of such a shift happening before 2050 in regions like China and Japan, but whether this turning point is reached sooner or later, the stabilization of stocks implies that material demand will, at some point, likely only be determined by the requirements for the maintenance of the stock. Consequentially, the material requirements for stock additions become zero and therefore the total material demand and the associated industrial energy demand may experience a sudden decline. This could mean that stocks become a net source of materials and could imply a sudden shift from scrap shortage to scrap surplus, potentially accompanied by dramatic shifts in waste material markets due to both the price and the size of newly generated waste flows. Models like the ones used here can be used to forecast the timing of such shifts in different regions and allow the world to prepare for large waste flows by or after 2050. Based on this, one obvious direction for further research could be to explore optimal investment strategies for regional recycling capacity deployment and the role of waste trade. Here it is worth exploring the potential to improve both the presentation and the understanding of such shifts in the scenario results of dynamic stock model applications by visually distinguishing between the fraction of annual material demand used for stock expansion and the fraction of annual material demand used for stock maintenance.

9.4 Industrial Ecology tools for global environmental assessment

Dynamic stock models are becoming an essential tool within the research field of Industrial Ecology. The dynamic perspective on material flows combines the best of both worlds between tools like Material Flow Analysis and Scenario Assessment. Product lifetimes and the resulting age structure of societal material stocks play an important role in defining the demand for materials, and the consequential environmental impacts through extraction of resources or emissions related to the production and recycling of materials. As such, dynamic stock models could be key in bridging research fields related to resource use and those oriented at climate change. A common understanding of the importance of stock dynamics could facilitate the integration of industrial ecology tools into the field of scenario-based climate change research (Pauliuk et al. 2017). Not in the least because of a common struggle to incorporate the effects of circular economy policies into existing modelling frameworks.

Throughout this research, the demand for materials was modelled using service demand as a driver of in-use stocks, and stocks as the ultimate drivers for annual material demand (flows). This is a departure from the existing modelling of demand for steel and cement in the IMAGE model, which was based on the presumption of saturation of per capita annual demand at higher income levels (van Ruijven et al. 2016). A so-called stock-flow-service nexus (Pauliuk et al. 2017; Haberl et al. 2017) presents a fundamentally different starting point for material demand modelling, and will thus lead to an adjustment of material demand scenarios and related model indicators such as industrial energy demand, if fully implemented in the IMAGE integrated assessment model. There is an increasing body of literature that explores this perspective of in-use stocks as a driver of annual material demand (Watari et al. 2020; Wiedenhofer et al. 2015; Pauliuk and Müller 2014), some even suggesting that it may be more appropriate for long-term forecasts (Watari et al. 2021; Schipper et al. 2018). Given that integrated assessment models have such a long-term focus, the adoption of a more stock-driven approach could lead to an improved representation of material demand in energy- and climate-oriented scenarios. While the analysis presented in this thesis does not look beyond the year 2050, it is hypothesized that an approach based on stock-driven material demand could lead to a reduction in the annual steel demand by 2100 compared to the current modeling approach. A model that is able to capture stabilization of in-use stocks, and the corresponding decline in annual material demand for stock-forming products and infrastructure, could potentially provide a more realistic as well as a more optimistic long-term outlook.

As highlighted in the introduction, the production of materials plays an important role in industrial energy demand and its related greenhouse-gas emissions. That is why the development of material demand is not only relevant to assessment of a circular economy, but also plays a key role in climate change scenarios. The chapters of this thesis detail some of the material end-use categories and the expected development of in-use stocks as well as the corresponding demand and waste-flows of various materials.

This provides potential model improvements in multiple ways. First, a stock-driven approach potentially presents a more realistic representation of material demand, especially for the long-term perspective as commonly used in integrated assessment models. Secondly, linking readily available information on the development of activity in specific economic sectors (e.g. transport or electricity) as material end-use categories allows to assess its material implications more consistently. Thus, providing a better representation as well as a better understanding of the dynamics underlying global materials demand. This also allow to capture the effects of climate policies on material demand explicitly. Finally, the simultaneous assessment of expected waste flow volumes provides another opportunity to improve energy- and emission-models. Recycling- and waste-management industries will provide an increasingly important basis of a future (circular) economy, while activity in the mining industry may start to decline at some point in time. The results on the expected size of waste-flows may be used to assess the future energy requirements of both the mining sector and the waste management sector, in order to more consistently capture the full range of trade-offs of circular economy policies.

The understanding of the long-term trends in global material use is becoming increasingly important in climate policy scenarios. With efforts to reduce greenhouse gas emissions well on their way in various sectors, it becomes evident that the industry sector, and its material producing sub-sectors in particular, are likely much harder to mitigate than other sectors like passenger transport or the production of electricity (Sharmina et al. 2020; Luderer et al. 2018). Combining these trends with the increase in material demand, as found throughout this thesis, inevitably leads to a larger role for material production and processing in the remaining emissions found in low-emission scenarios. This calls for a better understanding of both the drivers of material demand as well as the options to reduce the impacts of continued production of materials.

Finally, it is common in Industrial Ecology research to explore linkages in supply chains, environmental trade-offs and rebound-effects from a holistic perspective. That is why it needs to be emphasized that this thesis presents only a partial view on the interactions between energy models and material demand scenarios. While some of the findings presented throughout this thesis imply that transitions towards renewable energy and electric mobility could increase the annual material demand, the fact that they need more materials does not mean that a transition is undesirable from an environmental perspective. To encompassingly explore the environmental impacts of a low-carbon transition in a long-term scenario framework would require an assessment of the avoided material use in mining, processing, transporting and burning fossil fuels as well. Because this would require additional research, the results presented in this thesis should not be used as an argument against a transition towards electric mobility or renewable energy. In fact, a full supply chain perspective, provided for example in LCA studies, seems to favor such a transition at least with regards to climate impacts (Hertwich et al. 2015; Verma et al. 2021). The results do, however, show the importance of fully capturing the implications of the energy transition on material demand in global scenarios. Further efforts could therefore be focused on incorporating service-driven material demand models into an Integrated Assessment framework, which allows for the reciprocal assessment of climate- and circular economy policies as well as the implications for reaching the Sustainable

Development Goals, through explicit accounting of indicators relevant to development and prosperity, such as for example access to electricity (Dagnachew et al. 2018), lighting, clean cooking and appliances (Daioglou et al. 2012) or other material stocks that fulfill the basic needs of a growing population worldwide (Watari and Yokoi 2021).

9.5 Directions for future research

As suggested in the Synthesis chapter, there are a few key end-use categories remaining, which were not covered in this thesis research. Though the prioritization is dependent on the material of interest, the use of materials for industrial machinery and equipment appears repeatedly as an important missing end-use category. Therefore, it could be a logical choice to focus on machinery and equipment in future research efforts. Other stock-forming material end-use categories that potentially drive a relevant fraction of total material demand are infrastructure (other than the electricity sector) and consumer appliances.

Here it is important to note that not all material end-uses are stock forming. Some material uses are consumptive such as packaging materials. Since their in-use lifetime is short there is no need to account for lifetimes or cohort-based stock accounting. As such, an ideal model could combine models based on per capita annual demand for consumptive material demand and on (saturation of) per capita in-use stock for products with longer lifetimes, thus representing the nature of both stock- and flow-based drivers of material demand in society.

More practically, the newly available information on sectoral material demand may be used to expand the inter-sectoral linkages in the IMAGE model, and address the consequential interactions throughout supply chains in a way that is more in line with Industrial Ecology tools such as Life Cycle Assessment or Input Output Analysis. Examples of such linkages and opportunities to better incorporate a life-cycle perspective in IAMs are numerous, and only a few are listed here. The most obvious one is to capture the interactions between the sectoral annual demand for steel and cement calculated here with the existing steel and cement production modules in IMAGE. But other, more indirect, effects may also be captured more easily, such as the way in which lower demand for fossil fuels leads to a reduction of the demand for their transportation and lower demand for steel in ships for example. The level of detail in the vehicle material model presented in Chapter 7 may in fact enable such model improvements in the future. Another relevant inter-sectoral interaction that could be captured would be the indirect effects of energy efficiency improvements, such as efficient electrical appliances, which would allow for a reduction in electricity transmission- & generation capacity and, consequentially, a reduction in annual demand for steel, aluminum and copper from the electricity sector. The work presented in Chapter 6 could facilitate the explicit modelling of such indirect interactions with the electricity sector. Generally, modelling such explicit inter-sectoral linkages would make results from Integrated Assessment models more realistic, but possibly also more inspiring, by showing higher-order effects of energy- and resource efficiency measures, thus providing additional motivation for action.

Possibly relevant policy measures that could be modelled are for example the extension of product lifetimes through repair, refurbishing or remanufacturing, the reduction of demand through sharing or leasing services for cars and other products, increased collection and recycling schemes but also the substitution of construction materials with a better recyclability, such as replacing concrete with steel, or a lower impact on global warming, such as replacing steel with wood. A recent report by the International Resource Panel explores such interventions and their potential environmental impacts (Hertwich et al. 2020), which could be gratefully used to increase the policy relevance of the demand modelling in the IMAGE model. Vice versa, the broader coverage of both regions and material end-use categories in the work presented in this thesis could potentially be used to expand such work.

Ultimately, the environmental implications of a growing material demand are dependent on waste management practices. Recycling rates and scrap availability determine to which extent the use of virgin raw materials can be avoided. Though this thesis mostly addresses the demand-side development, it does provide an indication of the volume and the timing of end-of-life waste flows, and could therefore be expanded with a description of waste handling and recycling. Complemented with a material production perspective (including extraction and processing), such a model could eventually be used to evaluate the effectiveness of waste management practices and Circular Economy policies. Integrating these dynamics into a framework that consistently captures resource consumption, climate challenges and the broader social challenges of the Sustainable Development Goals requires bridging scientific fields through interdisciplinary exchange and cooperation.

The story of stuff is rooted in the story of a lifetime. Not just because of the importance of product lifetimes in defining material demand, but also because the materials we use provide a basis for decent living. Material stocks provide a level of comfort and sustenance that cannot always be bargained with through continued reduction and efficiency improvements. The challenge of reaching a circular economy is a balancing act, that will require planning, patience and possibly a radical departure from the way we consume today. Yet it is a generational venture with opportunities to share and connect, to develop a new definition of ownership and a new appreciation of quality and craftsmanship. With a destination that lies beyond the horizon this can be an exciting adventure, a road-trip that we take together. Just make sure to pack lightly.

10.

Conclusions

Over the 20th century, in-use stocks of materials have increased substantially, and it is expected that a further increase will take place during the 21st century. The increase in global material consumption has led to concerns about environmental impacts and resource depletion. Such concerns have been around for a while (e.g. the Limits to Growth publication) but are increasingly intertwined with discussions on climate policy and the Sustainable Development Goals (SDGs). This is partly because climate policies may lead to increased material demand through deployment of new technologies and infrastructure that tends to be more material intensive than existing fossil fuel alternatives. Similarly, achieving the SDGs requires investment in infrastructure and the development of basic levels of prosperity that require an expansion of in-use stocks of materials. This seemingly introduces a paradox between multiple policy objectives because the growth in material demand, in turn, leads to increased energy demand, greenhouse gas emissions and other environmental impacts. At the same time, reducing the production of primary materials can also contribute to climate policy and achieving the SDGs.

Over the last few years, the Circular Economy has been coined as a solution to this policy paradox. The Circular Economy represents a new economic system that aims to limit the impacts of resource consumption through a reduction of demand for products and materials and by stimulating a more circular supply of products and materials. The reduction of material demand can be achieved, for example, through more efficient & long-lasting product designs, through repairing and sharing products or through service-based business models. Stimulating a more circular supply can be achieved, for example, through increased reuse and recycling. This concept of ‘circularity’ is grafted in the idea that closing the loops of societal material flows will eventually reduce the reliance on raw material inputs and reduce the associated environmental impacts.

In order to assess the true potential of such a circular economy, models dealing with long-term global environmental change need to be expanded with a clear perspective on material use. This starts with a better understanding of what drives material demand in the long term. Throughout this thesis, efforts have been made to improve this understanding and to perform some of the groundwork required to incorporate material cycles more explicitly and consistently in integrated assessment models.

This is addressed in Chapter 2-9. Chapter 2 started by exploring how detailed information on product consumption could be used to assess what drives the demand for a critical metal like tantalum. This work led to the realization that product lifetimes might be essential information to estimate future material waste-flow generation due to a delaying residence in in-use stocks. This idea was further applied in a forward-looking study presented in Chapter 3. In this chapter, a dynamic stock model was applied in combination with results from the IMAGE integrated assessment model to derive the expected annual demand for metals in cars, appliances and electricity generation technologies under different scenario assumptions. Chapters 4 through 7 explored such relations in more detail for three material end-use sectors the construction sector (buildings), the electricity sector and the transport sector (vehicles), respectively. Each chapter addresses the dynamic relations between stock formation, annual material demand, and the resulting waste flows of materials.

Based on the results of these chapters, as compiled in the synthesis in Chapter 8 and the considerations and limitations addressed in the discussion Chapter 9, the following section will address the research questions as formulated in the introductory Chapter 1, followed by some final conclusions.

10.1 Main findings

10.1.1 Research question 1

How is the future global material demand expected to develop towards 2050 and how does this affect the prospects of achieving global policy goals related to climate change, the SDGs and the circular economy?

Global material demand is expected to grow continuously towards 2050. Chapters 3-7 and the Synthesis Chapter 8 indicate that if current trends of consumption & expansion of in-use material stocks continue as under the SSP2 scenario (middle-of-the-road development), material use is expected to increase significantly. Though this observation is based on assessing only three material end-use sectors, being buildings, electricity infrastructure and vehicles, their combined material use explains about half of the global material demand for key materials, thus giving a reasonable indication of the expected growth in the overall material demand. The used method based on tracking the role of in-use stocks of products and infrastructure as drivers of annual material demand could be expanded by including other sectors and material end-use categories to complete the picture.

The continued expansion of global stocks of buildings, vehicles and electricity infrastructure leads to continued growth of annual demand for materials. An increase in demand is projected for the three sectors covered. However, given that some stocks, such as commercial buildings, electricity infrastructure and freight vehicles, grow faster than others and given their distinct material compositions, the growth in annual demand is highly material-dependent. By the end of the scenario period (2045-2050), global steel demand in the three modelled end-use applications is expected to grow by 45% compared to recent years (2015-2020). However, the expected growth of annual demand for aluminium and copper in those applications over the same period is higher at 56% and 94%, respectively.

Buildings constitute the largest stock of bulk materials, and they continue to play a dominant role in material stocks worldwide towards 2050. Due to their long lifetimes, however, the importance of building material use as a driver of annual material demand is somewhat smaller and end-use applications with shorter lifetimes, such as vehicles, become more important in the relative sense.

It is possible to reduce overall material use compared to the SSP2 projection, but other pathways may increase the demand for specific materials like copper and neodymium. The demand for materials depends strongly on socio-economic development and policies. As a result, some of the observed growth in annual material demand may be avoided under different assumptions on development of population and consumption patterns. Chapter 3 showed that annual demand for neodymium and copper under a SSP3 baseline scenario is lower than in an SSP1 baseline (by 9% to 20%, respectively). However, that same chapter also showed that climate policies may increase the expected demand for those materials by about 20%.

Additional climate policies are likely to increase the use of some bulk materials and specific critical materials used in electric vehicles and electricity infrastructure. Climate policies can lead to a shift in demand for vehicles and electricity. This can lead to additional demand for critical materials (such as neodymium) and bulk materials such as steel and aluminium. This possible trade-off between climate policy and material use has often been disregarded in global emission scenarios. The research presented in this thesis shows that this trade-off should be addressed more consistently in long-term emission scenarios as generated by Integrated Assessment Models, and it also presents examples of how this could be accounted for. However, this does not mean that climate policies only have a negative effect on resource consumption per se. Assessing the full scope of such trade-offs in an integrated assessment model framework requires further expansion of this work to include the effects on material use in industrial and (especially) fossil fuel supply chains.

The combination of continued growth of annual material demand and the simultaneous effect of climate policies will likely lead to a more important role of material production and processing in overall volumes of greenhouse gas emissions in the coming decades. This is partly because emissions from other sources such as electricity production and transportation are expected to be mitigated more rapidly. At the same time, some of the materials supply chains are hard to abate. The circular economy provides a framework to limit such environmental impacts of material use by consuming more efficiently and through closing societal material cycles. This emphasizes the need for integrated modelling approaches that capture the dynamics of both climate change and material cycles.

Explicit accounting of in-use stocks as a driver of material demand reveals that per capita in-use stocks of products and materials are expected to go up, limiting the options to

move towards a circular economy in the following decades. Whether one looks at the per capita floor space as discussed in Chapter 4 and 5, or the ownership rates of cars as addressed in Chapter 3 and 7, such indicators are typically subject to strong upward trends as a consequence of increasing affluence. So, while one way to achieve the objective of the circular economy is to bend these trends with regards to consumption and product ownership, for some regions, this may be at odds with the Sustainable Development Goals, which emphasize the goal of shared prosperity and sustainable development. Especially in developing regions, products and infrastructure play a crucial role in fulfilling human needs and achieving decent living standards. Material demand should not be minimized everywhere but instead optimized according to the regional dynamics presented in this thesis. Another way to reach the objective of circular economy policies (i.e. reducing or even eliminating societal dependence on virgin raw-material inputs) is through maximizing the re-use and recycling of products. While this is a sensible strategy in all regions, the potential to supply all material demand based on a secondary flow of materials is likely severely limited until 2050 under baseline assumptions, at least for the materials in vehicles, buildings and the electricity sector, as discussed in this thesis. These observations suggest that a combination of regionally appropriate demand reduction strategies and an expansion of waste management capacity worldwide are prerequisites to achieving a more circular economy.

The potential for truly closing material cycles depends on the delayed availability of materials in waste-flows. The application of dynamic stock models suggests a continued dependence on raw material inputs for stocks with long lifetimes, such as buildings, vehicles, and electricity infrastructure in the coming decades. This limits the potential for reaching a fully circular economy before 2050. Under an SSP2 baseline, the mismatch between inflow and outflow (the circularity gap) by 2050 will be around 40% for materials like copper, steel and aluminium. Though this is highly region and time dependent, as elaborated in the following section.

10.1.2 Research question 2

How do stock dynamics affect the availability of waste flows, and what does this mean for the potential to reach a circular economy by 2050?

Product lifetimes and the resulting stock dynamics dictate a long delay between inflow and outflow of materials to and from in-use stocks of buildings, vehicles and electricity infrastructure. The volume of materials in generated waste flows catches up only slowly with the annual demand for materials, which means that even when all material would be recycled without losses, the world will likely be dependent on virgin raw material inputs at least until 2050. This suggests that it is very difficult, if not impossible, to reach a fully circular economy by 2050.

The availability of scrap materials depends on regional developments such as population growth and product-specific demand in relation to income levels. Both are captured in the approach presented in this thesis, which combines the Shared Socio-Economic Pathway scenarios from the IMAGE Integrated Assessment Model and product-specific stock modelling. The results provide examples of specific in-use stocks of products that may become a net source of materials before 2050, such as rural residential housing (except in fast-developing regions), fossil-based power plants (under climate policy assumptions), and bicycles or even buses in regions like China and Japan. More generally, the scenario results can already be used to improve material demand estimates based on sectoral activities, thereby improving the inter-sectoral consistency of models like IMAGE, or to explore regionally optimal waste management strategies and the future role of the trade of scrap materials. In the future, this work may be expanded to explore the interactions between specific circular economy policies and climate mitigation efforts.

A continued global shortage of scrap materials is likely until 2050 as the annual demand for materials continues to grow in most regions. However, dynamic stock models also show that when population stabilizes or starts declining, stock expansion may no longer be required, and annual material demand may consequently drop quickly to levels required only for stock maintenance, while scrap availability continues to grow. This highlights the potential for a rapid shift from a material shortage to a surplus within a matter of years. Such a sudden shift in material demand is not effectively captured by the premise of saturating per capita annual demand that is currently the basis of material demand modelling in many integrated assessment models. However, it may play a fundamental role in determining long-term material demand and has important implications for industrial energy demand modelling and the potential for reaching a circular economy beyond 2050. Therefore, it is advisable to adopt dynamic-stock modelling in integrated assessment models and expand the scope of research to look at the implications beyond 2050.

10.1.3 Research question 3

What type of data and data sources are essential to better understand societal material flows and assess the implications of a circular economy?

Of particular importance is the availability of product-level data regarding in-use stocks, product lifetimes, and the material composition of products. Such data requirements make a product-specific and stock-driven approach to material demand modelling more data-intensive than the method based on a statistical relation between per capita income and per capita annual demand as previously applied in the IMAGE model. Furthermore, such data may not always be readily available as it may be unknown or only available as confidential intellectual property of companies. The further development and integration of dynamic material flow accounting for application in Integrated Assessment Models (IAMs) would greatly benefit from a more accessible and central availability of such product-level data. While Life Cycle Assessment (LCA) studies, Product Environmental Passports (PEPs) and even some patents have repeatedly proven helpful as sources of data throughout this thesis, they tend to be scattered, making model development time-consuming. Future work on this topic could be made easier by adapting and expanding more centralized databases, as reflected below.

Existing Life Cycle Inventory (LCI) databases are instrumental to assess material use related to product stocks, but a clearer specification of the fraction of materials used in the production, maintenance & final products would facilitate dynamic MFA studies. The Ecoinvent Life Cycle Inventory database has been an important source of in most chapters because it contains information on material use during the production of multiple products. However, their application as a basis for global dynamic MFA studies is limited by two factors. First, the coverage of production processes in LCI databases is limited, which means that not all relevant new products and technologies are described. Throughout this thesis, Ecoinvent data had to be complemented with data from specific LCA studies and other literature. Expansion of LCI-databases with newer technologies, or at least the shared development of an open-source list of LCA studies transparently defining unit process information for new products and technologies, might improve the availability of the data required in such global dynamic MFA studies. Secondly, it is not always clear what part of the materials used during the production process ends up in the actual final products based on the unit process definitions in LCI databases. A clearer specification of what part of materials inputs represent manufacturing losses, production auxiliaries or maintenance requirements of products would allow for a more useful accounting of those material fractions that actually end up in final products. This would facilitate the expansion of the type of modelling presented in this thesis and improve it by explicitly capturing the material flows involved in the production or maintenance of products.

The important role of material stocks in achieving the sustainable development goals (SDGs) and as drivers of material demand and climate change, would justify efforts of (inter)national statistical offices to collect and provide more data on in-use stocks. The increasing emphasis of in-use or per capita stocks of products in both the research field of Industrial Ecology and the Integrated Assessment research community may imply an increasing dependency on unofficial data sources. National statistical offices and other official data sources, frequently used in both research fields, tend to report mostly on annual flow indicators rather than on in-use stocks. The increasing awareness of the importance of material stocks as drivers of material demand, climate change, but also their crucial role in achieving the sustainable development goals (SDGs), would certainly justify efforts of (inter)national statistical offices to collect and provide more data on in-use stocks of vehicles, buildings, infrastructure and so on. This would help to check and improve the outcomes as presented. However, even without such efforts, an open-source database of key data on stocks, lifetimes and composition of products, developed and shared across research fields, would catalyze the improvement and expansion of this type of research.

In the absence of such an encompassing official database, the use of input-data and their sources have been documented as transparently as possible in this thesis (see appendices). Proxies, scaling and averages have been used occasionally to fill missing information on material composition or product lifetimes, for example. While this may be justifiable for some applications of established products and data on bulk materials, the use of proxies to fill missing data on new product types or critical material composition should only be done with caution. Chapter 2 showed that data at a sub-component level of detail might be required for this. Chapter 6 showed that many new technologies will be required in some sectors, thus making it hard to use accurate lifetime assumptions. Finally, Chapter 5 showed that even for established stocks such as housing, lifetime estimates might be uncertain. Continued improvement of, and reflection on, realistic model assumptions and input data is important for any model, and the work presented here is no exception.

9.2 Implications

Implications for environmental assessment

In short, the results of the analysis presented in this thesis, based on practical application of dynamic material flow assessment in combination with long-term scenarios from the IMAGE integrated assessment model, has the following implications for environmental assessment:

- Accounting of stocks of products and infrastructure as drivers of material demand provides a) a more explanatory relation between income levels and per-capita material demand, b) additional detail with regards to sectoral contributions to material use, c) coverage of the effects of climate policies on material demand and d) possibilities to improve internal model consistency.
- Under baseline assumptions annual demand of most materials used in buildings, vehicles and electricity infrastructure is expected to grow, by about 45% for steel and up to 94% for copper, towards 2050.

- Climate policy may lead to additional material demand for example through additional demand for electricity infrastructure and higher material demand for electric vehicles. Accounting for those trade-offs in terms of additional energy demand or related emissions is something that should be incorporated more explicitly in long-term scenario analysis, and this thesis presents some of the groundwork to make that possible. However, not all climate policy effects with respect to increasing- or avoided material use are assessed in this thesis, so further research and more comprehensive coverage of trade-offs is required.
- Buildings tend to dominate stocks of bulk materials like steel, while vehicles are likely to play an increasingly important role in annual demand for materials like aluminium, and copper. Not just as a result of their material composition, but also because of the shorter lifetimes of vehicles.
- In general, lifetimes of products and infrastructure are a very important factor in dynamic stock models. They determine how in-use stocks drive annual demand, but they also cause a delay between annual demand (inflow) and the availability of scrap and waste-flows (outflow), which has real implications for maximum recycling rates and the potential of closing material cycles.
- Regional model outcomes, however, provide examples of specific products with lifetime dynamics that may imply a rapid shift from shortage to a surplus of scrap materials in regions with stabilizing populations. The methodology and the results as presented in this thesis capture such shifts and may therefore be used to improve industrial energy demand modelling and to derive optimal waste-management strategies.

Implications for policymaking

This has some consequences with regard to policy objectives related to climate change mitigation, the circular economy and the Sustainable Development Goals:

- Due to the fact that long lifetimes of products & infrastructure cause a delay between inflow and outflow of materials in societal stocks worldwide, it is impossible to reach a circular supply of materials while the demand is still rising. Results show that under business-as-usual assumptions, global annual demand for most materials is likely to continue to rise at least towards 2050, making it very difficult to achieve a fully circular economy in the first half of the 21st century.
- Given the likelihood of a continued increase in material demand towards 2050 (this thesis) and the difficulty in reducing the emission related to their production, combined with the potentially rapid decarbonization pathways for other sectors such as electricity production and passenger transport it is likely that materials and their production will play an increasingly important role in the remaining global emissions of greenhouse gases into the future. This highlights the need for a better

understanding of both the demand and the supply of materials, and it highlights the importance of proper strategies and investments aimed at stimulating product innovation and waste-management capacity to achieve climate change mitigation through a more circular economy.

- Increasing attention to per capita in-use stocks as drivers of material demand provides an opportunity to assess the role of stocks in providing services and fulfilling the needs of a growing and more affluent population worldwide. While some climate- and circular economy policies may be oriented at reduction of material demand, it is important to realize that in many regions a growing material use and development of the stocks of products and infrastructure play a crucial role in achieving decent living standards and in reaching the Sustainable Development Goals. So, while improving waste-management practices is a sensible policy strategy everywhere, policies oriented at extensive reduction of demand for materials may be most sensible in high-income regions.
- In the future, this work could benefit from integration into integrated assessment models. At the same time, this work could be further expanded by covering more material applications and by incorporating an explicit circular economy policy scenario based on interventions aimed at reducing raw material requirements. Only then can claims about the importance of circular economy policies to achieve climate policy goals truly be assessed in their dynamic and long-term context.

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Summary

Growing resource consumption and increased global demand for materials is causing concern for environmental impacts, mostly related to their production. At the same time, reaching climate policy targets, the Sustainable Development Goals and decent living standards may require an expansion of in-use stocks of materials. The concept of a more Circular Economy may provide a solution to this potential policy paradox as it aims to reduce the global dependence on virgin raw material inputs through more efficient use of products and materials, as well as through closing their cycles. Integrated Assessment Models are used to analyze long-term global environmental challenges, and possible policy responses, but are not typically well suited to assess global material flows or Circular Economy policies.

This thesis addresses some of the groundwork needed to incorporate material cycles more explicitly and more consistently in the IMAGE integrated assessment model. Using dynamic stock modelling and detailed information on the composition and lifetimes of products in combination with scenarios from the Shared Socioeconomic Pathways towards 2050, this thesis explores how the demand for services provided by products such as buildings, vehicles and electricity infrastructure translates into in-use stocks of materials worldwide and how the corresponding annual material demand and waste generation may consequently develop in the coming decades. This stock-driven approach to scenarios on global material demand enables a better model consistency and detail with regard to sectoral contributions to material demand, it adds the possibility to explicitly account of the effects of climate policy on material demand, and builds upon the latest knowledge from Industrial Ecology research.

Scenario analysis is applied to answer the main research question on how the future global material demand is expected to develop towards 2050 and how this affects policy goals related to climate change, sustainable development and the circular economy. Chapters 2 & 3 show that critical materials like tantalum, neodymium and cobalt are applied in a wide range of modern applications and an increased demand for mobile digital devices, renewable electricity generation and electric vehicles may strongly and rapidly drive the demand for those materials as well. For bulk materials, the relative growth in global annual demand is less pronounced over the coming decades, but the implications in terms of environmental impacts may nonetheless be important as the increasing production volume of materials like steel, aluminium and concrete would contribute to energy demand and related greenhouse gas emissions. Chapters 4 to 7 describe the contribution to global bulk material demand of three applications, being buildings, vehicles and electricity infrastructure.

Buildings (Chapter 4 & 5) generally play a large role in defining the total weight of in-use stocks of materials like steel and concrete. The presented analysis is based on a database of construction material intensities in kilograms per square meter of floorspace and a disaggregation of four different service building types and four different residential building types. Results show the dynamic development of material stocks in buildings and the associated demand for construction materials and building waste generation. Given the detail in the underlying scenarios it is possible to distinguish trends in the development of stocks for both rural and urban residential buildings which indicate that while rural housing stocks show a stabilizing trend in various regions, urban housing shows a continued growth towards 2050. Notably, the expected growth of service-related building stocks is even stronger than that of urban housing stocks, indicating the importance of modelling material demand in buildings beyond residential applications only.

Material use in electricity infrastructure (Chapter 6) is described for electricity generation capacity, transmission and distribution, as well as for electricity storage requirements. These represent most of the infrastructural elements required to provide electricity based on a stable electricity grid. Based on the second Shared Socioeconomic Pathway scenario (SSP2), increasing electrification and electricity demand will likely translate into a rapidly increasing infrastructural stock, causing a relatively strong growth in the sectoral annual demand for materials like copper and aluminium. When combining the same SSP2 scenario with climate policy assumptions (in line with a 2-degree climate policy target), the results show a mixed effect of improved energy efficiency measures, leading to a temporary decrease in electricity demand and sectoral material demand at first. However, towards 2050, increased electrification combined with higher material intensities for renewable energy technologies, like solar panels and windmills, will likely lead to higher sectoral material demand under climate policy assumptions.

Finally, a baseline scenario for material use in vehicles is presented in Chapter 7, which provides a detailed elaboration of vehicle fleets for both passenger- and freight vehicles based on the IMAGE model. This input data accounts for both shifts in transportation modes, as well as the development of different vehicle types over time. A detailed data set on material composition and the use of different vehicles was established to derive material stocks in vehicle fleets, and the corresponding annual material demand and waste-flows. Results show that, by 2050, the weight of the total vehicle fleet of roughly 5 Gt is dominated by passenger cars, and by steel as a main material. But other vehicles like ships and trucks are not negligible. In addition, explicit accounting of batteries and their market shares, material compositions and weights in several electric vehicles allows to trace the increasing demand for critical metals like cobalt. With typical average lifetimes of about 15 years, vehicles cause a relatively large fraction of the annual demand for materials like steel, aluminium and copper compared to stocks with longer lifetimes like electricity infrastructure (ca. 40 yr) or buildings (ca. 60 yr). At the same time, their shorter lifetimes ensure that the availability of scrap materials from vehicles catches up with annual material demand for vehicles relatively quickly.

Combining these results shows that global demand for materials like steel, aluminium, copper, concrete and others will likely continue to grow towards 2050 as a consequence of growing in-use stocks of buildings, vehicles and electricity infrastructure. Compared to recent years, steel demand in these applications is expected to grow by 45%, and copper demand is expected to grow by 94% towards 2050. Driven mainly by an increasing population and increasing income levels. Results show a particularly high rate of growth in specific applications like service-related buildings, freight vehicles and electricity infrastructure. The dynamic assessment of individual product stocks, each with a different material composition, lifetime and region-specific deployment, has fundamental consequences with respect to achieving a circular economy.

The way in which stock dynamics affect the availability of waste flows, and what this means for the potential to reach a circular economy, is explored based on the second research question. In general, product lifetimes play an important role in defining the dynamic relation between the in-use stocks of materials, and their corresponding annual demand or waste-flows. Buildings, for example, define the largest part of in-use material stocks, but their construction requires a smaller fraction of the total annual material demand due to their typically long lifetimes. The relatively long lifetimes of the end-use applications studied in this thesis dictate a delayed availability of scrap or secondary raw materials, thus implying a continued reliance on virgin raw material inputs towards 2050. This presents a fundamental challenge to achieve a fully circular global economy in the first half of the century, under the assumption of business-as-usual development as described by the second Shared Socioeconomic Pathway.

The regional perspective provided by the IMAGE model shows that much of the demand increase for products and materials originates in fast developing regions. In those regions, in-use stocks of products and infrastructure may provide an essential physical basis of decent living standards and wellbeing that contribute to achieving the Sustainable Development Goals. Therefore, circular economy measures aimed at demand reduction may not always be appropriate in those regions, and may mostly be suitable in high-income regions. In other regions with stabilizing populations, however, results show the potential to close material cycles from particular applications before 2050. There, some in-use stocks like rural housing or bicycles have the potential to shift from a net sink to a net source of materials before 2050. This highlights the importance of demand-dynamics and demand reduction to fully close material cycles for different products and sectors in the future. This has consequences in terms of preparing proper waste management strategies and capacities, especially towards the second half-of the century, when increasing volumes of

materials are expected to become available as wastes or recycled secondary raw material flows. The results on the regional timing and dynamics of material flows can be used to assess implications to industrial energy demand, optimal waste management strategies or to explore the effects on secondary material markets and trade.

Higher electrification rates and deployment of electric vehicles under climate policy assumptions would likely lead to higher material demand in the electricity- & transport sector, though this thesis does not capture the full range of possible effects of climate policies on global material demand, so further research would be needed to systematically assess their interactions. Further research could also focus on expanding the coverage of sectoral materials use, for example to capture material use in industrial machinery and equipment, or in transportation infrastructure. The examples of product-specific dynamic stock modelling and dynamic material flow analysis presented here may serve as a blue-print for future work in that direction, requiring mostly data on material composition and lifetimes of products. Eventually, a full integration of the sectoral material demand models developed here would benefit the IMAGE model in multiple ways as it enables internal model consistency, a more detailed and intuitive relation between income levels and material demand as well as coverage of the effects of climate policies on material demand.

Overall, this thesis concludes that under typical baseline development, global demand of various materials used in buildings, vehicles and electricity infrastructure will likely continue to grow towards 2050. In addition, the long lifetimes of these applications cause a delayed availability of materials in waste-flows. Therefore, their production will likely continue to rely on virgin raw material inputs, even when all waste-flows are recycled without losses. Given that buildings, vehicles and electricity infrastructure stocks explain about half of the annual material demand suggests that it will be very difficult to achieve a fully circular economy in the first half of the 21st century. Even though environmental impacts or the effects of circular economy policies are not explicitly addressed in this thesis, the expansion of this work and its integration in integrated assessment models like IMAGE would ultimately enable the assessment of explicit circular economy policy scenarios based on interventions aimed at reducing raw material requirements. Only then can claims about the importance of circular economy policies to achieve climate policy goals truly be assessed in their appropriate dynamic and long-term context.

Samenvatting (Dutch)

De wereldwijde vraag naar grondstoffen en materialen groeit en de negatieve gevolgen van materiaalproductie op het milieu zijn een reden tot zorg. Tegelijkertijd zijn er materialen nodig voor het halen van beleidsdoelen met betrekking tot klimaatverandering en duurzame ontwikkeling (SDGs). Het concept van de Circulaire Economie biedt mogelijk een oplossing voor deze schijnbare beleidsparadox, omdat het de afhankelijkheid van grondstoffenextractie probeert te beperken door middel van efficiënter gebruik van producten en materialen en door het gelijktijdig sluiten van kringlopen. *Integrated Assessment* modellen worden gebruikt bij de analyse van wereldwijde milieuproblematiek, en de effectiviteit van beleidsopties, maar zijn op het moment nog niet geschikt om vraagstukken rondom de Circulaire Economie volledig te beantwoorden.

In dit proefschrift worden een aantal van de eerste stappen uiteengezet die nodig zijn voor het beter modelleren van materiaalstromen in het IMAGE *Integrated Assessment* model. Door gebruik te maken van dynamische modellering van gebruiksvoorraden en gedetailleerde informatie over de compositie en levensduur van producten, in combinatie met scenario's tot aan 2050, gedefinieerd door de *Shared Socioeconomic Pathways*, wordt onderzocht hoe de groeiende vraag naar de diensten die geleverd worden door gebouwen, voertuigen en de elektriciteitssector zich vertalen naar materiaalgebruik. Daarnaast wordt bepaald hoe de vraag naar nieuwe materialen leidt tot het ontstaan van afvalstromen, en hoe deze zich in de komende decennia kunnen ontwikkelen. Deze aanpak op basis van materiaal voorraden in producten in de gebruiksfase maakt de modellering zowel consistenter, als ook gedetailleerder, omdat de ontwikkelingen in verschillende economische sectoren expliciet kunnen worden meegenomen. Tevens kan hiermee het effect van klimaatbeleid op de vraag naar materialen beter in kaart worden gebracht, op basis van de meest recente inzichten uit industrieel ecologisch onderzoek.

In de verschillende hoofdstukken worden scenario's gebruikt om antwoord te geven op de onderzoeksvraag; hoe zal de wereldwijde vraag naar materialen zich ontwikkelen tot en met 2050, en hoe beïnvloedt dit de beleidsdoelstellingen rond klimaatverandering, duurzame ontwikkeling en de circulaire economie? Hoofdstukken 2 en 3 gaan hiervoor in op de oorzaak en de ontwikkeling van de vraag naar schaarse metalen zoals tantalum, neodymium en kobalt. Omdat deze materialen nodig zijn in verschillende moderne toepassingen zoals mobiele digitale technologie, hernieuwbare energie toepassingen en ook elektrische auto's, kan de toekomstige vraag van deze materialen snel en sterk groeien. Voor bulkmaterialen is de relatieve groei van de vraag in de komende decennia wellicht wat kleiner, maar toch zeker relevant met betrekking tot milieueffecten. De hogere productievolumes van materialen als staal, aluminium en beton kunnen een substantieel effect hebben op zowel de energievraag als de gerelateerde broeikasgasemissies. Hoofdstuk 4 tot en met 7 beschrijven daarom de bijdrage aan de vraag naar bulkmaterialen van drie belangrijke toepassingen, namelijk gebouwen, voertuigen en de elektriciteitssector.

Gebouwen (hoofdstukken 4 en 5) bepalen over het algemeen een groot deel van het totale gewicht van materialen zoals staal en beton in gebruiksvoorraden. Op basis van een database met gegevens over het gebruik van bouwmaterialen (in kilogram per vierkante meter vloeroppervlak) in verschillende gebouwtypen laten de resultaten de dynamische ontwikkeling van de hoeveelheid materialen in de staande gebouwvoorraad zien. Daarnaast geeft deze analyse ook inzicht in de ontwikkeling van de jaarlijkse vraag naar bouwmaterialen en de beschikbaarheid van afvalstromen zodra bestaande gebouwen gesloopt worden. Het detail in de onderliggende scenario's maakt het mogelijk om onderscheid te maken in de ontwikkeling van stedelijke en landelijke gebieden. Daardoor is duidelijk te zien dat de woningvoorraad buiten de steden in veel regio's stabiliseert, terwijl de vraag naar woonoppervlak in steden blijft groeien tot ten minste het jaar 2050. Daarnaast valt op dat het vloeroppervlak in commerciële en openbare gebouwen wereldwijd sneller groeit dan het totale stedelijke woonoppervlak. Dit betekent dat het belangrijk is om bij het bepalen van de ontwikkeling van mondiale materiaalstromen niet alleen te kijken naar woningen, maar ook naar andere gebouwen.

Materiaal gebruik in de elektriciteit sector (hoofdstuk 6) wordt berekend voor zowel de opwekkingscapaciteit, transmissie en distributie als ook voor de elektriciteit opslag. Daarmee dekt de analyse de belangrijkste infrastructuur die benodigd is om wereldwijd een stabiel elektriciteitsnetwerk te realiseren. Onder de aannames van het tweede *Shared Socioeconomic Pathway* (SSP2) scenario vertaald de groei in de vraag naar elektriciteit zich in een snelle groei van de benodigde infrastructuur, met als gevolg een relatief hoge groei van de jaarlijkse vraag naar materialen als koper en aluminium. Als datzelfde SSP2 scenario daarnaast gecombineerd wordt met streng klimaatbeleid (in overeenstemming met een 2-graden doelstelling), leidt dat in eerste instantie tot een tijdelijk lagere materiaalvraag als gevolg van verschillende energie besparingsmaatregelen. Echter, het gecombineerde effect van de groeiende elektrificatie en een hogere materiaal-intensiteit van hernieuwbare elektriciteit opwekkingstechnologieën zorgt er rond 2050 juist voor dat de materiaalvraag van de elektriciteitssector hoger ligt als gevolg van klimaatbeleid.

Ten slotte wordt het materiaal gebruik in voertuigen (hoofdstuk 7) besproken voor een baseline scenario. Hierbij wordt gebruik gemaakt van de bestaande uitwerking van de vraag naar zowel personenvervoer als vrachtverkeer uit het IMAGE model. Deze data beschrijven zowel de dynamische verschuiving tussen transport modi als ook de ontwikkeling van verschillende voertuigtypes binnen iedere transport modus. In de analyse worden deze scenario's gecombineerd met een gedetailleerde dataset over het gebruik en de compositie van voertuigen, om zo het materiaalgebruik in de bestaande voertuigvloot te bereken. De omvang van bijbehorende materiaal vraag en afvalstromen worden ook afgeleid op jaarbasis. De resultaten laten zien dat, rond 2050, het totale gewicht van voertuigen, van ongeveer 5 gigaton wereldwijd, vooral bestaat uit personenauto's en dat staal hierin het voornaamste aandeel heeft. Echter, andere voertuigen zoals schepen en trucks zijn niet verwaarloosbaar. Ook de materialen in batterijen van elektrische voertuigen worden berekend op basis van een dynamisch ontwikkelende markt, materiaal-compositie en batterij gewicht. Hiermee kan de ontwikkeling van de vraag naar kritische materialen als kobalt preciezer worden bepaald. Met een gemiddelde levensduur van ca. 15 jaar veroorzaken voertuigen een relatief groot deel van de jaarlijkse vraag naar staal, aluminium en koper, ten opzichte van gebruiksvoorraden met een langere levensduur zoals elektrische infrastructuur (ca. 40 jr.) of gebouwen (ca. 60 jr.). Tegelijkertijd zorgt de kortere levensduur voor een snellere beschikbaarheid van metaalschroot uit voertuigen.

Door de resultaten uit de verschillende hoofdstukken te combineren wordt duidelijk dat de wereldwijde vraag naar materialen zoals staal, aluminium, koper en beton waarschijnlijk zullen blijven groeien tot en met 2050, als gevolg van een groeiende vraag naar gebouwen, voertuigen en infrastructuur voor elektriciteit. Voor de vraag naar staal in deze toepassingen komt dit neer op een groei van 45% en voor koper ca. 94% ten opzichte van de afgelopen jaren. De groei van de populatie en de welvaart leiden tot een groei van maatschappelijke gebruiksvoorraden, in het bijzonder geldt dat voor publieke en commerciële gebouwen, vrachtvoertuigen en infrastructuur voor elektriciteit. De dynamiek in de ontwikkeling van gebruiksvoorraden van individuele producten, ieder met een eigen samenstelling, levensduur en regionale vraag, heeft fundamentele gevolgen voor de circulaire economie.

De tweede onderzoeksvraag richt zich op de dynamische ontwikkeling van gebruiksvoorraden, de beschikbaarheid van gerecyclede materiaalstromen en de consequenties voor de realisatie van een circulaire economie. De levensduur van producten is over het algemeen zeer bepalend voor de relatie tussen maatschappelijke materiaal voorraden, de jaarlijkse materiaal vraag en de daaruit af te leiden afvalstromen van materialen. Gebouwen zijn bijvoorbeeld de belangrijkste factor in de omvang van gebruiksvoorraden, hoewel de jaarlijkse materiaalvraag van de bouwsector relatief minder groot is omdat gebouwen een relatief lange levensduur hebben. Voor toepassingen met een lange levensduur zal de beschikbaarheid van afvalstromen voor recycling van materialen sterk achter blijven lopen op de groei van de nieuwe vraag naar materialen, met als gevolg dat de wereld waarschijnlijk tot in 2050 afhankelijk zal blijven van extractie van nieuwe grondstoffen. Dit is een fundamentele uitdaging voor het bereiken van een volledig circulaire economie, in ieder geval onder de aanname van een *business-as-usual* scenario.

Regio-specifieke ontwikkelingen, beschreven in het IMAGE model, laten zien dat een groot deel van de groei in de vraag naar producten en materialen waarschijnlijk plaats zal vinden in snel ontwikkelende regio's. In die gebieden vormen de ontwikkeling van de infrastructuur, gebouwen en voertuigen vaak een essentiële basis voor de ontwikkeling van welvaart en een behoorlijke levensstandaard, waarmee zij bijdragen aan de duurzame ontwikkelingsdoelen. Circulaire economie maatregelen die gericht zijn op het reduceren van de vraag naar producten en materialen zijn daarom wellicht meer geschikt in regio's met hogere inkomens. In andere regio's waar de populatie stabiliseert zullen specifieke toepassingen, zoals fietsen of huizen buiten de steden, al voor 2050 een netto bron van materialen vormen. Het is daarom van belang om op tijd een passend afvalbeleid en voldoende afval verwerkingscapaciteit te realiseren. Met name richting de tweede helft van de eeuw, wanneer een groeiende hoeveelheid materialen beschikbaar zal komen in afvalstromen. Regio-specifieke dynamiek en de resulterende timing van materiaalstromen, zoals gepresenteerd in dit proefschrift, kunnen helpen bij het bepalen van de effecten op de industriële energievraag, de ontwikkeling van secundaire grondstoffenhandel, en bij het bepalen van optimale strategieën voor het sluiten van kringlopen.

Klimaatbeleid leidt, daar bovenop, waarschijnlijk tot een hogere materiaalvraag in elektrische auto's en de elektriciteitssector, maar er is meer onderzoek nodig om het volledige effect van klimaatbeleid op materiaalvraag te bepalen. Verder onderzoek zou zich hiervoor kunnen richten op het uitbreiden van de modellering van materiaalgebruik in andere sectoren, zoals bijvoorbeeld in industriële machines of transportinfrastructuur. De product specifieke en dynamische materiaalstroom analyse zoals hier beschreven kan als voorbeeld dienen voor verder onderzoek, waarbij de beschikbaarheid van data over product-compositie en levensduur een belangrijke vereiste zijn. Uiteindelijk zou de volledige integratie van sectorspecifieke materiaalvraag modelering een toegevoegde waarde hebben voor *integrated assessment modellen* zoals IMAGE, o.a. omdat de modellering hierdoor consistenter wordt, maar ook gedetailleerder en intuïtiever.

Op basis van het gepresenteerde onderzoek wordt geconcludeerd dat in een *baseline* scenario, de wereldwijde ontwikkeling van de vraag naar verschillende materialen in gebouwen, voertuigen en de elektriciteitssector waarschijnlijk door zal groeien tot aan 2050. Daarnaast zorgt de lange levensduur van deze toepassingen voor een vertraagde beschikbaarheid van afvalstromen. Hierdoor zal de productie van materialen waarschijnlijk nog lange tijd afhankelijk blijven van primaire grondstoffen, zelfs als alle afval volledig gerecycled zou worden. Aangezien de gemodelleerde toepassingen ongeveer de helft van de wereldwijde materiaalvraag verklaren, zal het zeer moeilijk zijn om voor 2050 een volledig circulaire economie te realiseren. Hoewel milieueffecten of circulaire economie beleidsmaatregelen nog niet expliciet worden meegenomen in de gepresenteerde analyses, zou een voortzetting van dit werk en de integratie in *integrated assessment* modellen zoals IMAGE het uiteindelijk mogelijk maken om de potentiële impact van circulair economie beleid op klimaatmitigatie te analyseren in de passende dynamische context en voor de lange termijn.

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Curriculum Vitae

Sebastiaan Deetman was born on the 7th of August 1985 in Voorburg, the Netherlands. After finishing secondary school (VWO) in Groningen in 2003, he studied *Sustainable Molecular Science and Technology*, a combined Bachelor education programme at the Universities of Delft, Leiden and Rotterdam. He completed the Camino de Santiago pilgrimage by bike in 2007 and continued to study *Industrial Ecology* at Leiden University, where he graduated in 2010 with a master thesis on the co-benefits of climate change policy for air pollution. Continuing a career in research, he worked on Integrated Assessment modelling, climate policy and energy demand scenarios at the Netherlands Environmental Assessment agency for two years, where he contributed to various international research projects, such as the OECD Environmental Outlook to 2050, the Energy Modelling Forum (EMF), and the development of the Representative Concentration Pathways (RCPs). In 2013 he started work at the Institute of Environmental Sciences (CML) at Leiden University, initially with a focus on resource efficiency and the use of critical raw materials in several European research projects like DESIRE and SCRREEN. Later, he expanded this scope to include global use of bulk materials in an effort to make his work more relevant to climate policy scenarios, through connecting the research fields of Industrial Ecology and Integrated Assessment Modelling. Ultimately, this led to the combined work presented in a PhD thesis in 2021. Since 2018 up to the present, he has also been working at the Copernicus Institute of Sustainable Development at Utrecht University.

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Appendix 1

1.1 Scenario narratives of the SSPs

The narratives underlying the three selected SSP scenarios discussed throughout the chapters are given below. The text is copied from Riahi et al.[1] and a more elaborate background to these narratives is given by O'Neill et al.[2].

SSP1: Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation) The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2: Middle of the Road (Medium challenges to mitigation and adaptation) The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3: Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation) A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

1.2 IMAGE Region definitions

The regional classification used throughout the chapters and in the underlying model distinguishes 26 global regions, which can be seen in in Figure A1.1.

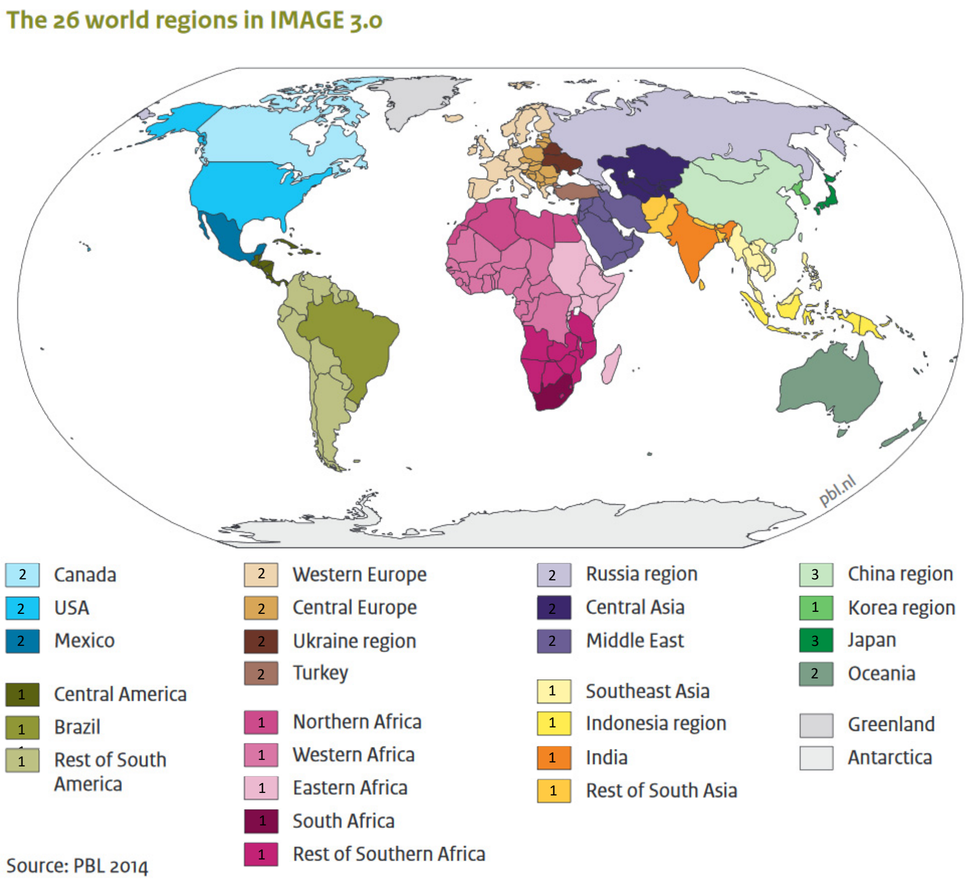

Figure A1.1. *The 26 world regions in IMAGE 3.0. Source: Stehfest et al.*[3]*, reproduced with permission of the editor. Regions tagged with a 1 are part of the group classified as fast-developing regions in the main text. Regions with a 2 represent the steady developed regions and group 3 indicates China & Japan.*

Regions are grouped under Fast developing regions are indicated with a 1, and Steady developed regions with a 2, according to the identified regional typologies used in various chapters. Greenland & Antarctica are not taken into account in any of the chapters.

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Appendix 2

Based on supplementary information provided with:
Deetman et al. (2017) - *Deriving European tantalum flows using trade and production statistics* - Journal of Industrial Ecology – Vol. 22, Issue 1, p. 166-179
https://doi.org/10.1111/jiec.12533

A2.1 Linking of relevant product categories in Europroms

Table A2.1, below, presents the linking between Europroms commodities and the tantalum containing product categories used in the main document[1]. Mind that the given quantities of imports, exports and production (in kilograms or pieces) are already completed for missing data, so the table presents the numbers used after step 3 as referred to in Chapter 2. Notice that the three types of vehicles (passenger cars, public transport vehicles and freight vehicles) are lumped into one category called 'automotive' in the main text and figures.

Commodity	Prodcom code	Export quantity	Import quantity	Production quantity	Unit	Link to product category
Non-ferrous metal ores and concentrates (including of cobalt, chromium, molybdenum, titanium, tantalum, vanadium, zirconium, antimony, beryllium, bismuth, germanium, mercury)	13201690	70671200	2.95E+09	96997489	kg	concentrates
Carbides whether or not chemically defined	24135450	44035100	1.65E+08	5.34E+08	kg	carbides
Non-agglomerated metal carbides mixed together or with metallic binders	24664740	2266100	5645800	9527520	kg	carbides
Tantalum, articles thereof, powders, waste and scrap (excluding carbide)	27453023	345200	492800	253782	kg	articles
Drilling tools with working part of sintered metal carbide, for working metal excluding unmounted sintered metal carbide plates, sticks, tips and the like for tools	28624027	268300	198200	5200000	kg	carbide tools
Turning tools with working part of sintered metal carbide, for working metal excluding unmounted sintered metal carbide plates, sticks, tips and the like for tools	28624071	115100	188800	6224332	kg	carbide tools
Interchangeable hand tools with working part of sintered metal carbide excluding unmounted sintered metal carbide plates, sticks, tips and the like for tools	28624087	536900	465400	16000000	kg	carbide tools
Indexable inserts for tools, unmounted, of sintered metal carbides and cermets	28625067	0	0	0	kg	carbide tools
Furnace burners for liquid fuel	29211130	441206	238140	1278878	p/st	furnaces
Furnace burners for solid fuel or gas (including combination burners)	29211150	761017.6	46651.96	1600000	p/st	furnaces
Non-electric furnaces and ovens for the roasting, melting or other heat-treatment of ores, pyrites or of metals	29211230	2053.327	183.3014	7420	p/st	furnaces
Non-electric furnaces and ovens for the incineration of rubbish	29211250	4576100	431600	8395159	kg	furnaces
Other furnaces and ovens	29211290	36380500	4064600	85789303	kg	furnaces
Parts for furnace burners for liquid fuel, for pulverized solid fuel or for gas, for mechanical stokers, mechanical grates, mechanical ash discharges and similar appliances	29211430	0	0	0	:	furnaces
Laptop PCs and palm-top organisers	30021200	4582293	32747581	13385580	p/st	Laptop PCs
Desktop PCs	30021300	4462230	1908385	2291445	p/st	Desktop PCs
Digital data processing machines: presented in the form of systems(1996-2500)	30021400	7057494	3065011	20221969	p/st	Desktop PCs
Other digital automatic data processing machines whether or not containing in the same housing 1 or 2 of the following units: storage units, input/output units	30021500	2926015	7097226	647512	p/st	Desktop PCs
Central storage units	30021730	1327225	3472262	592547	p/st	Central storage
Hard and floppy disk drives	30021757	18082030	1.12E+08	858232	p/st	HDD
Fixed tantalum capacitors	32101230	3.68E+09	2.01E+09	8E+09	p/st	capacitors
Television cameras (including closed circuit TV cameras) (excluding camcorders)	32201290	2353607	33670162	606664	p/st	Cameras

Appendix 2

Flat panel colour TV receivers, lcd/plasma, etc. excluding television projection equipment, apparatus with video recorder/player, video monitors, television receivers with integral tube	32302060	3157357	7175559	24609985	p/st	TVs
Electronic still cameras and video camcorders	32303335	6502389	60063259	2400000	p/st	Cameras
Video recorders or player/recorders (including laser or digital video disc players/recorders) (excluding those combined with a television, for magnetic tape)	32303370	2834678	51123937	6539524	p/st	DVD players
Artificial joints	33101735	1717467	1996521	6000000	p/st	Artificial joints
Appliances for overcoming deafness (excluding parts and accessories)	33101833	2069371	3794268	4045341	p/st	hearing aid
Parts and accessories of hearing aids (excluding for headphones, amplifiers and the like)	33101839	0	0	0	:	hearing aid
Pacemakers for stimulating heart muscles (excluding parts and accessories)	33101850	454941	714604	1144302	p/st	pacemakers
Instruments and appliances for aeronautical or space navigation (excluding compasses)	33201155	5052900	7241794	30000000	p/st	GPS
Instruments and appliances for navigation (including for marine or river navigation) (excluding for aeronautical or space navigation, compasses)	33201159	440479.6	243604.8	1564245	p/st	GPS
Parts and accessories for direction finding compasses and other navigational instruments and appliances	33208110	0	0	0	:	GPS
Unmounted spectacle lenses other than for the correction of vision	33401153	14854048	64397108	73170687	p/st	other lenses
Unmounted single focal spectacle lenses for the correction of vision, with both sides finished	33401155	8341712	85726775	72403009	p/st	vision correction lenses
Unmounted spectacle lenses for the correction of vision, with both sides finished other than single focal lenses	33401159	3235392	18422793	54123237	p/st	vision correction lenses
Unmounted spectacle lenses for the correction of vision, other than those with both sides finished	33401170	15983042	88218437	40261663	p/st	vision correction lenses
Mounted objective lenses of any material (excluding for cameras, projectors or photographic enlargers /reducers)	33402170	2384864	2252059	232529	p/st	other lenses
Mounted objective lenses, of any material, for cameras, projectors or photographic enlargers or reducers	33403100	596036	4298792	463393	p/st	camera lenses
Telephones for cellular networks or for other wireless networks	32202025	1.17E+08	2.05E+08	2.07E+08	p/st	Mobile phones
Motor vehicles with a petrol engine <= 1000 cm³ (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)	34102133	36288	517505	417162	p/st	passenger cars
Other motor vehicles (including motor caravans) with spark-ignition engine of a cylinder capacity > 1.000 cm³ but <= 1.500 cm³	34102136	405192	585992	3612995	p/st	passenger cars
Motor vehicles with a petrol engine greater than 1000cc but =< 1500cc excl. motor caravans - snowmobiles,golf cars and similar vehicles ,those for carrying =>10 people	34102135	0	0	0	:	passenger cars
Other vehicles with spark-ignition engine of cylinder capacity > 1500 mü, <= 2000 cmü	34102233	0	0	0	:	passenger cars
Other vehicles with spark-ignition engine of cylinder capacity > 2000 mü, <= 2500 cmü	34102235	0	0	0	:	passenger cars
Other vehicles with spark-ignition engine of cylinder capacity > 2500 cmü	34102237	0	0	0	:	passenger cars
Motor vehicles with a petrol engine > 1500 cm³ (including motor caravans of a capacity > 3000 cm³) (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)	34102230	0	0	0	:	passenger cars
Motor caravans with a spark-ignition internal combustion reciprocating piston engine of a cylinder capacity > 1500 cm³ but <= 3000 cm³	34102250	557	5472	8000	p/st	passenger cars
Motor vehicles with a diesel or semi-diesel engine <= 1500 cm³ (excluding vehicles for transporting >= 10 persons, snowmobiles, golf cars and similar vehicles)	34102310	100589	157206	1697146	p/st	passenger cars
Motor vehicles with a diesel or semi-diesel engine > 1500 cm³ but <= 2500 cm³ (excluding vehicles for transporting >= 10 persons, motor caravans, snowmobiles, golf cars and similar vehicles)	34102330	383870	735501	6165900	p/st	passenger cars
Motor vehicles with a diesel or semi-diesel engine > 2500 cm³ (excluding vehicles for transporting >= 10 persons, motor caravans, snowmobiles, golf cars and similar vehicles)	34102340	83611	217292	342214	p/st	passenger cars
Motor vehicles for the transport of >= 10 persons with a compression-ignition internal combustion piston engine (diesel or semi-diesel) of a cylinder capacity <= 2500 cm³	34103033	1259	831	3341	p/st	passenger cars
Public transport type vehicles for >= 10 persons, with a compression-ignition internal combustion piston engine (diesel or semi-diesel) of a cylinder capacity > 2500 cm³	34103035	18904	5124	23681	p/st	public transport vehicles
Public transport type vehicles for >= 10 persons, with a spark-ignition internal combustion piston engine of a cylinder capacity <= 2800 cm³	34103053	61	5	0	p/st	public transport vehicles
Public transport type vehicles for >= 10 persons, with a spark-ignition internal combustion piston engine of a cylinder capacity > 2800 cm³	34103055	659	26	1400	p/st	public transport vehicles
Public transport type vehicles for >= 10 persons (excluding with a compression-ignition or spark-ignition internal combustion piston engine)	34103059	31303	5822	3910	p/st	public transport vehicles
Goods vehicles with a diesel or semi-diesel engine, of a gross vehicle weight <= 5 tonnes (excluding dumpers for off-highway use)	34104110	170890	321846	1808255	p/st	freight vehicles
Goods vehicles with a diesel or semi-diesel engine, of a gross vehicle weight > 5 tonnes but <= 20 tonnes (including vans) (excluding dumpers for off-highway use, tractors)	34104130	35727	973	210207	p/st	freight vehicles

Goods vehicles with compression-ignition internal combustion piston engine (diesel or semi-diesel), of a gross vehicle weight > 20 tonnes (excluding dumpers designed for off-highway use)	34104140	27817	2123	151490	p/st	freight vehicles
Goods vehicles with a spark-ignition internal combustion piston engine, of a gross vehicle weight <= 5 tonnes (excluding dumpers designed for off-highway use)	34104230	23677	38287	62986	p/st	freight vehicles
Goods vehicles with a spark-ignition internal combustion piston engine, of a gross vehicle weight > 5 tonnes (excluding dumpers designed for off-highway use)	34104250	100	57	0	p/st	freight vehicles
Goods vehicles (excluding vehicles with a compression-ignition or spark-ignition internal combustion piston engine, dumpers designed for off-highway use)	34104290	4389	13036	25092	p/st	freight vehicles
Tools for tapping, with working parts of sintered met. carb.	28624011	0	0	0	:	carbide tools
Tools for threading, wiht working part of sintered met. car.	28624015	0	0	0	:	carbide tools
Tools for boring, for work metal, with work park of sintered metal carbide	28624041	0	0	0	:	carbide tools
Tools for broaching, for work metal, with work part, of sintered met. carbide	28624047	0	0	0	:	carbide tools
Tools for milling, for working metal, with working part of sintered metal carbide	28624053	0	0	0	:	carbide tools
Hobs for milling, for working metal, with working part of sintered metal carbide	28624055	0	0	0	:	carbide tools
Rock drilling or earth boring tools with working part of cermets	28625013	3587700	1524200	40266914	kg	carbide tools
Indexable inserts for tools, unmounted, of sintered metal carbides and cermets	28625067	0	0	0	kg	carbide tools
Plates for tools, unmounted, of metal carbides or cermet, tool-tip	28625070	0	0	0	:	carbide tools
Unmounted sintered metal carbides or cermet plates, sticks, tips and the like for tools (excl. indexable inserts)	28625090	2166400	1807800	7005005	kg	carbide tools
Mounted piezo-electric crystals (including quartz, oscillator and resonators)	32105270	1.4E+08	2.37E+08	1.24E+08	p/st	wave filters
Semiconductor diodes	32105120	0	0	0	:	semiconductors
Semiconductor diodes	32105125	9.86E+09	1.32E+10	9.72E+09	p/st	semiconductors
Semiconductor small signal transistors with a dissipation rate < 1 W	32105155	3.31E+10	2.38E+10	1.4E+10	p/st	semiconductors
Semiconductor power transistors with a dissipation rate >= 1 W	32105157	4.04E+09	4.98E+09	7.07E+09	p/st	semiconductors
Semiconductor thyristors, diacs and triacs	32105170	8.25E+08	5.08E+08	1.8E+09	p/st	semiconductors
Semiconductor devices (excluding photosensitive semiconductor devices, photovoltaic cells, thyristors, diacs and triacs, transistors, diodes, and light-emitting diodes)	32105250	3.87E+09	8.95E+08	3.59E+09	p/st	semiconductors
Milling tools with working part of sintered metal carbide, for working metal excluding unmounted sintered metal carbide plates, sticks, tips and the like for tools	28624050	252700	281600	19292183	kg	carbide tools
Turbojets or turbofans of a dry thrust <= 25 kN	35301210	6099	36245	0	p/st	Aerospace
Turbo-jets of a thrust <= 25 kN, for aircraft for civil and parapublic use	35301213	0	0	0	:	Aerospace
Turbo-jets of a thrust <= 25 kN, for aircraft for military use	35301215	0	0	0	:	Aerospace
Turbojets or turbofans of a dry thrust > 25 kN	35301230	2032	1857	2000	p/st	Aerospace
Turbo-jets of a thrust > 25 kN, for aircraft for civil and parapublic use	35301233	0	0	0	:	Aerospace
Turbo-jets of a thrust > 25 kN, for aircraft for military use	35301235	0	0	0	:	Aerospace
Turboprops of a power <= 1100 kW	35301250	2762	2075	1378	p/st	Aerospace
Turboprops of a power > 1100 kW	35301270	1344	4581	200	p/st	Aerospace
Parts of turbo-jets or turbo-propellers	35301600	0	0	0	:	Aerospace

Table A2.1. *Data extracts and linkage table between Europroms[1] and product categories used.*

A2.2. Elaboration on the data availability in Eurostat Europroms

The study only presented a detailed substance flow analysis for the year 2007. The reason behind this is the availability of data at the highest level of detail in the Europroms database. Out of the 88 Europroms commodities relevant to tantalum, data on 55 commodities was actually available in the year 2007. The database contained significantly less information on more recent years as can be seen in Figure A2.1, so it was decided to prefer completeness over recency and do the analysis for the year 2007.

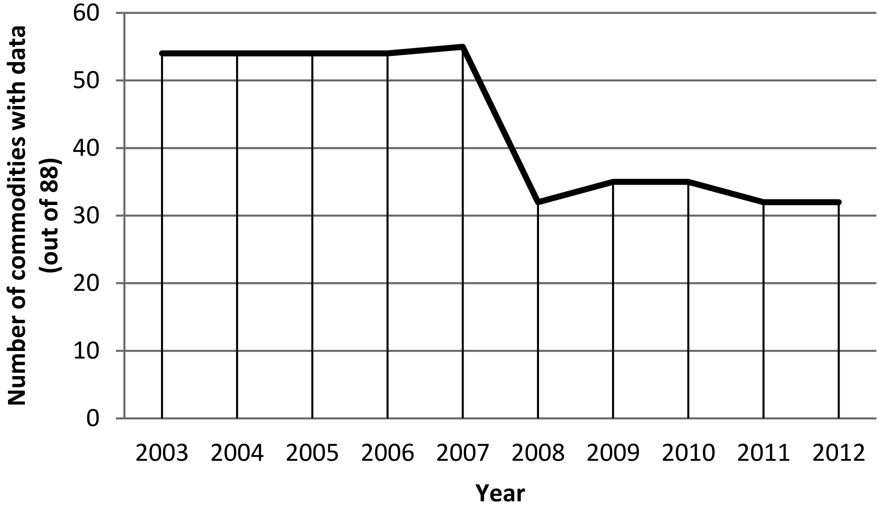

Figure A2.1. *Coverage of data on tantalum relevant products in the Europroms*[1] *statistics.*

A2.3. Elaboration on market shares & product weights

Table A2.2. *Weight conversion used, in case no weight conversion was available.*

Production commodity	Weight (kg/unit)	Source	Comments
Furnaces	3000	[2] & [3]	Supplier specification of large walk-in type ovens.
Capacitors (fixed Ta)	0.00014	[4] & [5]	Average of tantalum capacitor weight found in two sources
Artificial joints	0.175	[6]	Rough estimate ('one or two pounds')
GPS	0.0195	[7]	Average of 10 GPS products, based on commercial specs
Surface Acoustic Wave filters	3.7E-05	[8]	Company data sheet
Semiconductors	0.00031	[4]	Average of "diode, glass-, SMD type, for surface mounting, at plant" (32 mg) & "transistor, SMD type, for surface mounting, at plant" (0.593 g)

Table A2.3. *List of representative fractions applied to link product weights and tantalum concentrations.*

Prodcom Product name	Prodcom code	Applied	Assumption
Central storage units	30021730	0.112	assuming 5 disks in a single central storage unit of the given weight of 5,65 kg
Hard and floppy disk drives	30021757	0.268	Given the estimates of Coughlin (2006)[9], this represents the market-share of hard disks using perpendicular recording by 2007.
Instruments and appliances for aeronautical or space navigation (excl. compasses)	33201155	0.00157	Due to the high mass of products in this category, the factor adjusts the tantalum concentration assuming the functionality, and thus the tantalum content, of a single GPS device.
Semiconductor diodes, small transistors, thyristors, diacs, triacs & other devices	32105120, 32105125, 32105155, 32105157, 32105170, 32105250	0.01	1% of semiconductors contains tantalum, authors assumption

A2.4 Deriving tantalum concentrations

Table 2.3 in Chapter 2 contains indications of tantalum concentrations in products in kilograms tantalum per kilogram product. The indicated sources didn't always contain information on the tantalum content directly, but sometimes provided clues on the material composition, which needed further translation and interpretation. Below we provide the details to this translation for 6 products and components.

1) Glass lenses

Based on the average compositions of the 4 types of glass found in the patent of Kodak[10], we found that the described glass lenses contained 11.25 wt% tantalum oxide. Given the chemical composition of tantalum oxide in the form of Ta_2O_5, we derived that of the tantalum oxide, tantalum comprises only 82 wt%. This leads to 9.2 wt% tantalum, but since lenses are not all tantalum containing, we further assumed a 50% market share for tantalum-containing lenses, leading to an applied concentration of 0.046 kg of tantalum per kg of glass lenses.

2) Wave Filters

We found two sources containing clues to the tantalum composition of specific wave filters [11,12] and derived volumetric material compositions based on the cross-section drawing of the wave filters as indicated in Table A2.4 and A2.5 below. Then we applied the indicated densities to derive the weight percentage as also indicated.

Table A2.4. *Wavefilter material content based on Strijbos et al.*[12]*.*

	vol%	density (g/cm3)	wt%
Cu	12.5	8.96	16.9
Pt	12.5	21.45	40.4
AlN	25	3.26	12.3
SiO2	37.5	2.65	15.0
Ta2O5	12.5	8.25	15.5

Table A2.5. *Wavefilter material content based on Abbott*[11]*.*

	vol%	density (g/cm3)	wt%
Cu	2	8.96	3.7
SiO2	15	2.65	8.2
LiTaO3	45	7.46	69.7
Si	38	2.329	18.4

The subsequent application of tantalum weight of 82% for Tantalum Oxide and 77% for Lithium Tantalate lead to 12.7 wt% tantalum in one of the filters and 53.4 wt% in the other, thus leading to an average tantalum content in tantalum containing wavefilters of 33.05%. Mind that the market share was still applied. Mind that the market share given in Table A2.3 still has to be applied too this.

3) Computer Harddisk Drives (HDDs)

We assumed that tantalum was only contained in the harddisk platter (the disk actually storing the data), and that a harddisk platter accounts for 10,5% of the total harddisk weight, based on Yan et al.[13]. Furthermore, we used the average tantalum composition of the platters based on two studies [14,15]. In the study by Nunney et al.[14] we used the cross sectional drawing to derive volumetric material compositions based on the various layers that a harddisk platter contains. The elemental composition for each layer was given as a result of the x-ray analysis. Table A2.6 shows our interpretation of the study. Assuming that each layer has a similar density gives a tantalum composition of 45 wt% for the platter or 4.7 wt% considering the whole harddisk (including head motor, housing etc.).

Table A2.6. *Composition (wt%) of a harddisk platter according to Nunney et al. (2011)*[14]*.*

Layer name	**Layer**	Co	Pt	Ta	Cr	Ru	Ti	Ni	Al	Zr	C	O
Polymer	**4%**										90%	10%
Magnetic	**8%**	46%	13%		12%	30%						
nonmagnetic	**4%**	65%	18%		17%							
Magnetic	**8%**	46%	13%		12%	30%						
nonmagnetic	**4%**	65%	18%		17%							
seed layer	**10%**				90%		10%					
Tantalum	**3%**			90%	10%							
Buffer layer	**29%**			50%				50%				
Glass	**30%**								8%	2%		65%

A second source for the platter composition that we used was the Hitachi patent[15], which describes a layered structure that we interpreted according to Table A2.7 below. Similar to the case of wave filters and lenses, the weight percentage of the two layers containing tantalum was multiplied with the weight of tantalum in those layers based on their atomic description and then added, thus leading to a total tantalum content of 7.9 wt% in the data platter or 0.83 wt% in the total harddisk drive. This was combined with the numbers from Nunney et al. and averaged before applied in the main document.

Table A2.7. *Composition of a harddisk platter according to Hitachi (2007)*[15].

layer	Material	layer	density	weight %
coating	C/O	26%	3.9	13%
magnetic	(Co86Cr14)60Pt40	17%	15.175	34%
	Ta2O5	4%	8.25	4%
intermediate	Ru	3%	12.45	5%
	NiTa	4%	12.75	6%
	NiW	4%	14.15	7%
soft underlayer	CoNi	21%	8.9	24%
Substrate	glass	21%	2.6	7%

4) Artificial joints

The tantalum concentration in artificial joints is based on the materials mentioned in a study by Zardiackas et al.[16]. They mention 5 different types of alloying metals used in surgical applications. We also added a metal that we found repeatedly during a web-search, being a non-tantalum containing titanium alloy (Ti6Al4V), which together made 6 materials. Without information on the market shares of these alloys, we assume that all alloys were used in equal amounts. Thus, we can use the two materials that do contain tantalum, being Tantalum foam (Trabecular Metal) and a Ti-35Nb-7Zr-5Ta alloy (TiOsteum) alloy to derive the tantalum composition. We assume tantalum foam to be made a 100% out of tantalum, and we used a 5% tantalum content for the second alloy, thus leading to an estimated tantalum content of 17.5% by weight for artificial joints.

5) Semiconductors

The material composition was based on a study by Chaneliere et al.[17]. We used a visual representation of the components structure to derive material compositions by volume. Combining this with information on density lead to the composition by weight as elaborated in Table A2.8. The subsequent multiplication of the tantalum oxide weight with the 82 wt% tantalum (mentioned earlier) gives a total weight percentage of tantalum in semiconductors of 28,6 wt%, or 0,0286 kg tantalum per kg semiconductor.

Table A2.8. *Composition of a semiconductor according to Chaneliere et al.*[17]

	vol%	density (g/cm3)	wt%
Al	8	2.7	3.6
Ta2O5	25	8.25	34.9
HfO2	15	9.68	25.6
ZnS	23	4.09	16.2
ITO	6	7.16	7.6
AlO3	8	3.95	5.2
glass	15	2.6	6.9

6) Aerospace

As can be seen in Table A2.1, the only aerospace applications considered relevant to tantalum are aircraft engines. In fact, we assume the tantalum is only contained in the high temperature alloys of the turbine blades inside the aircraft engine. So, to find out how much tantalum is contained in aircraft engines, we started with a list of nickel-based superalloys for gas turbine blades as given by Muktinutalapati[18], out of the 17 materials listed, 6 contained tantalum. We used this indication to assume that 35% of high temperature alloys used actually contain tantalum. Of those materials containing tantalum we derived a tantalum weight as shown in Table A2.9 below, giving us an average tantalum content of 2.94% by weight.

Table A2.9. *Tantalum content in tantalum containing high temperature alloys based on Muktinutalapati*[18].

Alloy type	Ta weight %
MAR-M246	1.5
IN 792	3.9
M 22	3
MAR-M246+Hf	1.5
IN 738	1.75
TMD-103	6

Because only the turbine blades were assumed to contain tantalum, we used a NASA engine weight model[19] to derive that the weight of the turbine is 18% of the complete engine based on the numbers given in Table A2.10 below.

Table A2.10. *Composition of an aircraft engine derived by NASA*[19].

	volume	material	density (kg/ m3)	weight
inlet	10%	Aluminium	2723	4%
fan	29%	Titanium	4693	23%
compressor	17%	Titanium	4693	13%
burner	9%	Nickel alloy	8249	12%
turbine	13%	Nickel alloy	8249	18%
Nozzle	22%	Nickel Alloy	8252	30%

Finally, we assumed that 50% of the turbine weight is caused by the turbine blades, thus leading to an overall tantalum composition of 0.092% of the aircraft engine weight (35% of high temperature alloys containing tantalum, those that do contain 2.94 wt% tantalum in their turbine blades, which account for 50% of the turbine weight, which in turn accounts for 18% of the engine weight).

A2.5 Elaboration of Balancing Flow Allocations

In the Sankey diagram, Figure 2.2 in Chapter 2, we represent the flows of tantalum throughout various product stages, while respecting the conceptual representation as given in Figure A2.2 below, where A1 & A2 are the two steps requiring allocation of tantalum flows.

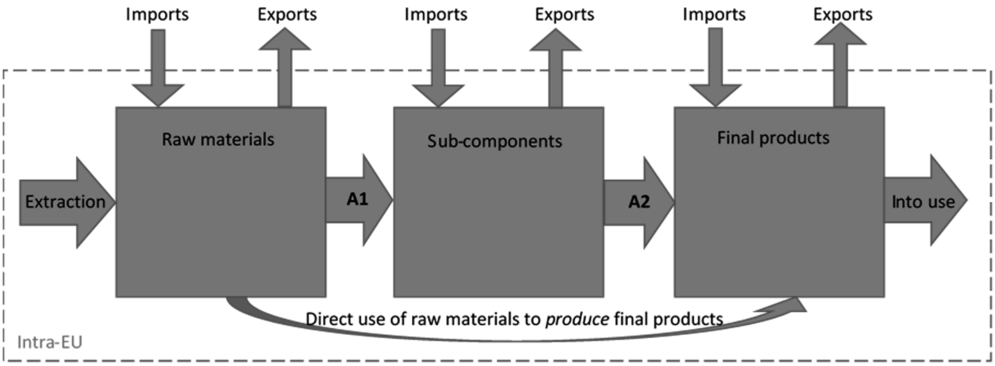

Figure A2.2. *Schematic overview of the tantalum flows considered in this study. A1 & A2 represent the flows that need further allocation, as described in the text.*

The allocation of tantalum flows between raw materials, subcomponents and final products is derived using an optimization as elaborated in the main document, except for the allocation of harddisks, which is based on literature. The use of this optimization in combination with exogenous allocation does not however guarantee a matching in demand and supply, nor does it guarantee a balanced system. To balance the system, the Sankey diagram contains balancing flows for both surpluses and shortages of tantalum supply. The actual mismatch in demand and supply for individual products is given in Table A2.11 and A2.12 below.

Table A2.11. Does supply of tantalum raw material fulfill the demand for production of sub-components in Europe?

From (Raw Material apparent consumption)	To (Sub-component production)	Fulfills production? (supply/ demand)
Tantalum carbides	Carbide Tools (F)	100% by assumption
Tantalum metal	Artificial joints (F)	100%
	HDDs	100%
Tantalum oxide	Vision correction lenses (F)	210%
	Camera lenses	245%
	Other lenses (F)	143%
	Wave filters	114%
Tantalum powder	Capacitors	100%
Tantalum ingots	Semi-conductors	100%
	High-temperature alloys	100%

Table A2.12. Does supply of tantalum sub-components fulfill the demand for production of final products in Europe?

	Fulfills production?
Mobile phones	56%
Cameras	99% (of Ta in camera bodies)
Desktop PCs	98%
Laptop PCs	432%
External HDD	*balancing factor*
Central storage	241%
DVD Players	100%
GPS devices	99%
TVs	99%
Hearing aid	94%
Pacemaker	98%
Vehicles	85%
Furnaces	100%
Aerospace	100%

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Appendix 3

Based on the Supplementary Information provided with:
Deetman et al. (2018) - Scenarios for demand growth of metals in electricity generation technologies, cars and appliances – Environmental Science & Technology, Vol. 52, Issue 8, p. 4950–4959 https://doi.org/10.1021/acs.est.7b05549

A3.1 Assumptions on product compositions

Below we discuss the approach and assumptions used to derive the complete overview of product compositions for cars, appliances and electricity generation technologies. Together with the sources provided in Chapter 3, these provide the basis for Table A3.1.

A3.1.1 Cars

Table A3.1 presents the metal composition of cars based on the minimum and the maximum composition as found in following studies (Please note that if the study specifies multiple data points or sub-technologies, an average of the data points within each study is taken):

Internal Combustion Engines (ICE): Cullbrand & Magnusson[1], Habib[2] only for Nd, Alonso et al.[3], Widmer et al.[4], Hawkins et al.[5] only for Cu.

Hybrid Electric Vehicles (HEV): Cullbrand & Magnusson[1], Habib[2] only for Nd, Moss et al.[6], Elwert et al.[7], US Dept. Of Energy[8]

Plugin Hybrid Electric Vehicles (PHEV): Moss et al.[6], Elwert et al.[7], US Dept. of Energy[8]

Battery Electric Vehicles (BEV): Hawkins et al.[5] only for Cu, Moss et al.[6], Elwert et al.[7], US Dept. of Energy[8]

Fuel Cell Vehicles (FCV): Moss et al.[6] or similar to conventional ICE vehicle

A3.1.2 Consumer electronics

The following assumptions were applied to derive the metal content estimates for consumer electronics (appliances):

Air coolers & Fans: If no information was available, we assumed 50% or 15% of the metal composition of an air-conditioner, respectively (authors own estimate).

Tumbler dryers & Dishwashers: If no information was available, we assumed the same concentration as in washing machine, but adjusted for the weight ratio based on tumbler dryer weight: 43.2kg (dryer) OR 45.5kg (dish washer) over 71.4 kgs (washing machine).

Televisions (TVs): We assumed an average PCB weight in Flat Screen TVs based on Oguchi et al.[9], but using the tantalum content from PCBs of a PC according to Ewasteguide.info[10]

Personal Computers (PCs): average of Desktop & Laptop PCs in Oguchi OR average of available other studies.

Other small appliances: average of all other appliances in Oguchi OR average of available other studies.

A3.1.3 Electricity generation

The following assumptions were applied to derive the metal content estimates for energy generation technologies:

Off-whore wind: The minimum estimate of neodymium content in offshore windmills was based on the permanent magnet weight according to Alonso et al.[3] and the permanent magnet composition according to Long et al.[11]

Other renewables: The metal content of the IMAGE category “other renewables” was determined as the average of renewables

Oil-based technologies: The metal content of oil-based electricity generation was derived as the average of coal & gas based generation technologies.

Combined cycle power plants: Unless specific sources were available, we assumed the material use in conventional technology applies.

Carbon Capture and Sequestration (CCS): If no specific studies were available, the additional material use as specified by Moss et al.[6] is added to the metal content of conventional plants. The study by Moss et al. does not specify additional tantalum use for CCS, so in that case the conventional reference was taken.

Combined Heat and Power (CHP): Unless specific studies are available, we assumed that CHP uses the same amounts of metals per MW as the conventional plants. Only for the case of copper, we assumed an additional metal content of 1/10th of a CHP plant according to Moss et al.[6].

	Concentration data (in grams)										Weibull parameters			Categorization
	Cu		Co		Nd		Ta		Li		scale	shape	Source / comments	
Car types (g/product)	low	high	low	high	Low	high	low	high	low	high				
Internal Combustion Engine (ICE)	22,300[5]	27,333[1]	27[4]	35[1]	2[4]	415[2]	1.1[4]	8[1]	0[1]	17[4]	1.89	10.3	[12]	All ICE types in IMAGE
Hybrid Electric Vehicles (HEV)	42,188[6]	62,500[1]	118[6]	4,400[7]	118[6]	995[2]	3.4[7]*	11[1]	120[6]	6,500[1]	1.89	10.3	[12]	All HEV types in IMAGE
Plugin Hybrid Electric Vehicles (PHEV)	41,797[7]	67,183[6]	995[6]	3,630[7]	473[7]	1,460[7]	3.4[7]*	10.3[7]*	988[6]	3,250[8]	1.89	10.3	[12]	All PHEV types in IMAGE
Battery Electric Vehicles (BEV)	53,373[7]	152,443[6]	4,400[8]	5,720[7]	567[7]	2,250[6]	3.4[7]*	10.3[7]*	3,598[7]	7,550[8]	1.89	10.3	[12]	All BEV types in IMAGE
Fuel Cell Vehicles (FCV)	22,300[5]	97,605[6]	27[4]	153[6]	2[4]	2,920[6]	1.1[4]	8[1]	0[1]	158[6]	1.89	10.3	[12]	All FCV types in IMAGE
Appliance types (g/product)														
Fan	129[13]	200[14]	0	0.3	3.5	22.5					1.3	9.4	2-01 in [15]	Cooling appliances
Air-cooler	3150	3300	0	1	11.5	75					2	13.5	1-06 in [15]	Cooling appliances
Air-conditioning	6301[9]	6600[14]	0	2[16]	23[16]	150[2]					2.8	12.3	[15]	Cooling appliances
Refridgerator	800[14]	1331[9]			1.5[17]	225[2]					2.2	16.5	[15]	Food appliances
Microwave	200[14]	1211[9]			33[2]						0.8	14.7	[15]	Food appliances
Washing Machine	1100[14]	2298[9]	0	3.2[16]	7.2[17]	312[2]					2.2	13.9	[15]	Washing appliances
Tumbler dryer	666	1391	0	1.9	4.3	189					2.6	16.5	[15]	Washing appliances
Dish washer	1250[18]	1465	0	2.0	4.6	199					1.6	13.1	[15]	Washing appliances
Television	500[14]	1260[19]					0.05[9]	0.19[9,10]*			2.1	12	4-08 in [15]	TV & video
VCR/DVD player	175[20]	196[9]			0.49[2]		0.01[9]	0.04[9]			1.7	10.5	4-04 in [15]	TV & video
PC & Laptop computers	245[9]	1070[14,19]	18.2[21]	70.4[9]	2.4[2]	2.8[22–24]	2.1[25,26]	2.6[9]	5.0[21]	8.4[9]	1.5	5.2	3-03 in [15]	Computers
Other small appliances	30[19,20]	129[9]	4.6[21]	5.5[9]	0.12[22]	0.54[2]	0.15[26]	0.97[9]	0.7[9]	1.3[21]	1.5	4	4-01 in [15]	Other small applaince s
Power generation ** (g/kW)														
Solar PV	2,194[27]	10,490[28]												Solar
Concentrated Solar Power	2,300[27]	3,992[29]												Solar
Wind (onshore)	1,143[30]	4,318[29]			0	41[27]								Wind
Wind (offshore)	1,143[30]	10,000[31]			119[3,11]*	198[2]								Wind
Hydro	67[6]	3,331[32]												Hydro & other
Other Renewable	1,369	6,426			24	48	64[6]							Hydro & other
Nuclear	60[27]	1,470[33]	0	0.2[34]										Nuclear
Conv. Coal	792[35]	1,500[33]	30[36]	201[6]			0.5[6]	17[36]*						Fossil
Conv. Oil /Biomass	399	1,125	16	119			0.3	9.2						Fossil / Biomass
Conv. Natural Gas	6[37]	750[33]	2[6]	36[38]			0.07[2]	1.45[38]						Fossil
IGCC	792	1,500	30	201			0.5	17						Fossil
OGCC / Biomass CC	399	1,125	16	119			0.3	9.2						Fossil / Biomass
NG CC	1,003[39]	1,100[33]	2	36			0.07	1.45						Fossil
Coal + CCS	1,068[35]	2,192	37	209			0.5	17						Fossil+CCS
Oil/Biomass + CCS	1,091	2,192	23	126			0.3	9.2						Fossil+CCS / Biomass+CCS
Natural Gas + CCS	698	1,442	9	44			0.07	1.45						Fossil+CCS
CHP Coal	5,237	5,945	30	201			0.5	17						Fossil
CHP Oil	4,844	5,570	16	119			0.3	9.2						Fossil
CHP Natural Gas	4,451	5,195	2	36			0.07	1.45						Fossil
CHP Biomass	305[33]	5,570	16	119			0.3	9.2						Biomass
CHP Coal + CCS	5,929	6,637	37	209			0.5	17						Fossil+CCS
CHP Oil + CCS	5,536	6,262	23	126			0.3	9.2						Fossil+CCS
CHP Natural Gas + CCS	5,143	5,887	9	44			0.07	1.45						Fossil+CCS
CHP Biomass + CCS	997	6,262	23	126			0.3	9.2						Biomass+CCS

Table A3.1. *Assumptions on metal content and lifetimes for three product categories (in grams per car, grams per car appliance or grams per kW of peak electricity generation capacity). The categorization applies to the figures in the main text as well as the SI. ** PV = Photovoltaic cells, IGCC = Integrated gasification and combined cycle, OGCC = Oil Gassification & Combined Cycle, NGCC = Natural Gas Combined Cycle, CCS = Carbon Capture and Sequestration, CHP = Combined Heat and Power. Asterisks (*) indicate the use of an own estimation based on the indicated sources.*

A3.1.4 Additional assumptions for cars

Table A3.2 below provides the data used to translate passenger vehicle kilometers (IMAGE output) into the number of cars on the road, by means of kilometrage (cf. mileage) of an average car per year.

	Canada	**US**	**Europe**	**Australia**	**Japan**	**China**
Also applied to IMAGE region >	Mexico, Ukraine, Middle East, Afghanistan a.o., Russia		Central Amerika, Brazil, South America, South Afrika, Turkey		Indonesia, South-East Asia,	North-, West- and East Afrika, rest of south Afrika, rest of South Asia, India, Korea
Source & comments	[40]	[41]	[41] as an average of Finland, Belgium, Norway, the UK and Germany	[41]	[41]	[41]
1975	12638	14982	14392	15480	8851	27200
1980	11839	14183	14475	15167	8386	27200
1985	12816	15159	14436	15500	8610	27200
1990	14196	16539	15614	14667	9863	27200
1995	15292	17636	15700	14300	8978	27200
2000	16950	19294	15400	14300	8812	26400
2005	16000	19915	14989	14100	8406	26000
2008	15200	19783	15157	13900	8276	26000

Table A3.2. *The annual average passenger car kilometrage per region. The kilometrage (how many kilometers does an average car drive per year) applied is assumed to be constant at 2008 levels after this year.*

A3.1.5 Sensitivity analysis

Table A3.1 presents the high and the low assumptions on the content of five metals in almost all listed products. Only three entries remained for which only a single estimate of metal content could be made (highlighted in grey). To assess the importance of these three products in the overall outcomes, we tested for the effect of introducing a probable artificial range, based on the average range for the available products within each metal column. We did so only for the SSP2 baseline. So for the example of tantalum content in 'other renewables' we started with the estimate for geothermal energy by Moss et al.[6] and assumed it to be a medium estimate (64 g/kW, see Table A3.1). Subsequently, we calculated the average deviation from the medium value based on all other products with a tantalum content (on average 81% higher or lower). Applying this deviation to both sides of the assumed medium estimate by Moss et al. creates an artificial range for tantalum in the 'other renewables' product category (of 11.8 g/kW to 116 g/kW). Running the model with these numbers gives an average total annual tantalum demand between 2045 & 2050 that is either 4% higher than the high baseline or 14% lower than the low baseline. When applying the same steps to the two missing estimates for neodymium products, we find a change in average annual neodymium demand that is either 1% higher than the high estimate or 9% lower than the low baseline, in the five last years of the scenario period. This indicates that excluding a range of estimates for the metal content of even a single product may in fact have a considerable effect on the outcomes in terms of total annual demand.

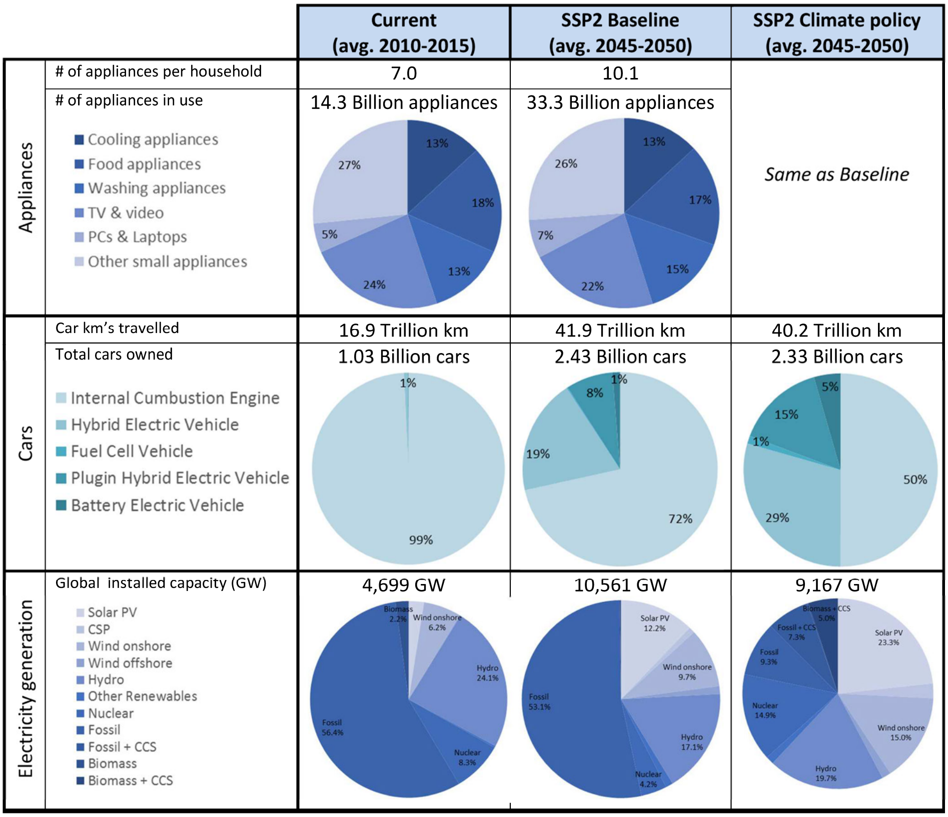

Figure A3.1. *Overview of scenario assumptions on in-use stocks of cars, appliances & electricity generation capacity.*

A3.2. Scenario assumptions and results

A3.2.1 Scenario assumptions

Figure A3.1 shows the assumptions on stocks-in-use of the three categories of applications. Though the numbers for electricity generation capacity are available independent of the dynamic stock model, they are also provided for completeness. Because numbers on annual demand can fluctuate a lot, we decided to present all numbers as averages of recent years (2010 to 2015) and compare these to averages of the last available model years (being 2045 to 2050).

A3.2.3 Summary of metal demand under various scenarios

Below, the metal demand numbers are presented in Table A3.4. Annual metal demand (in kilotons per year) is provided for appliances, cars and energy technologies, as an average of the most recent years (2010-2015) and projections for the latest model years (2045-2050) given the SSP2 baseline and its corresponding 2-degree climate policy scenario. Numbers are rounded to 2 significant digits. Using these numbers the effect of the uncertainty in data on metal content on the scenario outcomes is depicted more visually in Figure A3.2.

Table A3.4. *Annual metal demand for appliances, cars and energy technologies.*

			Current (avg. 2010-2015)			**Baseline (avg. 2045-2050)**			**Climate policy (avg. 2045-2050)**		
			Low	**med**	**high**	**low**	**med**	**high**	**low**	**med**	**high**
Annual Metal demand (kt /yr) for selected applications	Cu	Appliances	930	1400	1800	2000	2800	3600	2000	2800	3600
		Cars	2800	3100	3500	7800	9400	11000	8900	12000	15000
		Energy tech	230	490	750	430	960	1500	520	1400	2200
		Total	**3900**	**5000**	**6000**	**10000**	**13000**	**16000**	**11000**	**16000**	**21000**
	Nd	Appliances	7.2	57	110	15	110	200	15	110	200
		Cars	2.3	27	53	33	110	180	62	160	260
		Energy tech	0.15	0.90	1.7	0.93	2.3	3.6	1.2	4.0	6.8
		Total	**10**	**85**	**160**	**49**	**220**	**380**	**78**	**270**	**470**
	Ta	Appliances	0.49	0.96	1.4	1.3	2.3	3.4	1.3	2.3	3.4
		Cars	0.14	0.56	1.0	0.48	1.5	2.4	0.61	1.5	2.5
		Energy tech	0.08	0.64	1.2	0.44	1.4	2.4	0.36	0.6	0.7
		Total	**0.71**	**2.2**	**3.6**	**2.2**	**5.2**	**8.2**	**2.3**	**4.4**	**6.6**
	Co	Appliances	7.5	12	17	18	30	45	18	31	45
		Cars	4.3	15	26	62	200	340	160	390	622
		Energy tech	2.0	8.5	15	3.4	14	25	0.91	3.3	5.6
		Total	**14**	**36**	**59**	**83**	**250**	**410**	**177.5**	**420**	**670**
	Li	Appliances	1.4	2.0	2.6	3.6	5.0	6.4	3.6	5.0	6.4
		Cars	1.3	17	33	52	249	450	140	470	800
		Energy tech	-	-	-	-	-	-	-	-	-
		Total	**2.7**	**19**	**36**	**55**	**250**	**450**	**140**	**480**	**810**

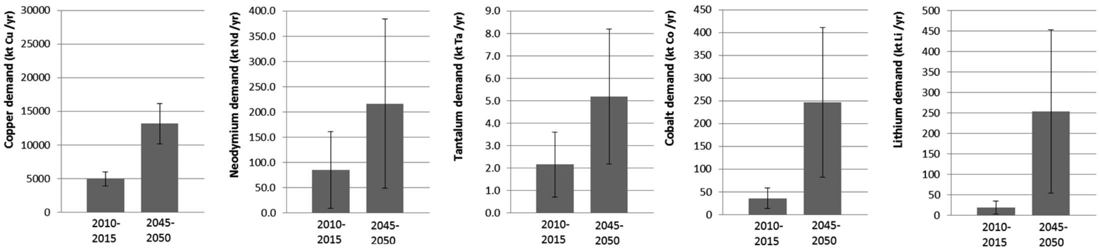

Figure A3.2. *Assessment of the effect of uncertainty for metal content data on scenario outcomes. Based on the SSP2 Baseline, presented in Table S4, the bar charts indicate the total demand of the three considered applications for each metal (in kt/yr), while the error bars show the outcomes using the low and the high metal content estimates.*

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Appendix 4

Based on the supplementary information provided with:
Marinova et al. (2020) - *Global construction materials database and stock analysis of residential buildings between 1970-2050* - Journal of Cleaner Production, Vol. 247, p. 119146 https://doi.org/10.1016/j.jclepro.2019.119146

A[4]

A4.1 Corrigendum

The following corrigendum was reported to the journal of Cleaner Production, under ref. 119146: The authors regret to report that despite extensive efforts to review the work presented in this study, an error was made in the calculations. This has led to inaccurate reporting of the results for aluminium and glass in residential buildings detailed in Section 4.3.2.2. Results regarding floor space, other materials and service-sector buildings remain unchanged, and textual conclusions drawn from this work remain accurate. However, we feel the responsibility to provide the corrected figures and outcomes as detailed below. A corrected version of the model code can be found through the following link: https://github.com/SPDeetman/BUMA. Because the text in the manuscript remains unchanged, we only provide the corrected figures as shown below. The authors would like to apologise for any inconvenience caused.

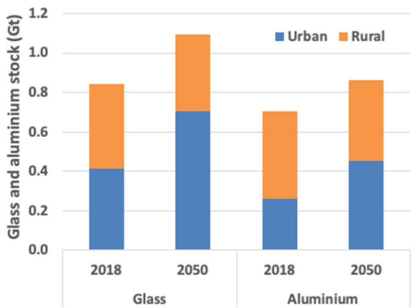
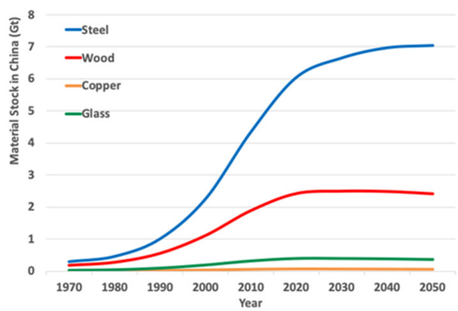
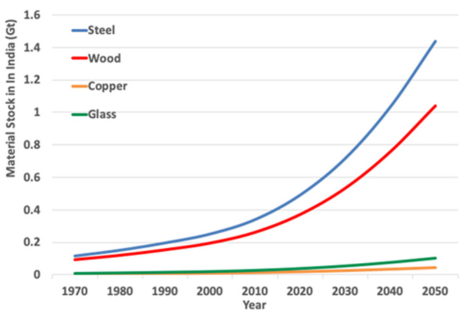


Figure A4.1 *a) Updates to Figure 4.3, for glass and aluminium (left), b) Updates to Figure 4.5, Four materials in residential housing stock in China (bottom left) & India (bottom right).*





A4.2 Usable floor area

In Table A4.1 we present detailed information on the average per capita floor space disaggregated in four dwelling types: detached house, row house, apartment buildings, high-rise buildings. The data is based on all available studies reviewed and presented in Chapter 4.

Due to lack of data we cannot provide accurate estimations of the average per capita square meters for certain regions and building types. In these cases, we apply global average values. The asterisk identifies the data directly available from the literature. The rest of the table is filled with the global average on all other available studies.

It is important to note that we use the global averages displayed in Table A4.1. solely to allocate the IMAGE data to the four building types. This approach is not ideal since our data is based mostly on developed regions and therefore it could be considered biased when applied to less developed countries. However, given the experimental nature of our model we believe that for the time being the numbers which we obtained are suitable to distribute the IMAGE data across the different building types. It is important to mention that future development of the data is necessary in order to provide as accurate as possible predictions for the development of the building stock.

Interestingly, the static data on per capita floorspace in the four building types suggests that urban housing, on average, provides a larger per capita floorspace than rural housing. This is in contrast to the IMAGE data, which assumes rural houses to be larger (even at a per capita basis, see Table A4.1). This difference is influenced by two data points from one individual study conducted by Bhochhibhoya et al. (2017)[1] included in the database. The paper focuses on the greenhouse gas emissions associated with three buildings located at rural area in Nepal. The data points display significantly lower value for per capita square meter (7.67 m^2/cap) in comparison to per capita floorspace values for rural buildings located in Turkey (22 m^2/cap) [2], India (32.63 m^2/cap) [3] and China (63.51 m^2/cap) [4]. Despite the fact that two data points are shifting the results, we decided to not exclude the study from the per capita floorspace calculations since Nepal is one of the few representatives for rural areas in Least Developed Countries (LDCs) [5]. In addition, we chose to not adjust our model for this discrepancy. However, we believe this issue should be explored and adjusted in future research, as elaborated in the discussion.

Table A4.1. *Average per capita floor space (m2/cap) (L). The asterisk (*) identifies the regional data directly available from the literature. The rest of the table is filled with the global average on all other available studies.*

Region	Area	Detached houses	Row houses	Apartments	High-rise buildings
1	Urban	42.88*	40.65	28.61	39.00*
1	Rural	33.00	32.61	22.00	31.40
2	Urban	50.98*	40.65	25.81*	20.90*
2	Rural	33.00	32.61	22.00	31.40
3	Urban	34.36	40.65	28.61	31.40
3	Rural	33.00	32.61	22.00	31.40
4	Urban	34.36	40.65	28.61	31.40
4	Rural	33.00	32.61	22.00	31.40
5	Urban	41.55*	40.65	28.61	13.93*
5	Rural	33.00	32.61	22.00	31.40
6	Urban	22.70*	35.00*	29.00*	31.40
6	Rural	33.00	32.61	22.00	31.40
7	Urban	34.36	40.65	28.61	31.40
7	Rural	33.00	32.61	22.00	31.40
8	Urban	17.12*	40.65	27.00*	31.40
8	Rural	33.00	32.61	22.00	31.40
9	Urban	34.36	40.65	28.61	31.40
9	Rural	33.00	32.61	22.00	31.40
10	Urban	13.67	40.65	13.67*	31.40
10	Rural	33.00	32.61	22.00	31.40
11	Urban	31.71*	28.13*	35.69*	34.50*
11	Rural	56.52*	32.61*	22.00	31.40
12	Urban	23.90*	40.65	37.00*	35.27*
12	Rural	33.00	32.61	22.00	31.40
13	Urban	34.36	40.65	28.61	65.00*
13	Rural	33.00	32.61	22.00*	31.40
14	Urban	34.36	40.65	28.61	31.40
14	Rural	33.00	32.61	22.00	31.40
15	Urban	34.36	40.65	28.61	31.40
15	Rural	33.00	32.61	22.00	31.40
16	Urban	34.36	40.65	28.61	31.40
16	Rural	33.00	32.61	22.00	31.40
17	Urban	57.52*	40.65	28.25*	31.40
17	Rural	33.00	32.61	22.00	31.40
18	Urban	13.27*	40.65	10.00*	28.04*
18	Rural	32.63*	32.61	22.00	31.40
19	Urban	34.36	40.65	16.32*	28.65*
19	Rural	33.00	32.61	22.00	31.40
20	Urban	17.50*	40.65	41.37	25.47*
20	Rural	35.20*	32.61	22.00	31.40
21	Urban	34.36	44.28*	27.77*	31.40
21	Rural	33.00	32.61	22.00	31.40
22	Urban	29.00	40.65	28.61	21.25*
22	Rural	33.00	32.61	22.00	31.40
23	Urban	31.34*	40.65	28.61	30.08*

23	Rural	33.00	32.61	22.00	31.40
24	Urban	38.25*	49.55*	36.85*	17.18*
24	Rural	33.00	32.61	22.00	31.40
25	Urban	34.36	40.65	28.61	31.40
25	Rural	7.67*	32.61	22.00	31.40
26	Urban	34.36	40.65	28.61	31.40
26	Rural	33.00	32.61	22.00	31.40

A4.3 Material content

Table A4.2 presents data on the material contents in each region across the four dwelling types. The building types are depicted by a code: 1 for detached houses, 2 for row houses, 3 for apartment buildings and 4 for high-rise buildings. The construction materials presented in this study we considered as commonly used in the built environment and are steel, cement, concrete, wood, copper, aluminium and glass.

Table A4.2. *Average material contents (kg/m^2) across the four different dwelling types and are separated into seven different construction materials: steel, cement, concrete, wood, copper, aluminium and glass. The asterisk (*) identifies the regional data directly available from the literature. The rest of the table is filled with the global average on all other available studies.*

Region	**Building types**	**Steel**	**Concrete**	**Wood**	**Copper**	**Aluminium**	**Glass**
1	1	32.31*	876.71*	48.75*	1.73	9.27*	2.68
1	2	32.89	1208.13	34.97	0.01	0.23	1.07
1	3	97.36	995.92	37.17	0.31	1.94	6.35
1	4	45.78*	1040.35*	28.66*	0.01	2.20	1.20*
2	1	7.26*	472.10*	48.45*	0.80*	1.84*	3.32*
2	2	32.89	1208.13	34.97	0.01	0.23	1.07
2	3	1.24*	57.69*	37.17	0.31	4.92*	6.35
2	4	61.48*	265.24*	54.48	0.01	3.05*	4.42
3	1	32.63	846.33	53.07	1.73	3.56	2.68
3	2	32.89	1208.13	34.97	0.01	0.23	1.07
3	3	97.36	995.92	37.17	0.31	1.94	6.35
3	4	116.98	910.21	54.48	0.01	2.20	4.42
4	1	35.50*	735.00*	90.00*	1.73	3.56	2.68
4	2	27.00*	1315.00*	40.00*	0.01	0.23	1.07
4	3	97.36	995.92	37.17	0.31	1.94	6.35
4	4	116.98	910.21	54.48	0.01	2.20	4.42
5	1	32.63	897.65*	868.96*	1.73	3.56	0.80*
5	2	32.89	1208.13	34.97	0.01	0.23	1.07
5	3	97.36	995.92	37.17	0.31	1.94	6.35
5	4	116.98	611.19*	20.63*	0.01	2.20	0.66*
6	1	35.15*	607.64*	19.78*	1.73	3.56	1.18*
6	2	39.29*	894.86*	17.68*	0.01	0.23	1.07*

Region	Building types	Steel	Concrete	Wood	Copper	Aluminium	Glass
6	3	37.50*	933.00*	2.70*	0.31	1.94	1.80*
6	4	116.98	910.21	54.48	0.01	2.20	4.42
7	1	32.63	846.33	53.07	1.73	3.56	2.68
7	2	32.89	1208.13	34.97	0.01	0.23	1.07
7	3	97.36	995.92	37.17	0.31	1.94	6.35
7	4	116.98	910.21	54.48	0.01	2.20	4.42
8	1	8.93*	675.66*	6.89*	1.73	2.89*	0.04*
8	2	32.89	1208.13	34.97	0.01	0.23	1.07
8	3	26.73*	995.92	42.06*	0.31	1.94	6.35
8	4	116.98	910.21	54.48	0.01	2.20	4.42
9	1	32.63	846.33	53.07	1.73	3.56	2.68
9	2	32.89	1208.13	34.97	0.01	0.23	1.07
9	3	97.36	995.92	37.17	0.31	1.94	6.35
9	4	116.98	910.21	54.48	0.01	2.20	4.42
10	1	32.63	846.33	53.07	0.77*	3.56	2.68
10	2	32.89	1208.13	34.97	0.01	0.23	1.07
10	3	97.36	995.92	37.17	0.39*	1.94	6.35
10	4	116.98	910.21	54.48	0.01	2.20	4.42
11	1	47.90*	1507.04*	77.29*	3.11*	0.93*	2.51*
11	2	24.63*	796.02*	35.77*	0.01	0.23*	1.07
11	3	76.24*	567.99*	49.88*	0.15*	0.46	11.21*
11	4	142.30*	850.70*	27.00*	0.01*	2.20	4.75*
12	1	32.63	1892.83*	99.36*	1.73	3.56	33.54*
12	2	32.89	1208.13	34.97	0.01	0.23	1.07
12	3	97.36	810.86*	22.71*	0.31	1.94	6.35
12	4	116.98	902.59*	2.54*	0.01	2.20	4.42
13	1	32.63	846.33	53.07	1.73	3.56	2.68
13	2	32.89	1208.13	34.97	0.01	0.23	1.07
13	3	75.50*	1507.64*	9.57*	0.31	1.94	6.35
13	4	40.65*	768.27*	8.08*	0.01	2.20	4.42
14	1	32.63	846.33	53.07	1.73	3.56	2.68
14	2	32.89	1208.13	34.97	0.01	0.23	1.07
14	3	97.36	995.92	37.17	0.31	1.94	6.35
14	4	116.98	910.21	54.48	0.01	2.20	4.42
15	1	32.63	846.33	53.07	1.73	3.56	2.68
15	2	32.89	1208.13	34.97	0.01	0.23	1.07
15	3	97.36	995.92	37.17	0.31	1.94	6.35
15	4	116.98	910.21	54.48	0.01	2.20	4.42
16	1	32.63	846.33	53.07	1.73	3.56	2.68
16	2	32.89	1208.13	34.97	0.01	0.23	1.07
16	3	97.36	995.92	37.17	0.31	1.94	6.35
16	4	116.98	910.21	54.48	0.01	2.20	4.42
17	1	102.55*	1641.98*	11.88*	1.73	0.73*	2.72*
17	2	32.89	1208.13	34.97	0.01	0.23	1.07
17	3	335.19*	1926.32*	37.17	0.31	1.94	6.35

Region	Building types	Steel	Concrete	Wood	Copper	Aluminium	Glass
17	4	116.98	910.21	54.48	0.01	2.20	4.42
18	1	20.77*	1069.50*	17.41*	2.02*	3.56	2.60*
18	2	32.89	1208.13	34.97	0.01	0.23	1.07
18	3	21.16*	1005.80*	37.17	0.31	1.94	6.35
18	4	121.21*	1733.60*	54.48	0.01	2.20	4.42
19	1	32.63	846.33	53.07	1.73	3.56	2.68
19	2	32.89	1208.13	34.97	0.01	0.23	1.07
19	3	106.51*	2319.18*	37.17	0.73*	1.94	6.35
19	4	63.31*	932.62*	54.48	0.01	2.20	9.25*
20	1	25.80*	2613.94*	36.92*	1.73	10.21*	7.82*
20	2	32.89	1208.13	34.97	0.01	0.23	1.07
20	3	374.30*	995.92	15.04*	0.25*	1.94	6.35
20	4	128.95*	295.01*	61.89*	0.01	3.43*	1.97*
21	1	32.63	846.33	53.07	1.73	3.56	2.68
21	2	37.93	2729.51	54.65	0.01	0.23	1.07
21	3	33.95*	1164.02*	11.26*	0.31	0.44*	0.78*
21	4	116.98	910.21	54.48	0.01	2.20	4.42
22	1	28.39*	25.78*	107.15*	1.73	3.56	1.60*
22	2	32.89	1208.13	34.97	0.01	0.23	1.07
22	3	97.36	995.92	37.17	0.31	1.94	6.35
22	4	116.98	910.21	54.48	0.01	0.33*	0.73*
23	1	57.22*	224.67*	76.00*	1.73	1.50*	4.00*
23	2	32.89	1208.13	34.97	0.01	0.23	1.07
23	3	97.36	995.92	37.17	0.31	1.94	6.35
23	4	304.33*	1871.00*	18.00*	0.01	2.00*	2.00*
24	1	21.05*	627.84*	67.25*	1.14*	1.90*	1.06*
24	2	35.58*	795.98*	29.49*	0.01*	0.23	1.07
24	3	49.41*	701.25*	37.17	0.01*	1.94	6.35
24	4	120.72*	1136.39*	176.66*	0.01	2.20	7.30*
25	1	32.63	846.33	34.04*	1.73	3.56	2.68
25	2	32.89	1208.13	34.97	0.01	0.23	1.07
25	3	97.36	995.92	37.17	0.31	1.94	6.35
25	4	116.98	910.21	54.48	0.01	2.20	4.42
26	1	32.63	846.33	53.07	1.73	3.56	2.68
26	2	32.89	1208.13	34.97	0.01	0.23	1.07
26	3	97.36	995.92	37.17	0.31	1.94	6.35
26	4	116.98	910.21	54.48	0.01	2.20	4.42

A4.4 Steel in residential buildings in China: literature comparison

The Chinese in-use steel stock data coming from our model show very high values in comparison with the rest of the world regions. We therefore performed a sanity check of our results by comparing them with steel stock estimations from the literature (see Table A4.3).

Pauliuk et al. (2013b) [6] developed a dynamic stock model to estimate the present in-use stock of the steel on a global level. The in-use stock is divided into four product categories (transportation, machinery, construction and products) within ten regions. In addition, Pauliuk et al. (2013a) [7] modeled the in-stock and future demand of the steel on a global level. Table A4.3 shows that our estimates are in the same order or magnitude as ours. Compared to our results Pauliuk et al. (2013a and b) [6,7] show a smaller initial steel stock, but a larger stock in 2050 compared to our estimates.

Hatayama et al. (2010) [8] analysed global steel use using a dynamic MFA. The steel in-use stock and future demand is estimated for three categories (buildings, civil engineering (infrastructure) and vehicles). The future building stock is modelled by a logistic function including parameters such as GDP, population density and saturation value per capita. Hatayama shows results for the whole of Asia, of which China is an important part. According to Hatayama et al. (2010) [8], Asia's steel stock will be at the level of 35 Gt in 2050, 21 of which will reside in buildings. Our estimate for Asia as a whole is around 11 Gt. Note that our estimates include residential buildings only.

Table A4.3. *Comparison of steel in-use stock estimates for China.*

	Pauliuk et al. (2013a), 2000-2005, China [7]	Pauliuk et al. (2013b), 2050, China [6]	Hatayama et al. (2010) 2050, Asia [8]
Steel stock from literature (Gt)	2.6 in total, 1.6 in buildings*	17 in total, 10 in buildings*	35 for whole of Asia, 21 in buildings
Our estimated steel stock in residential buildings (Gt)	2.2	7	11 for whole of Asia

*calculated from Pauliuk et al. estimate of 2 tons/cap in the early 2000s and 13 ton/cap in 2050, and a population of 13 million in both 2000 and 2050 in accordance with SSP2.

A4.5 Sensitivity analysis

A4.5.1 Description

In order to estimate the uncertainties related to the material intensity parameter and its influence on the model outcomes, we performed a sensitivity analysis using three different alternative values for the material content in terms of kg/m2 UFA. The effect on the modelled material stock development is estimated under these three "sensitivity scenarios". As the number of measurements for the individual regions is often too low, we performed this analysis at the global level only and disregarded the regional specificity of the material intensities of residential buildings. In addition, we aggregated over the four different building types, for the same reason.

In sensitivity scenario 1, we estimate the global material stock considering the mean global value for each material. Sensitivity scenario 2 is based on the values representing the 20th percentile, and sensitivity scenario 3 considers the values depicting the 80th percentile. In that way, we have some idea of the variability of the results.

A4.5.2 Outcomes and discussion

The outcomes from the sensitivity analysis are presented in Table A4.4 and Figure A4.3. Table A4.4 displays the mean, the 80^{th} percentile, 20^{th} percentile and the median scenarios compared to the model outcome based on averages for the period between 2045-2050, as specified in Chapter 4. The numbers in Table A4.4 represent differences in the outcome compared to the modelling results in Chapter 4 in percentages. The red numbers represent lower modelling outcomes while the green numbers show an increase in the stock in relation to the original results. The outcomes presented in Table A4.4 show that assuming a global mean material intensity does not lead to very different results for the materials stock estimates near the end of the modelled period. Only for copper, using mean values lead to slightly higher stock estimates while the other material stocks show lower values.

This can be explained with the fact that the material content of copper for square meter for certain building types (e.g. copper in row houses and apartment buildings) is relatively low as shown in Table 4.2 in Chapter 4. In addition, the same table shows that the global average of copper for detached houses is rather high in comparison with the rest of the dwelling types.

Table A4.4. *Effects of the sensitivity variants on selected material demand indicators. The percentages indicate the change with respect to the same indicators under the default analysis presented in Chapter 4. The* ***bold*** *numbers indicate an increase in the stock, while the italic numbers indicate a decrease.*

Indicator	**Year**	**Mean MI**	**80th Percentile**	**20th Percentile**	**Median**
Steel stock	2045 - ’50	*-14%*	**8%**	*-67%*	*-35%*
Concrete stock	2045 - ‘50	*-16%*	**4%**	*-60%*	*-22%*
Glass stock	2045 - ‘50	*-18%*	**22%**	*-72%*	*-41%*
Wood stock	2045 - ‘50	*-10%*	**34%**	*-64%*	*-34%*
Aluminium stock	2045 - ‘50	*-17%*	**21%**	*-73%*	*-57%*
Copper stock	2045 - ‘50	**2%**	**35%**	*-86%*	*-53%*

A4

Thus, applying the global mean and disregarding of the different regions results in a higher value for building types which in reality contain low amount of the material. Copper and glass are the construction materials showing the smallest difference between the applied and the mean scenario. This might indicate that the intensity of the materials is rather standard and the fluctuations in the data range are limited. The lower mean values for the stock of the rest of the materials might be explained by a very high values for material intensities, for instance the amount of concrete in detached houses in China. The value for concrete used for detached houses in this region are two times higher than the global mean value which could lead to decline in the mean variant compared to the applied scenario, as China represents an important share of the global stock. This outcome suggests the importance of using (and collecting) regional specific data.

The 80th percentile variant shows significantly higher stock estimations for the period between 2045-2050, as expected. The only exception is concrete (4%). This once again can be explained with the significantly higher mean value of the material intensity of the concrete in detached houses in China in relation to the global average, that contribute so much to the global stock.

The stock estimates based on the 20th percentile values for material content are much lower than either the applied, the mean or the median scenarios, by 60-70% for most materials and by over 80% for copper. We explain that with the wilder range of the data for copper resulted from the differences in the material intensity in the different regions and dwelling types. One reason could be the limited amount of data for copper, another could be the actual differences in the amount of copper used in buildings given that the material has a various purposes and the amount used could significantly vary across residential buildings [9,10].

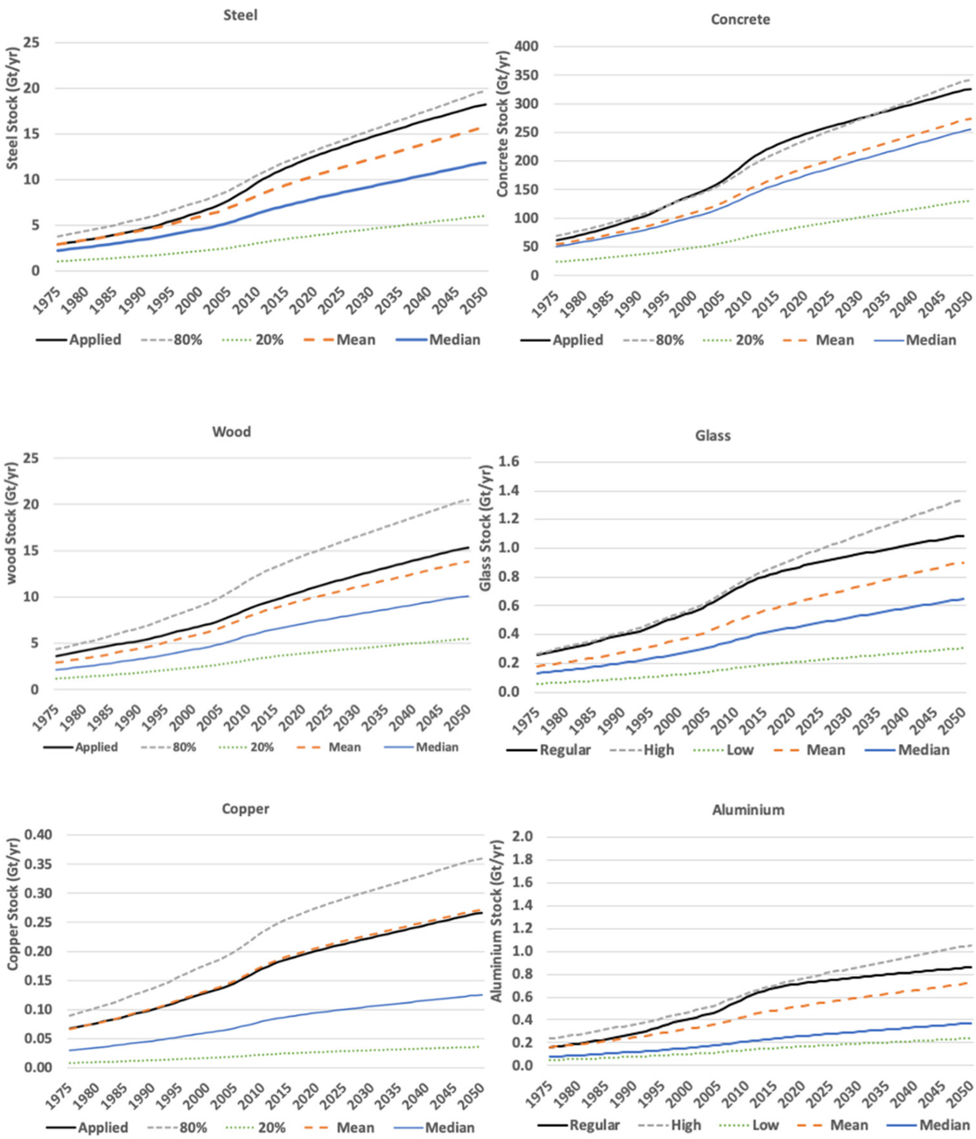


Figure A4.3. *Annual global stock development under four sensitivity variants. "Applied" shows the original data and the results as described in Chapter 4. The "Mean" depicts the global mean material content. The "Median" shows the "middle" value for each material. The "20%" assumes the global values for 20th percentile and "80%" represents the global values for 80th percentile as identified in Figure 4.2 in Chapter 4.*

The median scenario shows lower stock estimation in comparison with the applied, mean and 80th percentile scenarios. This can be explained with the fluctuation of the range of data and having extreme values for certain regions. This fact once again highlights the importance of the regional desegregation as the different regions are characterised by different architectural styles and preferred materials.

The 20th and 80th percentile values could be interpreted as the range of modelling outcomes based on data variability. The range is considerable: in most cases, a factor 4 difference between highest and lowest values is visible in the results, and a higher factor difference for materials with fewer data points. This indicates there is a high variability in the material content of dwellings. It also points to the need for a more consistent collection, as well as typology of buildings. Another interesting observation is that both the mean and the applied values are much closer to the 80th percentile values than to the 20th percentile values. Apparently, the bulk of the measurements are closer to the higher values, indicating the lower values might represent atypical situations.

In all, we can conclude that the database on material contents for doing such stock assessments is sufficient to arrive at order-of-magnitude credible values, but still is limited and lacks a lot of detail regarding regional differentiation and differentiation over the housing types. The sensitivity for reginal differentiation is large and the database not always allows regional differentiation. This is a challenge to be taken up by researchers, but especially by architects, construction companies and demolishers. We hope the database will be further developed to allow more robust outcomes.

References to Appendix 4

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Appendix 5

Based on the supplementary information provided with:
Deetman et al. (2020) - Modelling global material stocks and flows for residential and service sector buildings towards 2050 - Journal of Cleaner Production, Volume 245, pages 118658 - https://doi.org/10.1016/j.jclepro.2019.118658

A5.1 Corrigendum

The following corrigendum was reported to the journal of Cleaner Production, under ref. 118658: The authors regret to report that despite extensive efforts to review the work presented in this study, an error was made in the calculations. This has led to inaccurate reporting of the results for aluminium and glass in residential buildings detailed in Section 5.3.3 and 5.4.1 and the Supplementary Information. Results regarding floor space, other materials and service-sector buildings remain unchanged, and textual conclusions drawn from this work remain accurate. However, we feel the responsibility to provide the corrected figures and outcomes as detailed below. A corrected version of the model code can be found through the following link: https://github.com/SPDeetman/BUMA. The authors would like to apologize for any inconvenience caused.

With regard to Section 5.3.3, the total annual demand for glass by the end of the scenario period (2045-2050) changes to 61Mt (89Mt before), and the demand for aluminium changes to 39Mt (instead of the 52Mt reported before). This also affects the reported growth rates between 2015 and 2050, which increase to 35% for glass and to 9% for aluminium (up from 22% and 5%, respectively). The corresponding maximum fraction of the inflow that could theoretically be fulfilled by the outflow decreases to 60% for glass and to 68% for aluminium (down from 64% and 71% respectively). The latter is also mentioned in the abstract and the conclusions. Finally, the sensitivity analysis, reported in Section 5.4.1, indicated that assuming a mean global material intensity would lead to 18% lower demand for aluminium, which should have been 21%, given the model corrections. Per capita stocks for aluminium reported by our model, displayed in Table 5.4, should read 0.19 t/cap (globally by 2030) and 0.13 t/cap (for Japan, 2010). The corrected figures are shown below.

A5.2 Regression analysis for service sector floorspace

As indicated in Chapter 5, the starting point for our analysis is the 2017 data on service-related floor space in 231 countries, according to the Navigant Global Building Stock Database[2]. Because this is a commercial database, we cannot provide the original data. This

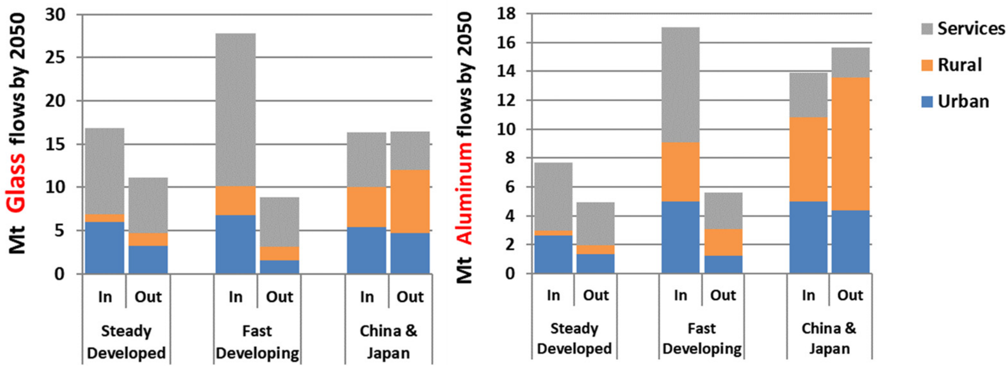

Figure A5.1 *Updates to Figure 5.5, for aluminium and glass*

section just explains the steps taken in the regression analysis, while providing additional detail.

First, we excluded countries for which we could not find the Gross Domestic Product (GDP) in Purchasing Power Parity (PPP) or the Service Value Added (SVA) fraction in the United Nation statistics[3,4]. The following countries were excluded for this reason:

Greenland, Andorra, Faeroe Islands, Gibraltar, Holy See, Isle of Man, Liechtenstein, Monaco, American Samoa, Cook Islands, French Polynesia, Guam, North-Korea, Mayotte, New Caledonia, Niue, Northern Mariana Islands, Taiwan, Tokelau, Wallis and Futuna Islands, Anguilla, Aruba, Belize, Cuba, Falkland Islands, French Guiana, Guadeloupe, Martinique, Montserrat, Saint Helena, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Sint Maarten (Dutch part), Suriname, Turks and Caicos Islands, Venezuela, British & US Virgin Islands, Bahrain, Oman, Syrian Arab Republic, Djibouti, Eritrea, Libya, Rwanda, Somalia, Sudan, Western Sahara.

Secondly, we excluded another group of countries which represented outliers in terms of per capita service sector floorspace, because they are island states, or typical city states. Because the model resulting from the regression is applied to 26 large global regions, we feel that calibrating a model to such atypical cases should be avoided. For this reason, the following countries were omitted in the regression analysis:

Cyprus, Bhutan, Brunei Darussalam, Comoros, Fiji, Hong-Kong, Kiribati, Macau, Maldives, Marshall Islands, Micronesia, Nauru, Palau, Samoa, Singapore, Solomon Islands, Tonga, Tuvalu, Vanatu, Antigua and Barbuda, Bahamas, Barbados, Caribbean Netherlands, Cayman Islands, Grenada, Puerto Rico, Trinidad & Tobago, Kuwait, Qatar, United Arab Emirates, Cabo Verde, Mauritius, Sao Tome and Principe, Seychelles

The remaining 147 countries yield data points which are used in the regression analysis, for which the results are shown in Figure A5.2. These figures show the resulting unweighted models as well as the population weighted model, using a Gompertz function (also see the main text):

$$y = \alpha \cdot e^{-\beta \cdot e^{-\gamma x}}$$

y being the service sector floor space demand in square meter per capita, and *x* the Service Value Added per capita in 2016-US$ for a particular country/yr, in Purchasing Power Parity. The coefficients α, β and γ were estimated using the Sequential Least Squares Programming (SLSQP) algorithm from the scipy package implemented in a python script (See Section S.6). We choose the SLSQP routine because as a sequential quadratic programming routine it has been shown to perform well (in terms of both efficiency and accuracy) for constrained non-linear optimization problems, such as ours[5,6]. The model is used to project the global floor space demand by applying the SVA for 26 IMAGE regions. As the SVA in IMAGE is expressed in 2005 US$ (PPP), we correct for inflation based on the inflation calculator of the United States Bureau of Labor Statistics[7].

A5.2.1 Weighted regression

As explained in Chapter 5, the model validation based on unweighted regression did not lead to a suitable fit with the 2017 data. The unweighted model (black line) would underestimate the known total global floorspace for 2017. This mismatch is addressed by means of a 'fit' indicator, ϕ, which represents the total modelled floor space over the total observed floor space in 2017, when multiplied with the population size for the 147 countries used in the regression:

$$\phi = \frac{\sum_{i=1}^{147}(y(x_i) \times p_i)}{\sum_{i=1}^{147}(y_i \times p_i)}$$

Here, $y(x_i)$ is the modelled per capita floor space, for country *i*, as derived from the estimated regression model, and using information on the Service Value Added per capita, x_i per country. y_i is the per capita floor space according to the data and p_i is the population in a country, according to the data. As indicated in Figure A5.2a, the total service-related floor space demand based on unweighted regression analysis would have a fit of $\phi = 0.67$. In other words, the model predicts a total service sector floor space demand that would be off by 33% in 2017.

<u>Appendix 5</u>

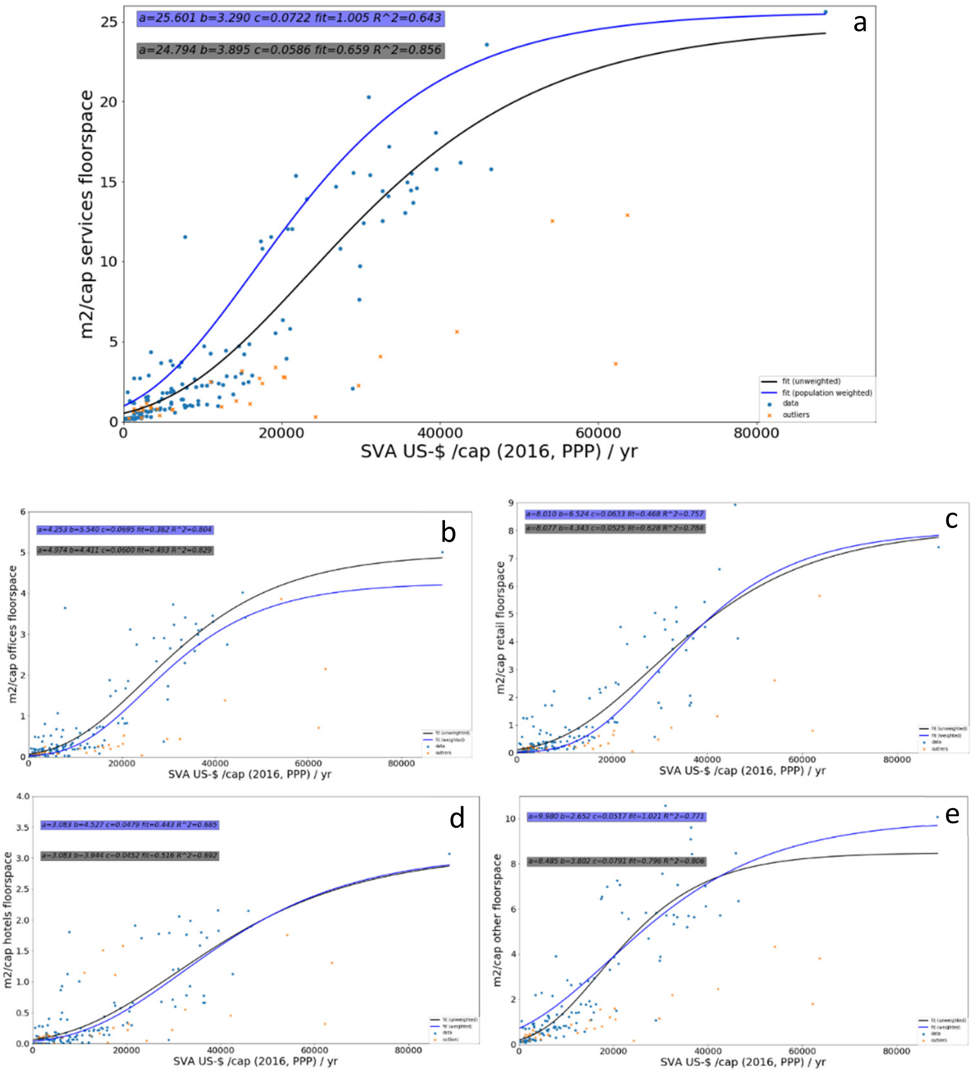

Figure A5.2a-e. *Development of per capita service sector floorspace demand, according to the unweighted regression (black) and a population weighted regression (blue). a) represents the total service sector floorspace (data points represent the sum of the data points in panel b-e). b) shows the office space, c) shows the floorspace for retail, shops & warehouses, d) shows hotels & restaurants & e) shows the per capita demand for other buildings (educational buildings, hospitals, governmental buildings, buildings for assembly and public transportation).*

This is caused by the fact that many countries with a large population size lie above the unweighted curve, while many countries with a small population size are below the curve. It was thus decided to use a population weighted regression model for the floor space demand from the service sector as a whole (top line in Figure A5.2a). This was done by minimizing the goodness-of-fit parameter, or the χ^2, according to Bevington & Robinson [8]:

$$\chi^2 = \sum_{i=1}^{147} \left\{ \frac{1}{\sigma_i^2} [y_i - y(x_i)]^2 \right\}$$

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Here, x_i is the Service Value Added in US$ (2016, PPP) and σ_i is the uncertainty of the y_i, so of the per capita floor space of country i, measured in terms of a standard deviation. An unweighted model assumes an equal (but possibly unknown) σ_i for all countries. There is no information on the value of these σ-values. We decided to construct them based on the (population or GDP per capita weighted) per capita floorspace y and a country-specific uncertainty weight w_i as follows:

$$\sigma_i = y \times w_i$$

Here the uncertainty weight w_i is assumed to decrease linearly (with population size or GDP/cap) until a maximum reached (200 million people or $40,000 GDP/cap, see Figure A5.3):

$$w_i(population\ weighted) = \begin{cases} -1.4 \cdot 10^{-9} \times p_i + 0.3 \text{ if } p_i \leq 2 \cdot 10^8 \\ 0.015 \text{ if } p_i \geq 2 \cdot 10^8 \end{cases}$$

$$w_i\left(\frac{GDP}{cap} weighted\right) = \begin{cases} -7.125 \cdot 10^{-6} \times p_i + 0.3 \text{ if } p_i \leq 4 \cdot 10^4 \\ 0.015 \text{ if } p_i \geq 4 \cdot 10^4 \end{cases}$$

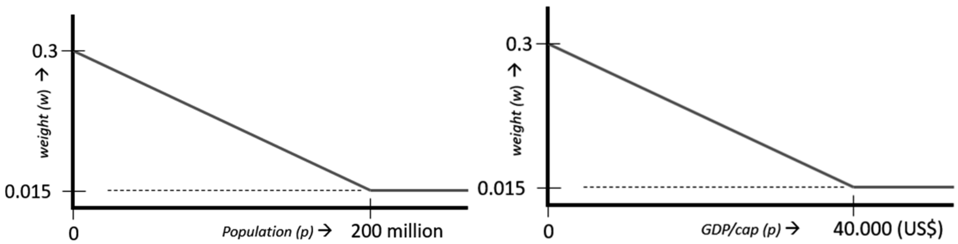

Figure A5.3. *Graphical representation of the uncertainty weighting factors (w) used in the weighted regression analysis. Left: population weighted regression; Right: regression weighted by GDP per capita.*

This means that we introduce a relatively large uncertainty weight (w), and resulting relative standard deviation of the service-related floor space (of 30%) for countries with a small population size (p), while countries with a population size beyond 200 million people are assumed to have a smaller relative standard deviation of the service-related floor space (of 1.5%). When implemented, these settings ensure that the model fit becomes more accurate, because it allocates more weight to data points representing countries with a larger population (since these have a lower uncertainty weight). Using the estimated Gompertz parameters resulting from the weighted regression leads to a much better fit of $\phi = 1.005$ for the year 2017, representing a mismatch of total global floor space of only 0.5%. A more accurate model verification in the year 2017, however, comes at the cost of lower R^2 values as can be seen from Figure A5.2.

While the total service-sector floorspace is represented using a population weighted regression, thus ensuring an appropriate model fit, it was decided to follow a different approach regarding the disaggregation of floorspace demand across the four service building types (Figure A5.2b-c). One reason being the lower resulting R^2 values from a population weighted regression. Another reason is that if the total service floorspace ensures a proper representation of the current situation, the need for population-based weighting diminishes for the specific building types. Instead we applied a more common weighting approach based on the reliability of the data. Here, we assume that reported data from countries with a higher per capita income have a higher reliability than data from countries with a lower income per capita. This could be defended by the common view that affluent countries tend to have better statistical offices for example. To translate a countries affluence into a proxy for the data reliability we used the per capita GDP (2016 US$/cap, PPP). Similar to the population weighted approach we use a high uncertainty weight of 30% at low income levels, and assume a linear decrease to 1.5% at high levels of GDP per capita (beyond 40.000 US$/capita yr^{-1}), as shown in Figure A5.3.

The disaggregation of the total commercial floor space demand (based on the weighted regression) was done based on the relative contribution according to the GDP/cap weighted regression fits for the four service-related building types, as can be found in Figure A5.4 a&b.

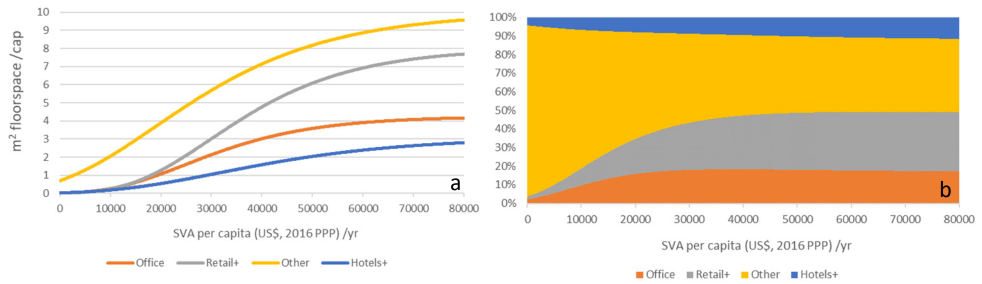

Figure A5.4a-b. *Per capita floor space demand for four service sector building types, used to disaggregate the total service-related floorspace demand (blue line in Figure A5.2a). a) Four regression models used for the four commercial building types (the corresponding Gompertz parameters for these curves can be found in Table 5.1). b) Relative contribution of the four service building types to the total service sector floorspace demand, at different levels of Service Value Added (in US$/capita yr^{-1}).*

A5.2.2. Reflection on model specification

In the current model specification, we use national data on per capita service value added to derive the development of the per capita floorspace for non-residential buildings. However, this does not mean that service value added is the only possible independent variable to explain the development of non-residential floorspace demand. From literature we know, for example, that the amount of some shops seems to be correlated with population density at the local level[9]. To see if this is true for our data, we displayed the per capita floorspace demand for four non-residential building types in relation to the population density in Figure A5.5. Using the figure one can identify some of the city-states, but other than that, the figures do not suggest any clear relationship between non-residential floorspace demand and population density.

That does not mean, however, that such relationship does not exist. If data on non-residential floorspace demand would be specified for smaller regions, or if it would distinguish between urban and rural areas, one may expect to find not only a better regression, but perhaps a better model by incorporating a second independent variable such as population density. The current model specification is therefore chosen based on data-availability, given the global scope of our research.

Furthermore, in the definition of a global model describing a generic development path we inevitably lose sight of exceptional regional factors such as culture and lifestyle, which surely play a role in floorspace demand. We would like to emphasize that therefore careful interpretation is required when using regional model outcomes. For this exact reason we provide both the data and the model used, which should make it easy to build and improve upon our work, for example by improving the regional representation.

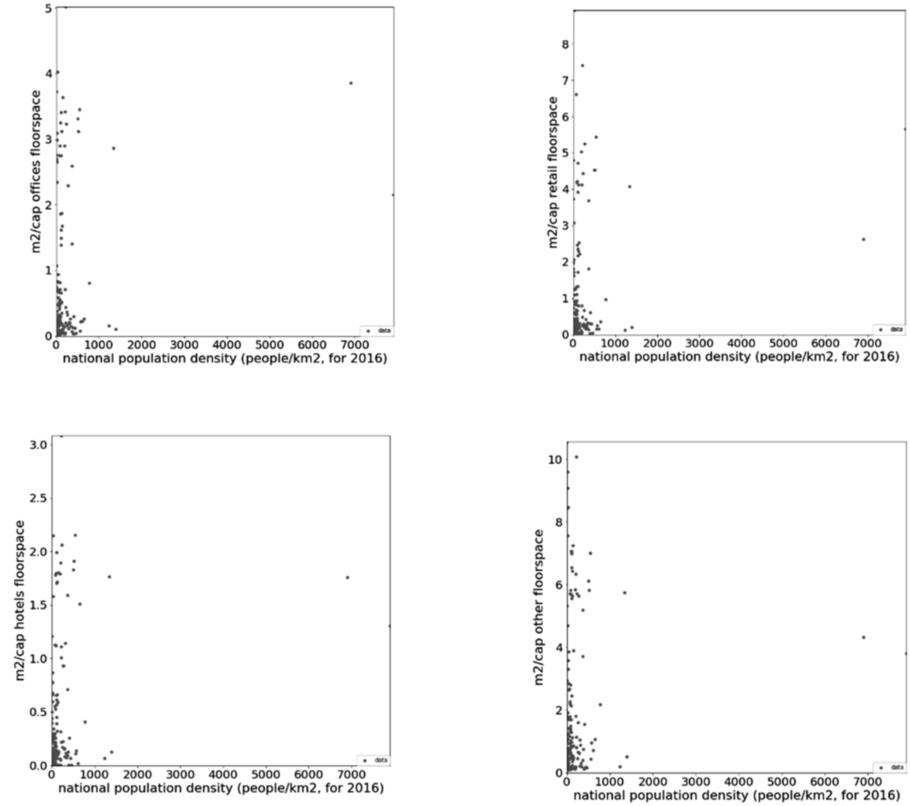

Figure A5.5. *Per capita floorspace demand in 4 non-residential building types (top-left: offices; top-right: retail+; bottom-left: hotels+; bottom-right: other) versus the population density. Data points represent countries, including outliers (N=176).*

Finally, the assumption of a fixed relation between demand (floor-space) and income (SVA) is only valid under a presumption of a 'business as usual' development. This is a legitimate assumption under the SSP2 scenario, as it explicitly assumes a "path in which social, economic, and technological trends do not shift markedly from historical patterns" according to Riahi et al.[10]. However, implementation of our model under different scenarios (SSP or other) could mean that this relation between service sector floorspace demand and SVA needs to be revisited.

A5.3 Dynamic stock modelling for service sector floorspace

A5.3.1 Lifetime assumptions

The dynamic stock model used was originally developed by Pauliuk and co-contributors[11], and was applied in this study using a stock-driven approach. This requires lifetime assumptions for the buildings in our model, which were based on the Weibull distribution parameters as found in literature. Table 5.3 shows the averaged Weibull parameters used, but as indicated in Chapter 5, we used building-specific Weibull parameters where possible. Table A5.1 shows the parameters used.

Averaging lifetime distributions based on given Weibull parameters cannot simply be done by averaging the available shape parameters and the available scale parameters. Therefore, we used a python least squares optimization routine to find the closest representation of the average, given multiple Weibull curves. In case we used an average to represent the multiple Weibull parameters found in literature, we indicate the coefficient of determination for the fitted curve with respect to the average of multiple curves (2 to maximum 5 curves) in brackets. Thus, representing how well our parameter settings matches the average of the lifetimes found in literature. For an example, please see Figure A5.6.

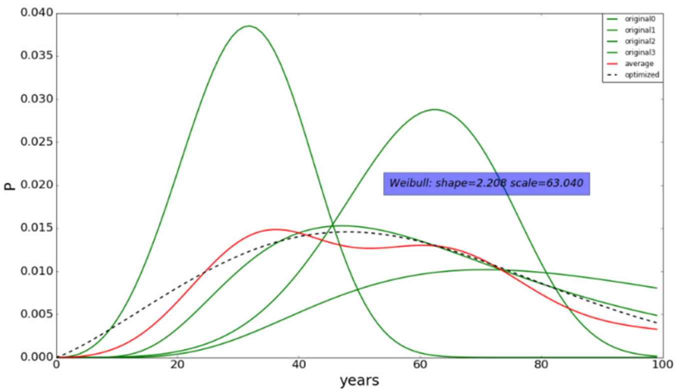

Figure A5.6. *Example of fitting a Weibull distribution to an average of multiple Weibull curves found in literature. This example shows the four literature-based Weibull curves for Western Europe in green, the red line is the resulting average for the 4 curves, and the dotted line is the fitted curve used in our model, which fits the average with an* R^2 *of 0.965.*

Appendix 5

Region	Building type	shape	scale	Comment
Japan	Detached	1.88	41.23	Building Specific Weibull parameters according to the average found in two studies [12,13] (R^2 = 0.99)
	Semi-detached	1.89	42.58	
	Apartments	1.90	43.95	
	High-rise	2.56	34.05	
China	Urban: detached	2	33.85	Region specific shape parameter and building specific scale parameter according to the mean indicated in Wang et al.[14]
	Urban: semi-detached	2	39.49	
	Rural: (semi)-detached	2	31.03	
	Apartments	2	53.60	
	High-rise	2	56.42	
Eastern Europe	(semi)-detached	2.5	73.26	Region specific shape parameter according to Novikova et al.[15,16]
	Appartments	2.5	101.43	
	High-rise	1.97	67.36	Global Average (see below)
United States	All	4.16	85.19	Region specific parameters according to average [17–19] (R^2 = 0.951)
Western Europe	All	2.95	70.82	Region specific parameters according to average [19–21] (R^2 = 0.965)
Canada	All	1.97	57.53	Global shape, regional mean [22,23]
Mexico	All	1.97	63.17	Global shape, regional mean [23,24]
Brazil	All	1.97	112.80	Global shape, regional mean [25]
Rest of South Amerika	All	1.97	68.24	Global shape, regional mean according to the average of Argentine, Chile, and South-Amerika in [22–24,26]
Southeastern Asia	All	1.97	56.40	Global shape, regional mean [22]
Oceania	All	1.97	94.00	Global shape, regional mean according to Buyle et al. [22] and Stephan et al.[27]
Global Average	All	1.97	67.34	These lifetime parameters are applied when no information is available, it is a constructed average of parameters from 5 regions, being Japan, China, US, East & Western Europe. (R^2 = 0.994)

Table A5.1. *Weibull parameters describing the lifetime distributions used. Where possible, we used lifetime estimates specific to the building type.*

A5.3.2 Historic stock development

Since we have no data on the age distribution of the initial stock, we needed to extend the historic time series to derive the age-distribution of buildings based on historic inflow. We did so using the historic population dating back to 1820 based on Bolt et al. [28], and an additional 100 years of linear increase in population from 0 in 1720. During this model-setup period, we also assumed that the per capita floor space increased at the average global rate found in the first ten years of the IMAGE data (about 1% per year). For the development of the share of urban population before 1971 a similar approach was used, but based on regionally specific annual growth-rate. Both for the per capita floor space and the urban population fraction a minimum was maintained based on the lowest regional value in 1971. To assess the viability of these historic model assumptions, we checked whether our model was able to re-create the known age-distribution of the building stock in two European test-cases (See Figure A5.7 for an elaboration). The model managed successfully, but to ensure a proper fit, both test-cases required relatively high lifetimes, compared to those found in Table 5.3. This suggests that some of the mean building lifetimes found in literature could be rather low.

A5.3.3 Lifetime verification

We performed a model verification exercise, in which we tested assumptions on the historical model setup (Section 5.2.2.2) as well as the lifetime assumptions for residential buildings. We were able to find two sources describing the age distribution of residential buildings in great detail. One for the Netherlands in the year 2018 [29] and the other for Western Europe as a whole in the year 2010 [30]. Given the age-structure of the building stock for these regions and years, we were able to see whether the model is able to re-create these numbers. We thus run our model given the historic assumptions as described in the main text , lifetimes as found in the literature and historic population development based on Bolt et al. [28] . The Weibull parameters for Western Europe are the same as used in the main model (see Table 5.3), while for the Netherlands we used the same shape parameter, but an adjusted scale parameter, corresponding to an average lifetime of 120 years for residential building, based on Sandberg et al. [31]. Furthermore, in this test-case, we assume the historic development of per capita floorspace to be similar to that of Western Europe. Figure A5.7 shows the resulting model outcomes, compared to the available statistics. It shows that for the Netherlands the model is able to re-create the age-structure of the residential building stock quite well, based only on GDP and Population as a driver. Perhaps with the exception of historical artefacts such as a relatively high share of remaining houses from before 1900 (which could be explained by policies aimed at preservation of historical & monumental buildings in the Netherlands) and some noticeable historic abnormalities, such as the effect of the second world war on housing construction activities.

However, using the regular lifetime assumptions for Western Europe (i.e. a Weibull distribution with a mean lifetime of 63 years) seems to lead to an over-estimation of recent building activities (Figure A5.7b), because the model projects the demolition of buildings that in reality have remained in stock. Only when we assume a much higher average lifetime of 130 years, the model is able to match the known age-distribution of the stock in the year 2010 (Figure A5.7c). This suggests that the literature-based lifetimes of Western European residential buildings could be lower than in reality. Another factor that may explain the mismatch between our model and the available statistics for these two test-cases is the fact that we do not account for the lifetime dynamics of monumental buildings. The latter may be quite relevant for Western Europe, given the fact that historic and monumental buildings make up a large part of the (urban) building stock [32].

Though this highlights two important paths for future research and model improvement (introducing more realistic lifetime distributions and accounting for stock dynamics for monumental buildings specifically), we are currently unable to adjust our model for these findings. Given that we aim to develop a global model we currently lack the data and the time to perform a similar verification for all 26 regions in our model.

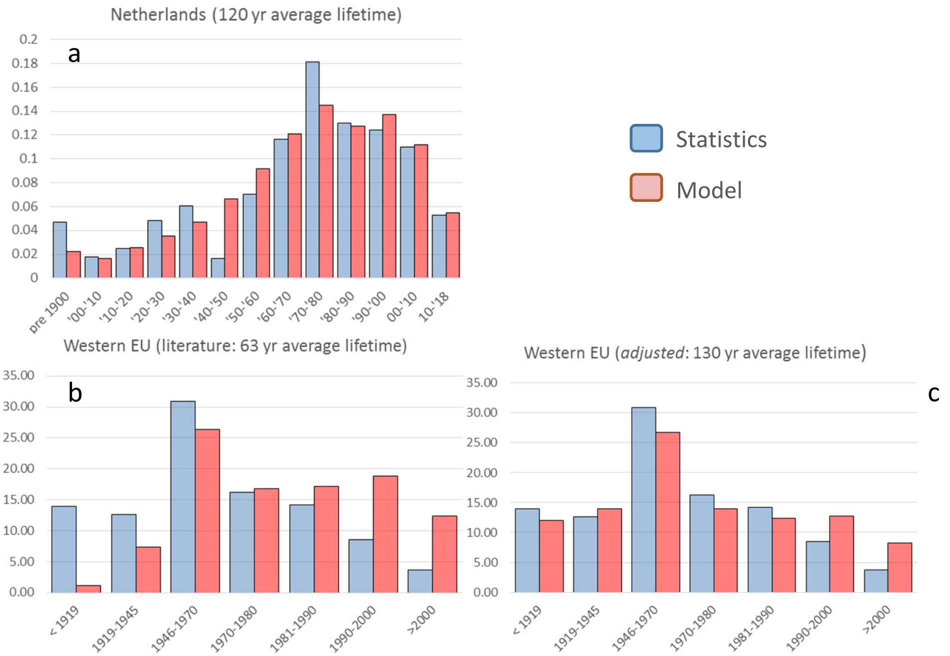

Figure A5.7. *Model verification results. Showing the fraction of residential buildings by age-cohort on the y-axis, according to the available statistics (blue), and according to our model (red). Data for the Netherlands (a) represents the year 2018 based on [29], while data for Western Europe (b&c) represents the year 2010 based on [30].*

	Source	Description	Region	Steel	Concrete	Aluminium	Copper	Wood	Glass
Offices	Ecoinvent [34]	Multi-storey building	-	24	393	8.5	8.5	24.7	3.1
	Kashkooli [35]	High-rise office building	Mexico	124	425		2.7	3.0	1.0
	Kofoworola [36]	Typical office building	Thailand	256	2118	0.3		1.5	9.6
	Oka [37]	Offices	Japan	158					
	Reyna [38]	Offices (low & high)	USA	42	533	9.7		0.2	4.6
	Schebek [39]	Offices	-	87	1057	0.6	0.7	4.2	13.9
Retail+	Ecoinvent [34]	Hall-type building	-	26	785	1.2		18.2	1.8
	Reyna [38]	Warehouse, department store & small store	USA	83	658	2.1			1.9
	Schebek [39]	Warehouse	-	85	349	1.1	0.7	4.2	13.9
	Gruhler* [40]	Wholesale & Car-shop	Germany	121	1009	5.2	3.9	11.0	
Hotels+	Reyna [38]	Hotel	USA	89	93	5.2			2.7
	Rossello-Batle [41]	Hotel	Spain	51	1007	3.0	3.3	12.0	5.1
	Gruhler* [40]	Hotel/guesthouse	Germany	113	1073	4.9	3.7	25.0	
Other	Kumanayake [42]	University	Sri Lanka	132	1543	5.0			7.6
	Reyna [38]	School & Hospital	USA	132	835	7.9			4.9
	Gruhler* [40]	Nursing-home & Emergency services	Germany	104	1037	4.5	3.4	25.5	
	Marcellus-Zamora [43]	Civic/Institutional	USA	40	702				31.0
Avg.				**97.9**	**850.9**	**4.2**	**3.3**	**11.8**	**7.8**

Table A5.2. *Material content of service-related building types in kg/m^2. Corresponding to the use in the main text, 'Retail+' refers to the combination of retail, shops and warehouses, 'Hotels+' refers to hotels and restaurants and 'Other' refers to other buildings such as hospitals, educational buildings, governmental buildings, buildings for assembly and transport-related buildings. *The study by Gruhler reports metals as a single category, we used an assumption on the share of 93% steel, 4% aluminium and 3% copper to disaggregate the three metals.*

A5.4 Material assumptions

All of the assumptions on material content of residential buildings (in kg per m^2) is described by Marinova et al. [33]. The material content estimates for service-related buildings applied in our calculations are summarized in Table 5.2. Table A5.2 shows how these averages were derived from the individual sources.

The Ecoinvent database gives the material use during the assumed lifetime of a building, and thus incorporates the replacement of some building elements with shorter lifetimes, such as the window-frames for example. As indicated in the main text, we adjusted the material use per m^2 to reflect the materials contained in the building, so not accounting for the maintenance & refurbishment. We adjusted for this using the indicated lifetimes of the building components which are replaced during the lifetime of the entire building. To give an example; if the Ecoinvent database indicated 3 kgs of Aluminium window-frame, with an expected service life of 25 years, per square meter of a hall-type building with an expected 50 yr lifetime, we assumed a 1,5 kg/m2 Aluminium demand based on our 'one-time-built' approach.

Other conversion factors used to derive the material content for service sector buildings as displayed in Table A5.2 are shown in Table A5.3. Figure A5.8 shows the distribution of the data on material intensities for buildings in the service sector as a whole (4 building types combined). The mean values displayed in this figure are used in the sensitivity analysis, where they are applied to all 4 building service-related types.

Table A5.3. *Conversion factors used in calculating the material intensities of service sector buildings*

Conversion factor	value	source
kg per m2 glass	10	[44]
kg per m2 corrugated steel roof plate	10	Appendix 1 in [45]
kg per cement block	12.25	'standard' according to [46]
kg per m2 steel cladding	3.66	26 Gauge according to [47]
kg per ft2 of concrete brick	18.07	3.4 kg per brick acc. to [48]

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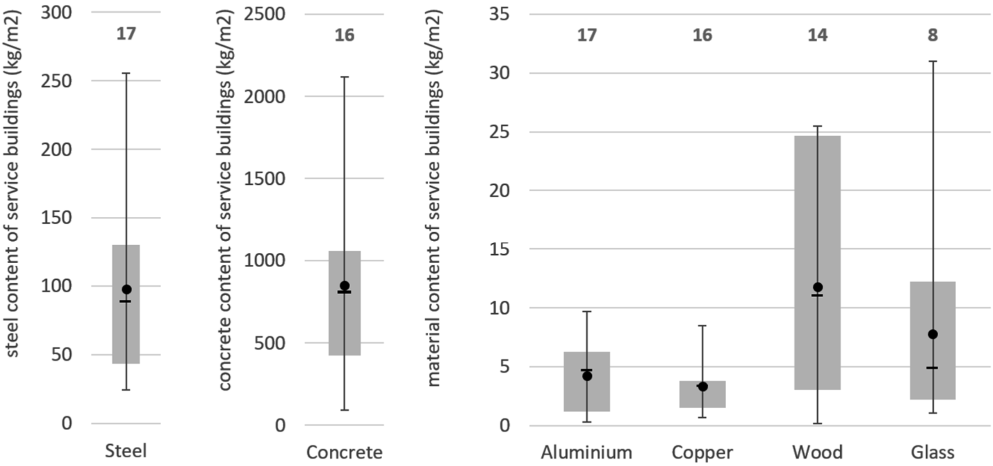

Figure A5.8. *Distribution of the data points on material intensity for buildings in the service sector. The boxes represent the 20th to 80 percentile interval range, while the whisker indicate the maximum and minimum values for each of the six materials. Numbers above the plots indicate the number of data points. Though our analysis applies average material intensities per service sector building type based on Table A5.2 (not shown here), these graphs are meant to give an impression of the overall data variability. Furthermore, the mean values displayed here are used in the sensitivity analysis.*

A5.5 Detailed results

A5.5.1 Per capita floorspace demand

Figure 5.2 shows the development of the global building stock in terms of floor space (in m^2) as a consequence of the development of population as well as affluence. To show the effect of increased affluence only, Figure A5.9 shows the development of the average per capita floor space (in-use stock) between 2000-2015 and 2035-2050, for both rural and urban residential purposes and for service-related purposes. The per capita floorspace demand in the service sector remains well below the residential floor space demand. It can also be seen that the per capita floor space for urban housing is slightly lower than the per capita floor space in rural areas, as elaborated by Daioglou et al.[49]. Though this seems to be a logical consequence of compact urban living, driven by scarcity of space in areas with a high population density, the available data on per capita floor space in our database for materials in residential buildings seems to suggest the opposite. For a more elaborate discussion about this interesting finding and possible future model improvements, please see Marinova et al.[33].

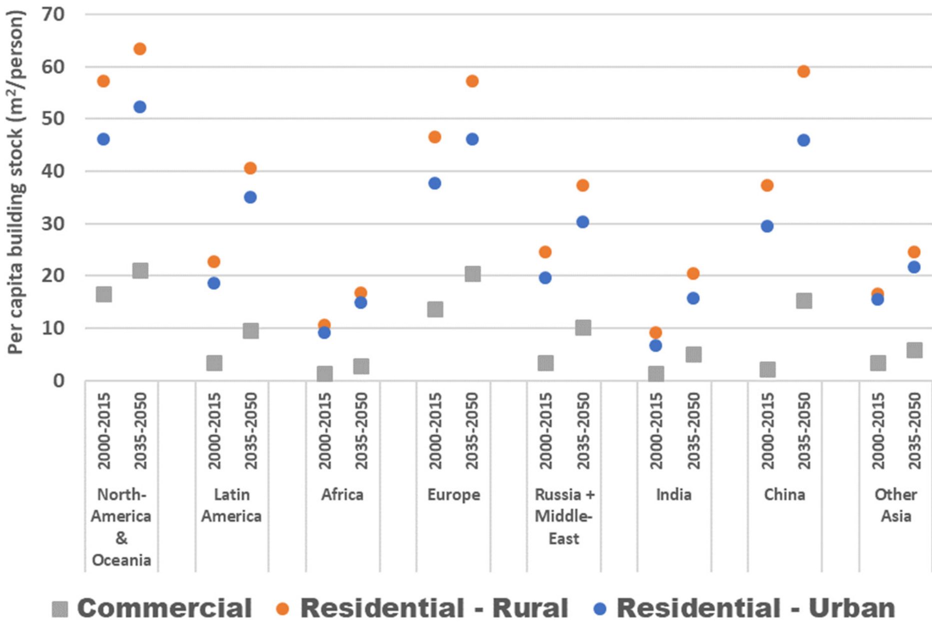

Figure A5.9. *Development of the average per capita floor space stock by region, for the period 2000-2015 and 2035-2050. Urban residential buildings are shown in blue, rural residential buildings in orange and service sector floor space in grey.*

Figure A5.9 shows the growth of the residential and service-related per capita floor space demand. As discussed in the main text, the latter grows more rapidly. As a consequence of the regression analysis and the resulting demand curves as shown in Figure A5.4a, some service sector building types grow more rapidly than others. Table A5.4 provides the relative contribution of each building type to the total commercial building stock and the resulting growth factors between 2018 and 2050. It shows that demand for retail and offices is expected to grow faster than the demand for other service-related building types.

Table A5.4. *The share of service sector building types in the total service-related building stock, and the resulting growth factors per building type. Using the same definition of building types as in Table A5.2.*

	Share		
	2018	2050	Growth
Hotels+	8%	9%	2.71
Offices	13%	16%	2.96
Other	63%	54%	2.10
Retail+	17%	22%	3.15

A5.5.2 Detailed model outcomes

The full set of model outcomes is available from the Supplementary Data, which provides data for the entire modelling period (1970-2050), for all 26 IMAGE regions, for 4 residential building types as well as 4 service sector building types, and for floorspace (in m^2) as well as material demand (in kgs), it contains the model outcomes for the building stock, but also for the inflow and outflow as derived from the stock. As discussed in the main text, it is not advisable to use detailed regional outcomes without critical reflection. We present a first attempt to model the global building stock, with regional detail. All assumptions are listed transparently where possible, but we cannot guarantee that the results make sense at the highest level of detail. We decided to provide the detailed results so that priorities for model improvement can be identified. We encourage people to use and expand this model as they see fit. Therefore, the model and the associated data are made available on Github, under a creative commons license[50].

To show the contribution of different building types on the demand of construction materials and the consequential outflow of scrap building materials, Figure A5.10 below shows the material flows by the end of the modelling period (average of 2045-2050) for each building type, and for all six materials.

A5.6 Sensitivity analysis

A5.6.1. Description of four sensitivity variants

1. **Mean Material Intensity (Mean MI)**

Based on the material intensity database as described by Marinova et al.[33] we defined a sensitivity variant in which we ignore the regional detail on material intensities of residential buildings, but instead assume a global mean material intensity for each of the four residential building types and the six materials, based on all available studies. Here, we further explore the effects on inflow and outflow related indicators. Please note that when no literature was available on the residential material intensities of a particular region, a global average was already used in the default analysis (main text). This means that for the residential buildings, this alternative assumption can be used to identify the sensitivity of overall outcomes to the regional assumptions on material intensities.

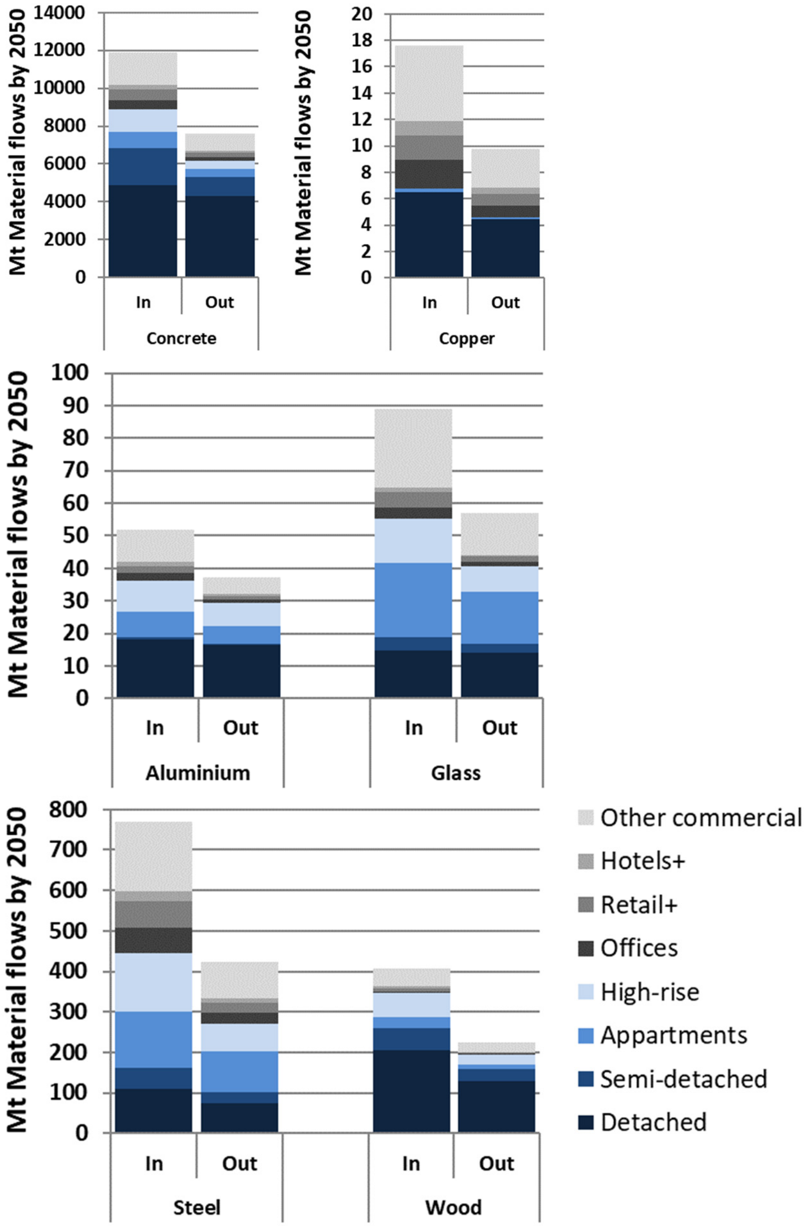

Figure A5.10. *Ratio between the total inflow and outflow of building materials by the end of the modelling period (average of the period 2045-2050). The contribution of service sector building types (in grey) and residential building types (in blue) is shown. For the definition of residential building types, please see* [33]*. The definition of service building types is similar to Table A5.2.*

Material intensities in service sector buildings, however, are not regionally specified to begin with. So, to come up with a sensitivity variant based on the material intensities described in this paper, we defined the mean material intensities for service sector buildings based on all available studies describing the service-related building types. The mean values used are shown in Figure A5.8 and represent the assumption that all service-related building types would have a similar material demand.

2. Normal distribution for building lifetimes

Stock dynamics in both residential and service sector buildings are based on the assumed Weibull lifetime distributions. To see the effect of different lifetime profiles, we defined a sensitivity variant based on a normal distribution.

We assumed the same mean lifetimes as in the regular analysis, but defined the normal lifetime distribution using a standard-deviation that would make sure that the distribution would be above zero (as opposed to the Weibull distribution, the normal distribution continues below zero, leading to unrealistic assumptions). To this end we linearly increased the standard deviation from 10 at a mean lifetime of 35 years to 20 at a mean lifetime of 60 years, leading to an increasing spread of the lifetime distribution at higher expected lifetimes (based on literature, see Table A5.1). The resulting lifetimes can be seen in Figure A5.11. To avoid disregarding the mass balance by any remaining 'tail' of the distribution before the building's actual lifetime, we actually deploy a folded normal distribution, which presents only a very slight deviation from the normal distribution during the first few years after construction. This method was applied for both residential and service sector buildings.

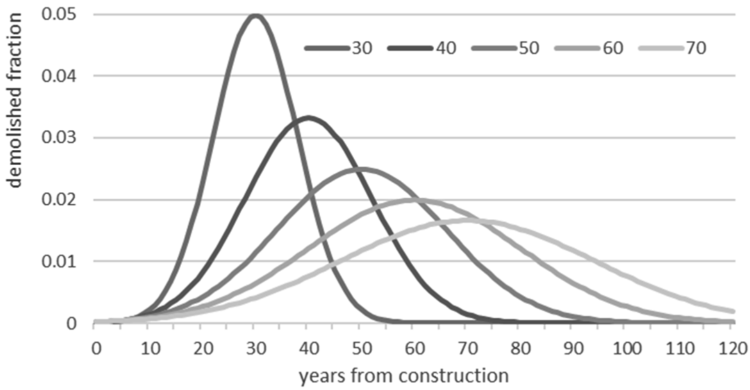

Figure A5.11. *Normal lifetime distributions used in the sensitivity variant. We assumed that an increasing mean lifetime leads to an increasing standard deviation as shown here.*

3. Increasing Alpha with 10%

The Gompertz parameters resulting from the regression analysis are key in determining the demand for service sector buildings. In particular the value of alpha, as it determines the maximum value for the per capita demand of service-related floor space. In the regular analysis the value of alpha was maximized to represent the highest value in the available data in the Global Building Stock Database by Navigant Research[2]. Our model thus assumes that demand for service sector buildings will grow towards what is currently known to be the highest value. However, wealthy regions like the United States seem to be approaching that maximum already[51]. To assess the effect of allowing a higher per capita service sector floorspace demand we defined a sensitivity variant that allows for a 10% higher value of alpha for the overall service sector. Mind that we only change the alpha for the total service sector, while keeping the original Gompertz parameters for the individual building types. As such, we assume that the sub-division of service-related building types remains the same.

If we only increase the value of alpha by 10%, the service-related building stock would simply increase by 10%, leading to a corresponding 10% increase in annual demand for each of the materials. This shows a high dependency of the outcomes on the value of alpha, but it does not make a very interesting sensitivity analysis. Therefore, we decided to change the assumptions in the regression by finding a new set of Gompertz parameters based on a regression in which alpha was maximized to the maximum in the data, plus 10%. This gives a slightly better population weighted R^2 of 0.685, based on the resulting parameters of alpha: 28.161, beta: 3.191 and gamma: 6.06*10^-5

4. Replacing the Gompertz model with an Exponential Decay function

Another key factor prescribing the development of service sector floorspace demand is the assumed Gompertz curve. To assess the effect of a different regression model, we implemented a sensitivity variant based on an Exponential Decay function:

$$y = \alpha - \beta e^{-\gamma x}$$

Similar to the model described in the main text, y is the service floor space demand in square meter per capita, and x is the Service Value Added per capita in 2016-US$ for a particular country, in PPP. While α, β and γ are the regression parameters. The method performing the regression remained the same as described in the main text. Again, we only change the model describing the total service related floorspace demand, thus using a population weighted regression. The sub-division of the total floorspace across the 4 service-related building types was unaltered.

The regression leads to the following alpha: 25.601, beta: 28.431 and gamma: 4.15*10^-5. This leads to a somewhat lower R^2 of 0.514 at a fit (ϕ) of 0.995, suggesting a somewhat inferior model than used in the regular calculations. Furthermore, the exponential decay function leads to negative values at lower levels of Service Value Added. To avoid this, we minimized the function below 0.542 m^2/cap, which represents the 25th percentile of the original data.

To understand the effects of choosing an alternative model function, we plot the development of service sector floorspace demand based on the regular model as well as the two sensitivity variants in Figure A5.12 below.

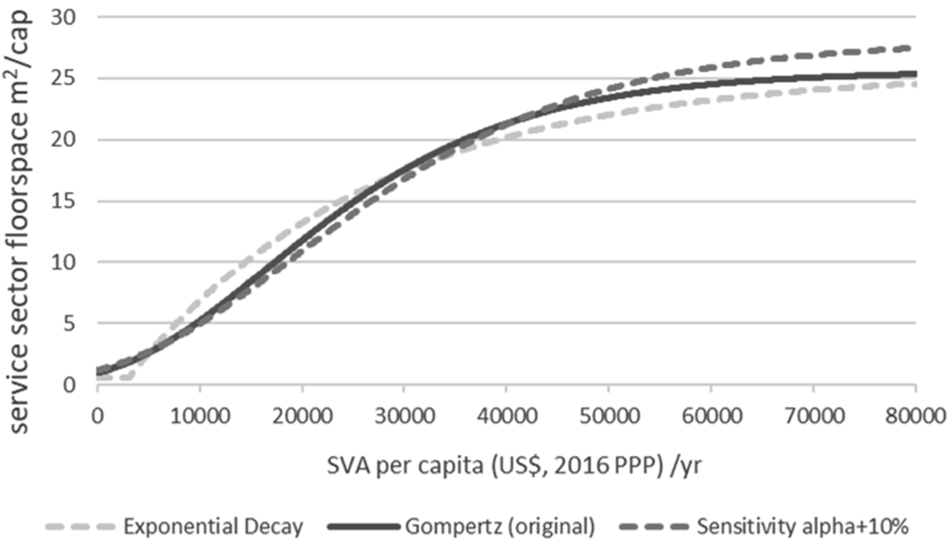

Figure A5.12. *Development of the service sector floorspace demand (expressed per capita).*

A5.6.2 Outcomes of the sensitivity analysis

The outcomes of the sensitivity analysis are displayed in Table A5.5 and Figure A5.13. Table A5.2 shows the changes in 3 different material demand indicators by 2045 (based on a 5-yr moving average) on 6 materials with regards to the regular analysis presented in the main manuscript. Two of the sensitivity variants only have an effect on the demand for materials in service-related buildings, while the other two sensitivity variants also affect the demand of materials in residential buildings.

Since Chapter 5 elaborates on the gap between inflow and outflow of construction materials by the end of the scenario period (2045-2050) in Figure 5.5, the sensitivity analysis also explores the effect of changing assumptions on the mismatch between inflow & outflow (thus, the potential for reaching a circular material flows). We do not display the ratio between inflow and outflow itself, but the extent by which this ratio changes. A positive number means that the mismatch between inflow and outflow becomes even larger, while a negative number means that the outflow of construction materials covers a larger fraction of the new demand for construction materials, compared to the analysis in the main text. Figure A5.13 shows the development of the annual demand for the six materials under investigation for service sector buildings only.

A5.6.3 Discussion on the sensitivity analysis

Looking at the outcomes of the sensitivity data in Table A5.5 it seems that the largest deviations from the regular outcomes arise when assuming global mean material intensities (in kg/m^2). This sensitivity variant can lead to both slightly higher or lower annual material demand by the end of the scenario period, depending on the material and the focus on either residential or service sector buildings.

For service sector buildings, the demand for glass and wood is most affected, given that the most important building type (being the 'other' service-related buildings, a.o. based on governmental and institutional buildings) has a relatively high material intensity for glass and wood according to the literature used (Table 5.2, or Table A5.2). Assuming a mean material intensity for all service-sector buildings leads to a lower value, and thus to a lower demand for wood and glass. On the one hand this may indicate that more data has to be acquired on the use of these materials, especially in service-related building types that are not offices, retail or catering related. However, building materials like wood and glass and aluminium are often non-structural and therefore their material intensities may simply have a wider range, leading to larger deviations based on alternative assumptions.

The effect of assuming a global mean material intensity for residential buildings is most noticeable for concrete and aluminium. This can be mostly explained the relatively high material intensities found for detached houses in China. Both aluminium and concrete intensities for detached houses in China are over 2 times the global mean, thus leading to a considerable drop in material demand in the sensitivity variant. As can be seen in Table A5.5 this translates to a decrease in the global demand of around 18-20% for both materials. As mentioned before, this sensitivity analysis highlights the importance of proper material intensity data, especially for dominant regions like China.

Interestingly, Table A5.5 also shows that a drop in the annual demand for concrete and aluminium in residential buildings under the assumption of a mean material intensity causes an increase of the Inflow-to-Outflow (I/O) ratio at the global level.

Sub selection	Indicator	year	**Mean MI** Mean of all service building types & Mean of all regions for residential buildings	**Normal distr. (lifetimes)** For all buildings, including residential	**Alpha + 10%** Only affects service sector floorspace demand	**Exponential Decay** Only affects service sector floorspace demand
Service sector buildings	Steel demand	2045-‘50	**1%**	*-13%*	*-2%*	**7%**
	Concrete demand	2045-‘50	*-6%*			**7%**
	Glass demand	2045-‘50	*-23%*			**9%**
	Wood dem.	2045-‘50	*-35%*			**9%**
	Aluminium demand	2045-‘50	*-10%*			**8%**
	Copper demand	2045-‘50	**2%**			**7%**
Residential	Steel demand	2045-‘50	*-10%*	**5%**	0%	0%
	Concrete demand	2045-‘50	*-20%*	*-8%*		
	Glass demand	2045-‘50	*-2%*	*-9%*		
	Wood dem.	2045-‘50	**2%**	*-5%*		
	Aluminium demand	2045-‘50	*-18%*	*-10%*		
	Copper demand	2045-‘50	*-0.3%*	*-8%*		
All (Services & Residential)	Steel I/O ratio	2045-‘50	**8%**	**2%**	**0.03%**	**1%**
	Concrete I/O ratio	2045-‘50	**36%**	**2%**	*-0.6%*	**2%**
	Glass I/O ratio	2045-‘50	*-1%*	**1%**	*-1.0%*	**3%**
	Wood I/O ratio	2045-‘50	*-13%*	**2%**	*-0.4%*	**1%**
	Aluminium I/O ratio	2045-‘50	**23%**	**1%**	*-0.7%*	**2%**
	Copper I/O ratio	2045-‘50	**2%**	*-0.3%*	*-1.3%*	**4%**

Table A5.5. *Effects of the four sensitivity variants on selected material demand indicators. See text for a description of the sensitivity variants. ‘I/O ratio’ stands for the Inflow-to-Outflow ratio. Please note that the numbers indicate the change with respect to the same indicators under the regular analysis presented in the main document.* ***Bold*** *numbers indicate an increase in demand or I/O ratio, while red numbers indicate a decrease.*

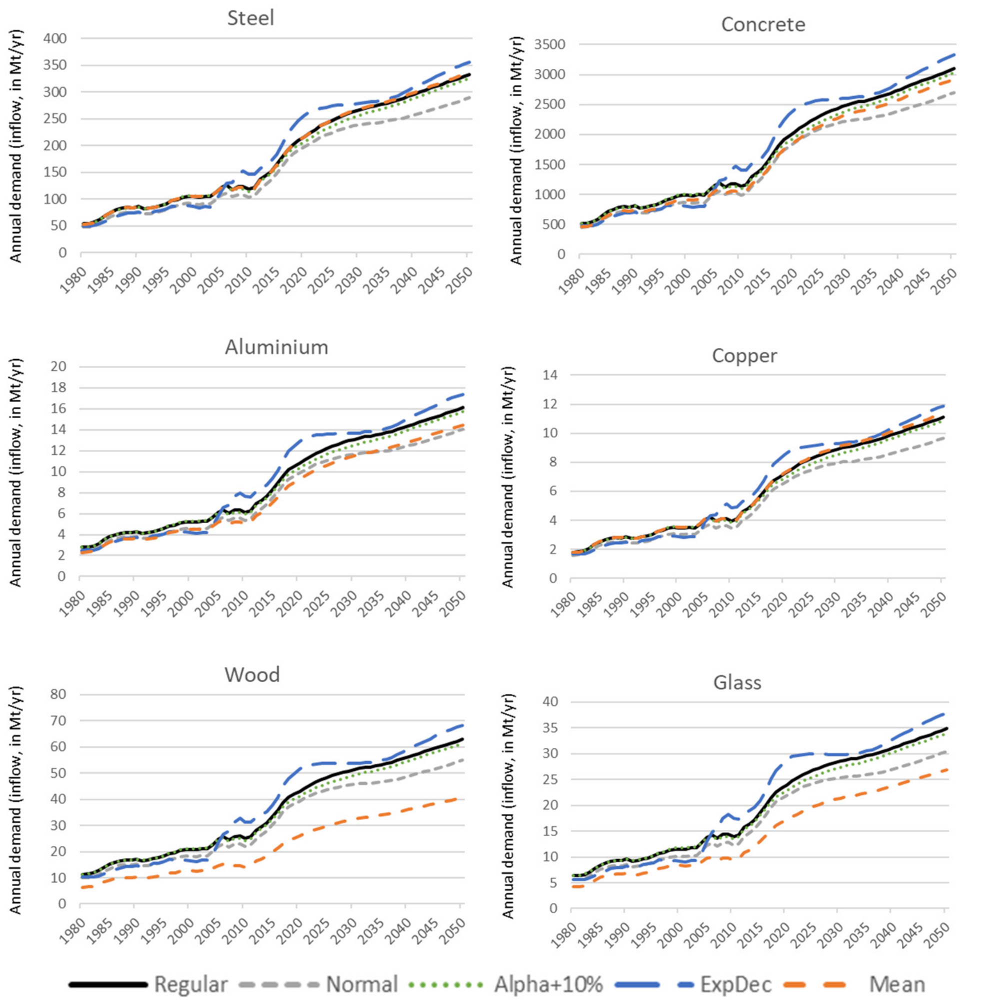

Figure A5.13. *Annual material demand in service sector buildings under the four sensitivity variants (5-yr moving average). 'Regular' indicates the regular (or default) assumptions as described in the main document. 'Normal' refers to the assumption of a normal lifetime distribution as opposed to a Weibull distribution. 'Alpha+10%' is the result of allowing a 10% higher maximum per capita floorspace demand in the regression describing the development of service sector building stock. 'ExpDec' refers to an alternative regression model for service-related floor space demand based on an Exponential Decay function as opposed to a Gompertz function. 'Mean' assumes global mean material intensities; the results for service-related buildings as shown here are the result of assuming a single global material intensity for all service sector buildings, based on the mean in the available data as shown in Figure A5.8.*

So, even though material demand from construction of residential buildings is lower, the gap between inflow & outflow increases. This has to do with a combination of stock dynamics and regional material intensities.

While the demand for concrete is lower in China under the mean material intensity assumptions, so is the Chinese outflow, which due to a relatively short lifetime is considerable towards 2050 as can be seen in Figure 5.4c. At the global level, the inflow (annual demand) of concrete towards 2050 is mostly determined by fast developing regions (see Figure 5.4b). Because the material intensities of most fast developing regions remain mostly the same as in the regular analysis, the inflow remains high in the sensitivity variant, while the outflow (mainly from China) is lower. Thus, leading to an increase in the Inflow-to-Outflow Ratio.

Replacing the Weibull lifetime distribution with a normal distribution has a slightly smaller effect on the annual demand. For service sector buildings it consistently decreases the annual material demand by 13%. As a consequence of a skewed probability density function (PDF) of the Weibull distribution, which leads to faster building replacement and higher inflow, compared to the normal distribution (which therefore has the effect of lowering material demand). This effect is temporary, as we use the same mean lifetimes. The Weibull distribution has a higher spread and consequentially offsets this higher inflow rates due to early decommissioning by lower inflow rates due to a larger surviving fraction at higher building lifetimes, as can be seen in Figure A5.14. A higher spread represents the real-life possibility that a building lasts longer than its envisioned service-life. However, in our model, the continuously expanding commercial stock leads to a larger emphasis on the short term effects than on the long term effects of considering a different lifetime distribution. Assuming a normal lifetime distribution thus causes less service sector buildings to be replaced in the short term.

The effect of implementing a normal lifetime distribution is similar for residential buildings, but there the regional stock dynamics also play a role. Global residential stock increases rapidly during the period 2000-2020, mostly as a consequence of Chinese stock expansion. Since Chinese buildings are assumed to have a relatively short lifetime, a large fraction of the residential cohorts built in this period is already demolished by the end of the scenario period (2045-2050), while most of these buildings are demolished a bit later under the assumption of a normal lifetime distribution, thus leading to an (additional) decrease in demand for most materials in residential buildings compared to the default model. Interestingly, the lower annual demand for materials in residential and service sector buildings does not translate to a smaller gap between inflow and outflow (I/O ratio), which actually increases slightly due to the same stock dynamics.

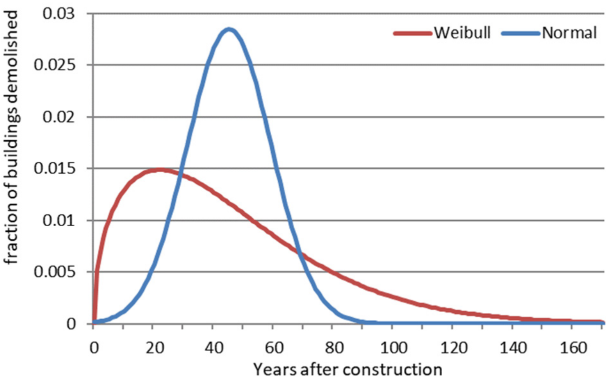

Figure A5.14. *Comparison of building lifetimes in the service sector under two lifetime distributions. The default analysis uses the Weibull distribution, while the sensitivity variant uses the normal distribution.*

The effects of increasing the maximum per capita floorspace demand for service sector buildings may seem counter-intuitive at first sight. One would intuitively expect that a higher maximum floorspace demand would lead to a higher material demand for service sector buildings. However, because of the implementation of this sensitivity variant the entire regression was changed. This means that not only the maximum per capita floorspace demand was increased, but also the beta and gamma parameters of the Gompertz function were changed. Together they lead to a higher demand for service-related floorspace at higher levels of per capita Service Value Added, but to slightly lower demand for service-related floorspace at lower income levels (<40.000 US$ SVA/capita yr^{-1}). Because most regions in the IMAGE model remain below that level, the overall effect is a slight decrease of annual demand for materials in service sector buildings by about 2%.

Finally, the effect of implementing a different regression model for the service sector floorspace demand can also be seen in the right-most column of Table A5.5. Replacing the default Gompertz curve for an Exponential Decay function results in a slight (7-9%) increase in material demand for service sector buildings. This is a consequence of the fact that the Exponential Decay function behaves opposite to the sensitivity variant on increasing alpha. As can be seen from Figure A5.12. This means that the function yields slightly higher per capita demand of floorspace for service sector buildings in the mid-range income regions (with an SVA between 5.000 to 30.000 US$/capita yr^{-1}). As most regions are moving up within this range during the scenario period, the Exponential Decay function leads to slightly increased floorspace demand and a subsequent increase in the use of building materials for buildings in the service sector.

A5.7 Model code

The code of the regression analysis is available in the supplementary information to the original article, the main model is available from Github at https://github.com/SPDeetman/BUMA

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Appendix 6

Based on supplementary information with:
Deetman et al. (2021) - *Projected material requirements for the global electricity infrastructure – generation, transmission and storage* - Resources, Conservation and Recycling, Vol. 164, p. 105200 - https://doi.org/10.1016/j.resconrec.2020.105200

A6.1 Detailed assumptions on electricity generation capacity

The development of generation capacity is one of two main drivers of our material model and is given as an output of the IMAGE/TIMER model [1] based on the SSP2 scenario used in this study [2]. Corresponding to the total global generation capacity as provided in the main text (Figure 6.3), Figure A6.1 provides some more regional detail with respect to the development of generation capacities by technology.

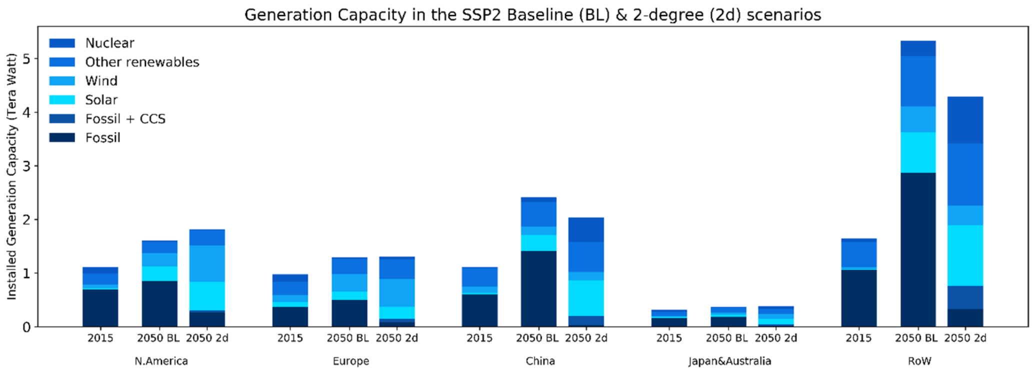

Figure A6.1. *Electricity Generation Capacity in the SSP2 Baseline and 2-degree scenarios according to the IMAGE model [1], [2]. More information on assumptions underlying the SSP scenarios, such as the development of population, economic indicators, land-use etc. can be found in the online at https://tntcat.iiasa.ac.at/SspDb based on [3].*

With generation capacity given, we came up with the corresponding material use as detailed in the results of the main manuscript. To do so, we required data on the materials per unit of generation capacity for each of the 27 generation technologies in the IMAGE/TIMER energy model, which is given in Table A6.2, below.

Even though the IMAGE/TIMER uses a vintage stock model based on fixed lifetimes to derive annual additions to stock (newly installed generation capacity) as described in [4], we also wanted to provide the outflow of scrap materials from electricity generation technologies, so we decided to apply a dynamic stock model, as part of an open source software platform developed & described by [5], to derive both the inflow and outflow of materials. The lifetimes are derived from [4], and are applied in combination with a standard-deviation of 0.214 times the mean lifetime, based on [6]. This translates to a relatively low spread in the lifetime distribution, which is typical for industrial capital as it is subject to standard maintenance & decommissioning contracts.

Technology	Technical lifetime (yrs)
Solar PV	25
CSP	25
Wind onshore	25
Wind offshore	25
Hydro	80
Other Renewables	30
Nuclear	60
Fossil Fuel Based	40

Table A6.1. *Technical lifetime assumptions for generation technologies, based on [4]. These are used in the calculation of the inflow and outflow of materials.*

A6.2 Electricity transmission, the grid

A6.2.1 Grid lengths

Using a preprocessed version of Open Street Maps for the year 2016, available from http://osm2shp.ru/#Data and the power_ln files, we extracted the length of the grid lines according to the IMAGE region definition detailed in Appendix 1. Because underground lines are typically not identified or distinguished, the resulting line lengths were interpreted as being overhead high voltage (HV) lines, given their typically prominent visibility. Unless this was counter-indicated by any of the sparse national statistics, as displayed in Table A6.4 below. It shows that the OSM data provides a reasonable estimate of HV line lengths in quite a few cases. However, it also shows cases of possible overreporting (e.g. Ukraine) or underreporting (e.g. China) compared to national studies.

Table A6.2. *Material intensities for electricity generation technologies in ton/MW peak (or kg/kW peak capacity), corresponding to the 27 generation technologies in the IMAGE/TIMER energy model [4]. * For offshore wind farms, more information was available on steel monopile base structures, we assumed that only 10% of the base structures are composed of concrete monopiles. ** assumed to be the same as an onshore windmill. Material intensities for copper, cobalt and neodymium are based on the medium estimates found in [7].*

						Based on [7]			
Technology	Con-crete	Steel	Al	Pb	Glass	Cu	Co	Nd	Sources & Comments
Solar PV		150	10.2	0.122		6.34			[8–11]
CSP	1351.8	576	5.50		156	3.15			[8,11–13]
Wind onshore	434	121	0.87			2.73		0.02	[8,14–21]
Wind offshore	509*	158	1.44			5.57		0.16	[8,9,17,19,20,22–24]
Hydro	2833	71		0.005		1.70			[11,25,26] & 10% run-off river
Other Renewables	1026	216	3.6	0.03	31	3.90		0.04	Assumed: Average of above
Nuclear	235	43	0.08	0.034		0.76	1.2E-4		[11,27], table 24 & 25 in [28]
Conv. Coal	352.8	84.6	0.504			1.15	0.12		[29–31]
Conv. Oil	213.4	72.9	0.6			0.76	0.07		[32] *or avg. of Conv. Coal/NG CC*
Conv. Natural Gas	43.0	4.0	0.4			0.38	0.02		[33] *or avg. of Conv. Coal/NG CC*
Waste	213.4	72.9	0.6			0.76	0.07		Assumed: same as Conv. Oil
IGCC	165	34.9	0.504			1.15	0.12		[12] or if no data: same as Coal
OGCC	213.4	72.9	0.6			0.76	0.07		Assumed: same as Conv. Oil
NG CC	64.6	29	0.65			1.05	0.02		[26,33]
Biomass CC	89.2	33.4	0.3			0.76	0.07		[12,26]
Coal + CCS	352.8	109.2	0.504			1.63	0.12		[31], or Conv. Coal if no data
Oil/Coal + CCS	213.4	94.1	0.6			1.45	0.07		Based on 29% more steel & [31]
Natural Gas + CCS	43.0	5.2	0.4			1.07	0.03		Based on 29% more steel & [31]
Biomass + CCS	89.2	43.1	0.3			1.45	0.07		Based on 29% more steel & [31]
CHP Coal	352.8	84.6	0.5			5.59	0.12		Mn: added 10% of CHP in [34]
CHP Oil	213.4	72.9	0.6			5.21	0.07		Mn: added 10% of CHP in [34]
CHP Natural Gas	43.0	4.0	0.4			4.82	0.02		Mn: added 10% of CHP in [34]
CHP Biomass	243.8	6.2	0.05			2.94	0.07		Table 8.3 in [35]
CHP Coal + CCS	352.8	109.2	0.5			6.28	0.12		Assumed: Same as CCS variant
CHP Oil + CCS	213.4	94.1	0.6			5.90	0.07		Assumed: Same as CCS variant
CHP Nat. Gas + CCS	43.0	5.2	0.4			5.52	0.03		Assumed: Same as CCS variant
CHP Biomass + CCS	243.8	43.1	0.3			3.63	0.07		Assumed: Same as CCS variant

Table A6.3. *Projected global average material intensities of the generation capacity (in ton/MW installed capacity) for 7 materials. These are a result of combining the changes in installed capacity (from IMAGE, see Figure 6.3a in Chapter 6) with the material intensities by technology as provided above (Table A6.2).*

	2015	2050, Baseline	2050, 2-degree
Steel	65	84	101
Aluminium	0.6	1.7	2.8
Concrete	859	691	741
Glass	0.10	1.5	3.8
Cu	1.7	2.2	2.9
Nd	0.0015	0.0044	0.006
Co	0.041	0.041	0.012
Pb	0.007	0.017	0.035

This highlights the importance of further improving the data in the lengths of transmission lines. For now, however, the data used was deemed adequate, given that we were able to check the majority of the global circuit kilometers against at least one national study. In fact, only 12.6% of the total global circuit length used in this study (Table A6.4) could not be validated against national studies. This indicates that the possible underestimation or (most likely) overestimation of the data for these countries represents a small fraction of the global line length.

Once we derived the HV voltage line lengths from Table A6.4, we continue by calculating the length of lower voltage transmission lines based on a static ratio between high voltage and medium voltage (MV) or low voltage (LV) according to [37] and [38] as detailed in Table A6.5. It shows that national studies provided more information on the MV network than on the length of the LV network. It is difficult to determine whether this is a realistic representation, or a definition issue due to the use of different sources for example. So, this might be an area for future research.

A6.2.2 Undergrounding of power lines

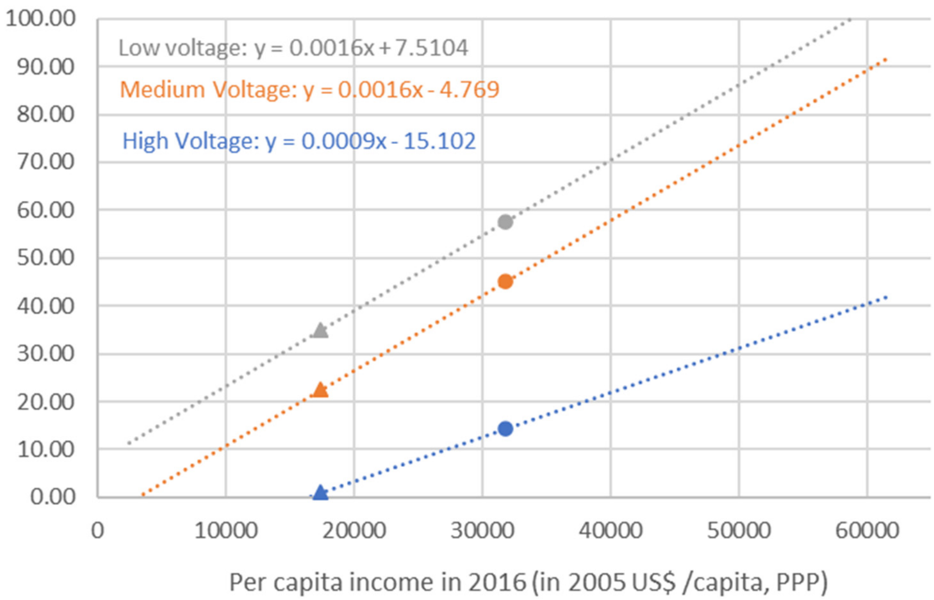

Figure A6.2. *Assumed relation between income levels and percentage undergrounding of transmission lines of different voltage levels, based on the indicated data points for Western Europe (circles) and Eastern Europe (triangles) as reported by* [37].

Table A6.4. *Length of grid lines in several studies, in km. Data in the first column is copyrighted by OpenStreetMap (OSM) contributors and available from https://www.openstreetmap.org. If available, the second column gives an indication of the grid length from national studies. Similar to [38] we assume that most of the OSM coverage represents high-voltage lines (overhead + underground). Highlighted cells indicate the numbers used in this study (average of the highlighted cells per row). Data was selected (highlighted) based on the following rationale: by default, we use the average between our own calculations and the Arderne study, unless the study by Arderne et al. reported a HV line length more than 3 times the value from national statistics (indicated with an asterisk *), in that case we chose to ignore the values from Arderne (as we expected over-reporting of the HV network in these cases) and incorporate the national estimates in the average used. In other cases where we suspected over reporting of HV lines in the OSM data (USA, Europe, India & Oceania), we used the two lowest available values. In cases where we expected under-reporting of HV line lengths (Mexico, China, Korea, Indonesia & Rest of South Asia), we chose to ignore the two highest available estimates. For National studies, voltage levels are defined as follows: LV: <1kV, MV: 1-135kV, HV: >135kV. For the study by Arderne et al. Voltage classifications deviate slightly for the Medium & High Voltages (LV: <1kV, MV: 1-75 kV, HV: >75kV), which may explain slightly higher numbers for HV transmission line lengths.*

	Open Street Maps	**National Studies**			**Nature Scientific Data**		
Sources:	*Calculation by the Authors*	*globaltransmission.info,* [36, 37]			*(Arderne at al.)*		
Year of data:	*2016*	*2013-2017*			*2019*		
	HV	**HV**	**MV**	**LV**	**HV**	**MV**	**LV**
Canada	95,100	96,500	37,500		114,000	180,700	713,800
USA	641,400	441,900	171,900		647,700	959,800	8,647,400
Mexico	48,000	51,200	52,900	749,400	49,600	171,000	1,666,600
Central America	8,900	7,600	8,166		16,700	79,800	626,700
Brazil*	94,335	67,200			232,900	370,700	3,105,800
Rest of South America	66,800				111,300	335,600	2,462,700
Northern Africa	86,700				96,300	150,800	2,012,500
Western Africa	20,700				41,100	232,500	130,800
Eastern Africa	18,900				27,200	90,800	41,300
South Africa*	54,200	15,200			57,200	89,600	58,600
Western Europe	560,300	251,200	2,857,800	4,894,000	491,500	706,000	8,871,000
Central Europe	165,100	67,100	716,100	1,072,600	175,700	291,200	2,662,900
Turkey	45,100				55,200	171,400	1,057,000
Ukraine region*	126,400	10,400			131,500	130,300	1,301,300
Central Asia	40,600				60,600	156,100	916,100
Russia Region*	322,900	69,200			388,800	631,300	2,783,600
Middle East	123,100	123,400	94,500		135,900	337,900	2,516,300
India	319,800	273,500	298,600		422,400	693,100	604,400
Korea	9,300				14,400	36,400	536,100
China	183,900	646,500			284,500	827,000	17,508,600
South Eastern Asia	22,700				68,900	237,500	2,817,800
Indonesia Region	12,100				24,100	143,500	3,324,200
Japan*	43,800	18,800			62,700	68,600	2,122,800
Oceania	57,900	26,100			73,500	73,900	651,100
Rest of South Asia	18,700	21,900	12,200		50,700	142,700	1,952,400
Rest of Southern Africa	15,200	16,400			50,900	137,700	36,300

Table A6.5. *Transmission line length ratios. The values indicate the length of Medium Voltage lines (MV) or Low Voltage (LV) per km of High Voltage (HV) line. If multiple values are available, we apply an average. See Table A6.4 for sources and the lengths of HV lines. This table excludes regions with expected under-reporting or over-reporting as discussed with Table A6.4, except when a national statistics on MV/HV or LV/HV ratio were available.*

Region	**Km MV per km HV line**		**Km LV line per km HV line**	
Source	National studies	Arderne et al. [38]	National Studies	Arderne et al. [38]
Canada	0.39	1.58		6.3
USA	0.39	1.48		13.4
Mexico	1.03	3.45	14.6	33.6
Central America	1.07	4.77		37.5
Rest of South America		3.02		22.1
Northern Africa		1.57		20.9
Western Africa		5.66		3.2
Eastern Africa		3.34		1.5
Western Europe	11.4	1.44	19.5	18.0
Central Europe	10.7	1.66	16.0	15.2
Turkey		3.10		19.1
Central Asia		2.58		15.1
Middle-East	0.77	2.49		18.5
India	1.09	1.64		1.4
South East Asia		3.45		40.9
Rest of south Asia	0.56	2.82		38.5
Rest of Southern Africa		2.70		0.7
Average	3.04	2.65	16.7	18
Average used (for other regions)	**2.85**		**17.35**	

A6.2.3 Substations and transformers

To incorporate additional electricity transmission infrastructure, our analysis covers the material contents of substations and transformers. To do so, we first needed to derive the demand for these elements in units per kilometer of transmission line, specified for three different voltage levels as detailed in Table A6.6, below.

Table A6.6. *Assumptions on the number of substations and transformers per km of transmission line.*

(units/km)	**High**	**Medium**	**Low**
Sources →	[39]	[39,40]	[40]
Substations	0.0169	0.085	1.107
Transformers	0.0532	0.103	1.107

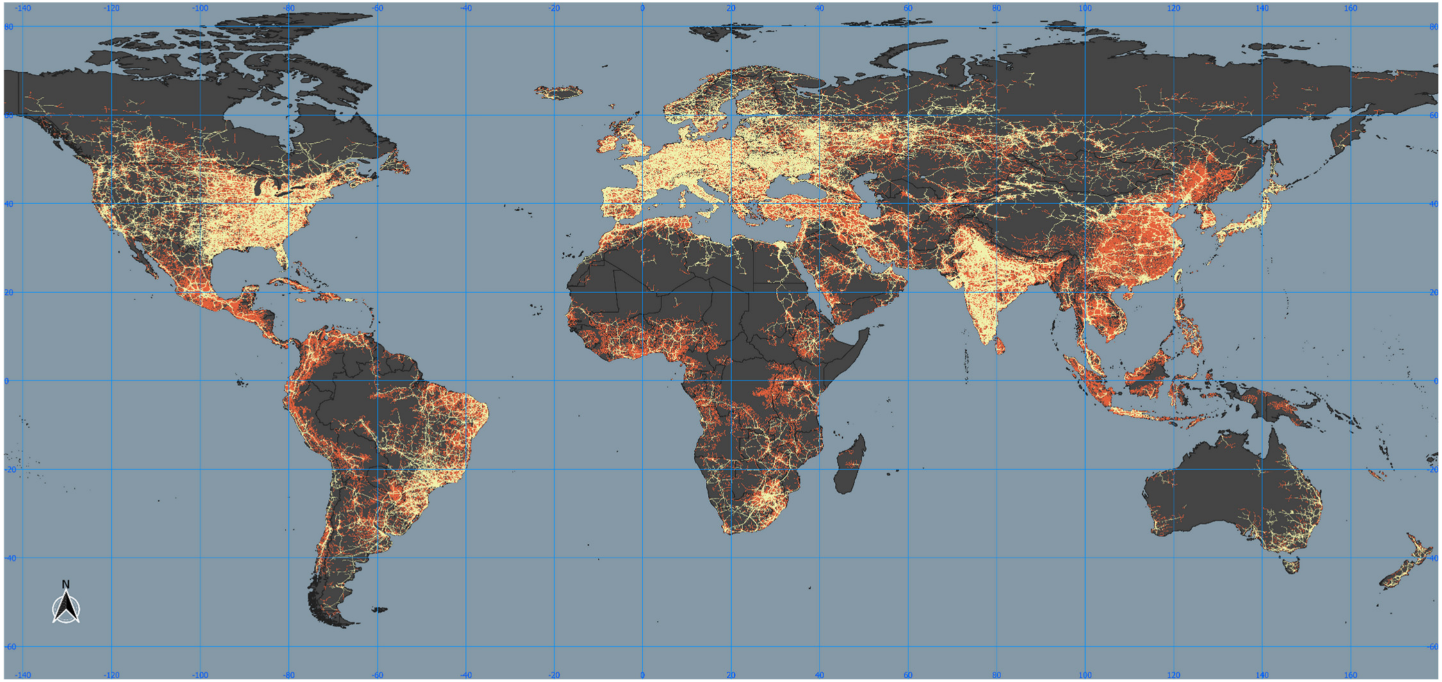

Figure A6.3. *Global High Voltage & Medium Voltage Transmission Lines. Data displayed here is based on the work by Arderne et al. [39], High Voltage lines are based on OpenStreetMap and displayed in yellow, Medium Voltage lines are modelled by Arderne et al. as published online at https://gridfinder.org/*

A6.2.4 Lifetimes of grid elements

To account for the lifetimes of power lines, substations and transformers, we applied the same dynamic stock model as described in section A6.1. We even apply the same standard-deviation, but on grid-specific mean lifetimes as detailed in Table A6.7.

Table A6.7. *Mean lifetimes applied to the grid elements. Numbers are based on* [39–42].

	Lifetime (in years)
transformers	30
lines	40
substations	40

A6.2.5 Material intensities of grid elements

Now that we have an indication of the length of the transmission line as well as the number of substation and transformers, we apply a fixed, but voltage-level specific, material intensity for each of the grid elements in Table A6.8 and Table A6.9, below.

Table A6.8. *Material intensities for substations and transformers (in kg/unit). These numbers are derived using our interpretation of data from* [39,40,42].

kg/km	Concrete	Steel	Aluminium	Cu	Pb	Glass
HV overhead	209138	52266	12883			1097
HV underground	17500			11650	14050	
MV overhead		802.3		1488		
MV underground		0	823.6	662.9		
LV overhead		0	981			
LV underground		177	531			

Table A6.9. *Material intensities for power lines, including towers/poles (in kg/km line). These numbers were derived using the following sources:* [40,41,43].

kg/unit	Concrete	Steel	Aluminium	Cu	Glass
Hv Substation	123900	14652	33204	4611	0.05
Mv Substation	127021	1815	1228	279.2	
Lv Substation	476	38	1228	1	
Hv Transformer	648000	296000	497	76047	
Mv Transformer	46826	22659	21	6877	
Lv Transformer	176	480	85	13	

A6.3 Electricity storage

A6.3.1 Electricity storage demand

Total electricity storage demand is the second main driver of the material model described in the main text and is provided as an output from the IMAGE model. Within the IMAGE model, it is calculated using a relation between the penetration of wind and solar in the mix as shown in Figure A6.4. Here, we show the demand for storage capacity expressed as a fraction of the installed generation capacity as an (unweighted) average of the 8 region specific residual load duration curves (RLDCs) available from [44]. It is important to note that these RLDCs were constructed using a fixed storage price based on flow-batteries of 100$/kWh and a round-trip efficiency of 76% [44]. This is a rather low price estimate compared to our price assumptions as detailed in Table A6.13, which might mean that the assumed storage demand is on the high side.

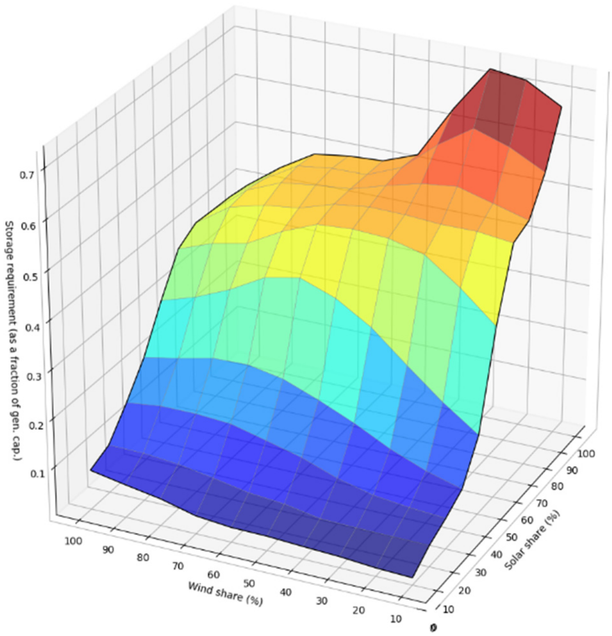

Figure A6.4. *Storage demand as a fraction of peak generation capacity, given different levels of solar and wind energy penetration, based on data from [44]. The numbers are an (unweighted) average of multiple regions, and only serve as an illustration of the approach to determining storage demand. Combined solar and wind shares of more than 100% are possible, because at high renewable penetration, peak demand can only be supplied by a surplus generation capacity.*

A6.3.2 Pumped hydro storage

Our analysis assumes a tiered approach to electricity storage deployment, in which pumped hydro storage is the first and default option. We use projections on pumped hydro storage availability according to [45], as shown in Figure A6.5.

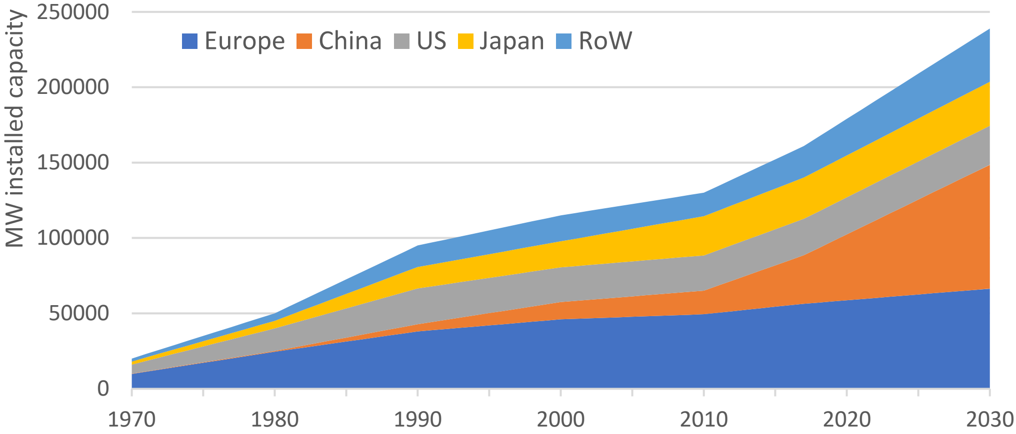

Figure A6.5. *Expected development of Pumped Hydro Storage availability (in MW installed capacity) according to [45]. We assume a regional disaggregation according to the IMAGE relative hydro-power capacity, and a continued growth of pumped hydro capacity according hydro-power expansion within regions [46].*

A6.3.3 Electricity storage in electric vehicles

In order to determine the availability of electricity storage in the electric vehicle (EV) fleet we first determined the number of cars based on the IMAGE model projections described by [47] and a dynamic stock model, including lifetime assumptions, in the same way as described by [7]. Secondly, we determine the average storage capacity in current electric cars based on a review of currently available plugin- and full battery EV models according to ev-database.org, as can be seen in Table A6.10.

The average battery capacity of full battery electric vehicles (BEVs) and plugin hybrid electric vehicles (PHEVs) found in Table A6.10. is used to represent the recent situation and applied for the year 2018. However, battery density is expected to increase, while battery costs are expected to go down over the coming years (see Table A6.13), which could lead to a variety of possible changes to the available Vehicle to Grid (V2G) storage capacity over time. Here, we assume that the weight (and not necessarily the costs) are the limiting factor for battery deployment in EVs. This means that an increase in battery density would allow for more storage capacity, without affecting the weight of the battery unit or the car. We therefore apply a fixed battery weight, which results in a changing total battery capacity per vehicle as can be seen in Figure A6.6. The figure also indicates the assumed penetration rate of vehicle to grid as a technology, which increases from 0% for 2025 (based on [48]) before reaching the maximum available percentage of the storage capacity of 10% (PHEVs) or 12% (BEVs) by 2040. Reiterating from the main text that these model settings may perhaps look optimistic regarding the adoption of vehicle to grid as a common practice, but is rooted in the idea that most of the perceived obstacles to its adoption (such as 'range anxiety') [49] are expected to become less of a problem given the expected increase in battery capacity as indicated in Table A6.13.

Table A6.10. *Battery capacity of recent BEV and PHEV car models, according to ev-database.org (accessed 11-11-2019). The average from all models is used to represent the current battery capacity in our analysis.*

BEVs			PHEVs		
Brand	**Model**	**Capacity (kWh)**	**Brand**	**Model**	**Capacity (kWh)**
Tesla	Model3, LR, Dual	75	Porsche	Panamera Sport Tur. 4 E-hybrid	14.1
Mercedes	EQC 400 4MATIC	85	Porsche	Cayenne E-hybrid	14.1
VW	e-Golf	35.8	Land Rover	Rover Sport p400e	12.4
Audi	e-tron 55 quattro	95	BMW	225xe iPerformance	7.6
Tesla	Model3, std range plus	55	Mitsubishi	Oultander	13.8
Kia	e-Niro	64	Mini	Countryman Cooper SE All4	7.6
MG	ZS EV	44.5	Hyundai	IONIQ	8.9
Nissan	Leaf	40			
Nissan	Leaf e+	62			
Tesla	Model3, LR, Perform.	75			
Hyundai	IONIQ	38.3			
BMW	i3 120Ah	42.2			
Jaguar	I-Pace	90			
Renault	Zoe ZE50 R110	55			
Hyundai	Kona	67.1			
Tesla	Model S	100			
Opel	Ampera-e	60			
Renault	Zoe ZE50 R135	55			
Tesla	Model X, LR	100			
Tesla	Model S, Perform.	100			
Nissan	e-NV200 Evalia	40			
Citroen	C-Zero	16			
BMW	i3s 120Ah	42.2			
Renault	Kangoo Maxi ZE33	33			
Peugeot	iOn	16			
Tesla	Model X, Perform.	100			
Peugeot	Partner Tepee	22.5			
Average		**59.6**	**Average**		**11.2**

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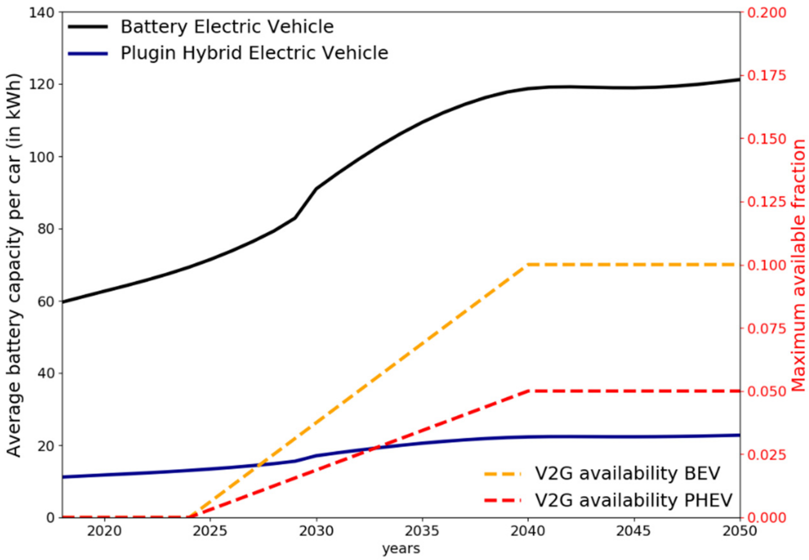

Figure A6.6. *development of EV & PHEV storage capacity (kWh), given a fixed battery weight assumption. Due to increased energy density of EVs, the average battery capacity will double from about 60 kWh to 120 kWh by 2040. The secondary axis displays the slow adoption of vehicle to grid technology from 2025 onward, ensuring a maximum of 12% of the vehicles battery capacity is available for energy storage.*

A6.3.4 Dedicated storage demand

Dedicated storage demand is the result of the tiered approach of the regional availability of pumped-hydro storage and electric vehicles for vehicle-to-grid storage as described in the main text. The sensitivity to regional circumstances is depicted in Figure A6.7. Which shows that in many regions there is no demand for additional storage capacity, even in the SSP2 2-degree climate policy scenario, because the growth of pumped hydro and electric vehicle availability is enough to fulfill the total storage demand. Only in the regions labeled as 'Rest of the World' a dedicated storage capacity is required. The resulting regional deployment of dedicated storage capacity is detailed in Figure A6.8.

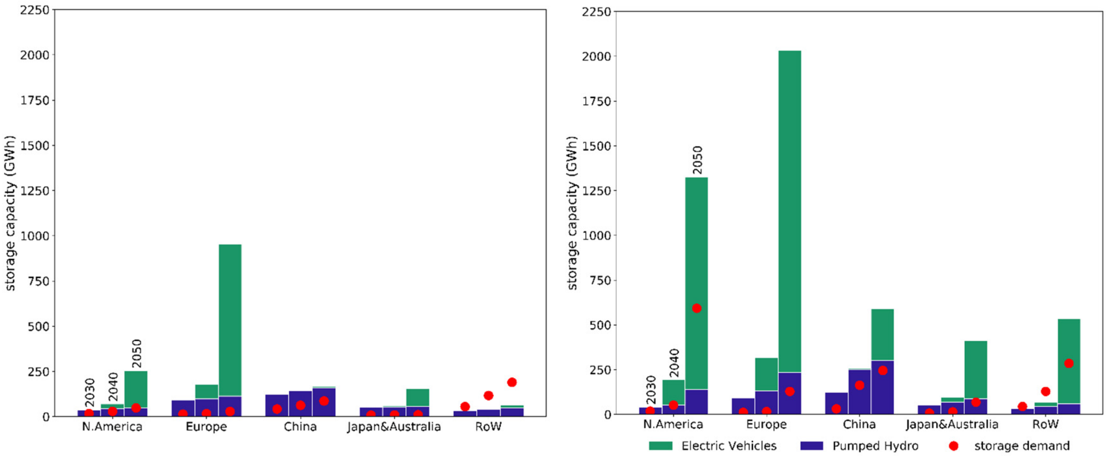

Figure A6.7. *Demand & supply of electricity storage capacity in 2030, 2040 and 2050, in 5 world regions, under the SSP2 Baseline (left) and under a climate policy scenario (SSP2 2-degrees, right). RoW: Rest of the World.*

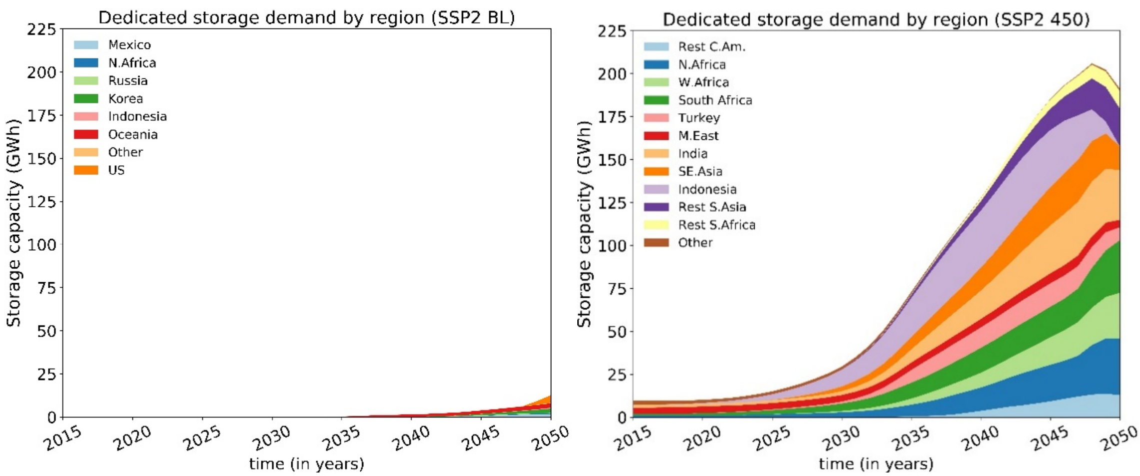

Figure A6.8. *Total demand for dedicated storage, by region. Results are given for the SSP2 baseline (left) and the SSP2, 2-degrees climate policy scenario (right).*

A6.3.5 Market shares of storage technologies

Once the size of the 'dedicated' storage demand has been determined as the remainder of the total storage demand minus the available capacity in pumped hydro and EVs, we need to determine the market share of individual technologies to fulfill the last tier of storage. This is done based on the basis of the lowest costs per kWh (cycled, not capacity) using a multinominal logit model, as detailed in the main text. Calibration of the logit parameter uses cost data from Table A6.13 and is checked against data by the IEA for the year 2016 [50] (p. 63), leading to a logit parameter (λ) setting of 0.2. A further set of cost penalties was applied to enhance the fit with the available literature by the IEA, as shown in Figure A6.9. These penalties are reduced towards 2030, but the implied cost-reduction of lithium- and nickel-based batteries is maintained beyond 2030 (due to an expected second hand market for batteries from former EVs as stationary storage). The combination of a low logit parameter and the need for high cost penalties (e.g. high for Compressed Air) needed to match historic markets suggest that the energy storage sector does currently not deploy technologies according to the cost-optimality principle.

Table A6.11. *Cost penalties (multipliers) applied to the costs of some energy storage technologies. These multipliers are applied to the costs in Table A6.13 in order to ensure a reasonable representation of the current market.*

	2018	2030
Flywheel	1.5	1
Compressed Air	18	1
NiMH	0.6	0.4
LMO	0.5	0.4
NMC	0.5	0.4
NCA	0.5	0.4
Zinc-Bromide	3	1
Vanadium Redox	3	1
Sodium-Sulfur	1.5	1
ZEBRA	1.5	1

The development of the market shares over time, of both the newly installed storage capacity as well as the resulting development of the technology shares within the stock are given in Figure A6.10a &b, below. The share of the stocks is based on two additional model assumptions, being: 1) that all dedicated electricity storage pre-1990 is based on deep cycle Lead-Acid batteries, and 2) a changing lifetime assumption by technology as detailed in Table A6.12.

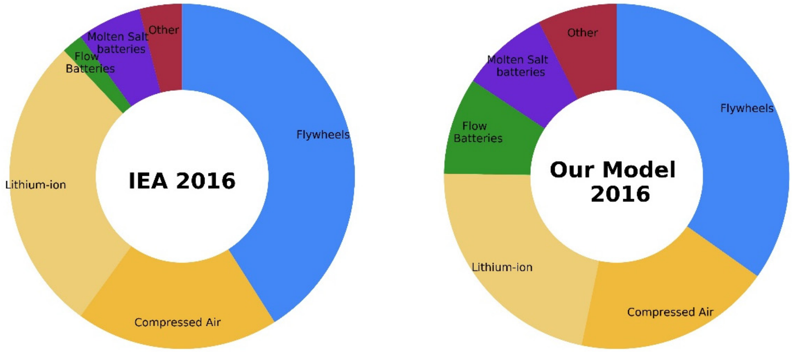

Figure A6.9. *Current market fit of our model compared to IEA 2017* [50].

Table A6.12. *Lifetime assumptions for storage technologies used in dedicated electricity storage (in yrs). The lifetime is based on 150% of the indicated cycle life given in Table A6.13, assuming a diurnal use or the shelf-life in years given by* [51] *(whichever comes first). The cycle life is extended by 50% to represent the idea that dedicated energy storage is subject to enormous capital investments and the fact that the cycle life is determined using the technical lifetime, beyond which about 80% of the storage capacity remains usable.*

	Lifetime (yrs)	
	2018	**2030**
Flywheel	20	30
Compressed Air	50	50
Hydrogen FC	4.1	9.6
NiMH	4.1	6.2
Deep-cycle Lead-Acid	6.2	12.3
LMO	2.1	3.3
NMC	6.2	8.2
NCA	2.1	3.3
LFP	10.3	20
LTO	15	23
Zinc-Bromide	12	20
Vanadium Redox	10	17
Sodium-Sulfur	17.0	22.0
ZEBRA	15.0	22.0
Lithium Sulfur	2.15	4.11
Lithium Ceramic	2.00	10.00
Lithium-air	2.98	4.44
PHS	60	60

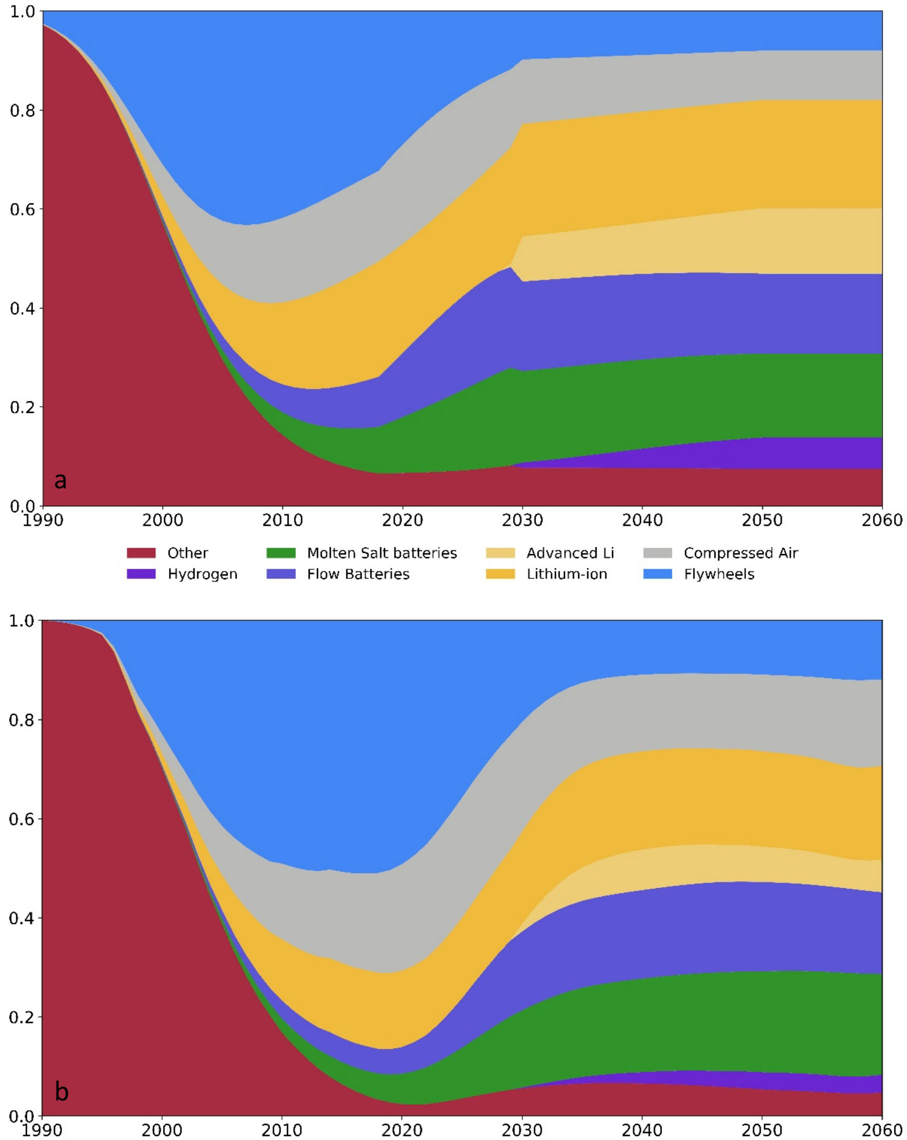

Figure A6.10a-b. *Market shares of the dedicated electricity storage technologies (a) & shares of the technologies within the stock (b).*

Now that the share of the dedicated electricity storage technologies (both stock & purchases) is known, they can be multiplied with the weights (using energy densities in Table A6.13) and the weight composition as shown in Table A6.14.

		Technology ↓	Energy density		(dis)charge cycles		Investment costs		Round trip efficiency		
		Unit →	Wh/kg		Nr. of cycles before end of life (@80% cap.)		USD/kWh (storage capacity)		%		
Grouping		Time →	2018	2030	2018	2030	2018	2030	2018	2030	Sources
Batteries	Nickel	NiMH	75	100	1000	1500	300	300	70%	80%	52,53
	Lead-acid	Deep-cycle Lead-Acid	40	40	150	150	150	150	70%	80%	51
	Li-ion	LMO	121	160*	500	800	400	225	96%	98%	51,54
		NMC	185	283*	1500	2000	420	225	96%	98%	51,54,55
		NCA	230	300*	500	800	350	200	96%	98%	51,54
		LFP	120	212*	2500	5000	580	230	94%	96%	51,54,55
		LTO	65	211	7500	20000	800*	400*	98%	99%	51,54,56,57
	Flow	Zinc-Bromide	40	67	10000	10000	538	250	70%	80%	51,58,59
		Vanadium Redox	25	35	15000	15000	475	131	70%	80%	51,58,60
	Molten-salt	Sodium-Sulfur	200	250	6000	8000	463	145	80%	85%	51,61
		ZEBRA	186	300	4500	7500	525	110	84%	87%	59,62
	Lithium-metal (/advanced Li)	Lithium Sulfur	328	750	523	1000	375	250	91%	98%	63,64
		Lithium Ceramic	299	740	600	6000	800*	110	70%	90%*	65,66,67
		Lithium-air	200	250	725	1080	700	275	50%	85%	68,69,70,71,72
Other	Mechanical	Pumped-Hydro	1	1	50000	50000	63	63	80%	80%	51
		Flywheel	100	100	112500	140000	4500	2000	85%	88%	51,73
		Compressed-Air	4	5	30000	40000	86	45	52%	63%	51,73
	Fuel-cells	Hydrogen FC	157	157	1000	2333*	747	133	25%	45%	51,74

Table A6.13. *Cost and performance indicators for electricity storage technologies between 2018 and 2030, based on various sources. * Some values indicated with an asterisk include estimates by the authors. Only highlighted battery types are assumed to be available for mobile applications such as electric vehicles.*

Grouping		Technology	Steel	Al	Plastics	Glass	Cu	Co	Ni	Pb	Mn	Nd	Sources & comments
Batteries	Nickel	NiMH	10%	0.26%	21%		1.77%	0.26%	44.3%		0.26%	4.7%	[52]
	Lead-acid	Deep-cycle Pb-Acid			10%	2%				61%			[34]
	Li-ion	LMO	21.5%	3.7%	8.4%		10 %				16.7%		[75]
		NMC	21.5%	3.7%	8.4%		10%	7.6%	7.6%		7.1%		[75]
		NCA	0.7%	24.4%			12.5%	3.1%	9.4%		2.9%		[76]
		LFP	14.1%	5%	10%*		5%						[77]
		LTO	4.5%*	14%	6.2%						7.7%		[78] and assuming: same wt% of anode as in LFP & Pure LTO as in [79]
	Flow	Zinc-Bromide	15%		4.3%		1%						[60]
		Vanadium Redox	10.6%		4.3%		0.8%						[60]
	Molten-salt	Sodium-Sulfur	30.4%		2.2%		3.5%						[80]
		ZEBRA	30.4%	11.1%	2.2%		3.5%		17.6%				[59]
	Lithium-metal (/advanced Li)	Lithium Sulfur	0.53%	18.4%	4.1%		7.82%						[64]
		Lithium Ceramic	0.53%	18.4%	4.1%		7.82%		16.8%		1.96%		Assumed: same as Li-S, but with NMC811 as cathode & wt% acc. to [78]
		Lithium-air			30.6%		9.4%						[69]
Other	Mechanical	Pumped-Hydro	94.8%	0.32%			2.17%		1.94%				Additional materials comp. to a hydro dam (Table S.2) based on [81]
		Flywheel	60.9%	20.2%			1.36%					0.64 %	[82] and own calculations based on: [83], [84] and [85]
		Compressed-Air	98.4%	0.77%			0.8%						[34,82]
	Fuel-cells	Hydrogen FC	96.2%	0.47%			1.77%						Table 34 in [34]

Table A6.14. *Weight composition (as a % of the total weight) of electricity storage technologies. Values indicated with an * were derived using assumptions by the authors.*

A6.4 Comparison to other sectors

In order to get a feeling for the importance of the electricity sector compared to other material demand sectors, such as buildings, we compare the growth rates of these sectors in Figure A6.11. It shows that the rate of expansion of infrastructure in the electricity sector towards 2050 is larger than the growth in housing stock, and comparable to the rate of growth in commercial buildings.

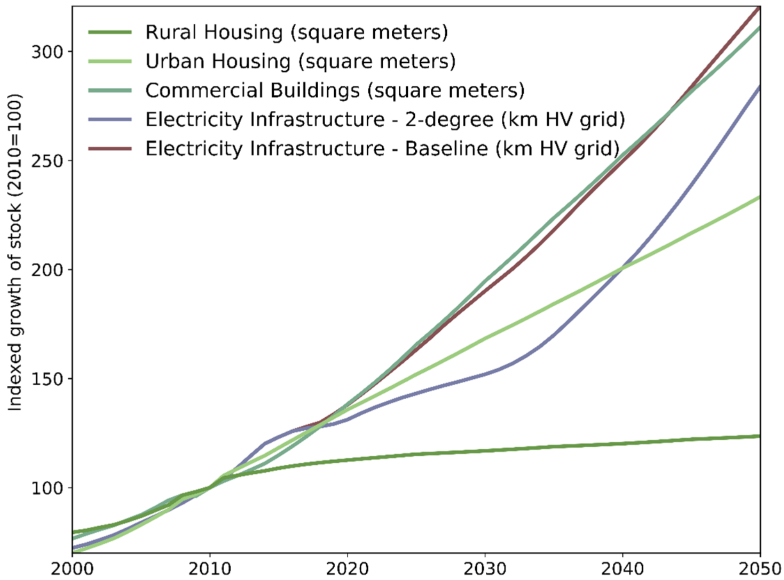

Figure. A6.11. *Indexed growth of buildings and electricity related infrastructure (2010=100). The indicators are based on the total kilometers of high-voltage (HV) grid lines discussed in this study, the development of floorspace in buildings is based on [86].*

A6.5 Sensitivity analysis

In order to better understand the uncertainties regarding some of the assumptions and their impact on the outcomes of the presented model, we perform a sensitivity analysis. In addition to the default model outcomes presented in the main text, we define three alternative model setting to represent a range of possible future developments with relevance to the material use in the electricity sector. We focus on three key uncertainties, being 1) the development & deployment of electricity storage, 2) the extent to which the transmission infrastructure requires expansion, and 3) the uncertainty regarding future material composition of several technologies. We start by explaining the alternative model settings on transmission and storage in conjunction.

A6.5.1 Alternative assumptions on drivers: transmission and storage

It is often highlighted that high shares of variable renewable energy such as solar and wind pose a challenge to relialably provide electricity to consumers, due to their intermittent nature [87,88]. Backup generation capacity, energy storage technologies, grid expansion and load-shifting practices are typically propsed as options to stabilize the grid, because they may all help to alleviate the temporary imbalance between electricity supply and demand. The difficulty with defining scenarios on future energy systems is that it remains highly uncertain to which extent these stabilizing technologies will be deployed, given that they may be used interchangeably and depending on local conditions.

To account for a wider range of possible future developments of infrastructure in the electricity sector, we define two so called sensitivity variants. The first sensitivity variant is focussed on the application of additional storage capacity and the second on additional expansion of transmission capacity. It is worth noting that most of the literature that we consulted on this topic stated that storage and grid expansion are considered to be interchangeable balancing solutions in cost-optimal models (grid expansion seems to reduce the need for storage and vice versa) [87–90]. This is why we define the first two sensitivity variants to be mutually exclusive.

Please mind that quantitative scenarios on global deployment of transmission infrastructure or storage capacity are scarce and the few studies that exist present a wide range of possible outcomes [87]. For example, the need for storage capacity in Europe towards 2050 could be much higher than our default model [89], but could also be negligible [91]. Therefore, we often had to define the sensitivity variants based on our own judgement and some proxys from data on Europe. We present and explore the effects on the model results only to get a better understanding of the sensitivities of the model and to identify materials for which the demand is highly dependent on the scenario storyline, and therfore more uncertain.

A6.5.1.1 Sensitivity variant 1: high storage, low V2G, low PHS

The first sensitivity variant assumes a higher storage demand by doubling the required storage capacity towards 2050. This alternatve assumption could be justified by [91], who find that the European storage requirements as reported by the IMAGE model might be low compared to other models. Combined with pessimistic assumptions on the addoption of vehicle-to-grid storage, this sensitivity variant could be considered a worst-case scenario, aimed to explore the additional material demand in dedicated (stationary) storage under less favourable conditions.

Compared to the default assumptions, the regional storage capacity is doubled between 2020 and 2050, while the available storage capacity in electric vehicles is halved towards 2050. Additionally, the installed capacity of Pumped Hydro Storage (PHS) does not grow after 2030 (the end of the predictions by the IHS [45]) and 50% of the remaining regional storage demand (after PHS) is considered to be fulfilled by dedicated storage, which could be due to financial incentives for consumer which produce their own electricity (prosumers, e.g. through rooftop PV) and might benefit from investing in distributued stationary storage applications (after [88,89]).

Implications for global storage capacity can be found in Figure A6.14, and the effects on overall material use are discussed in section A6.5.3. Figure A6.12, below, shows the implictions of the ‘high storage’ assumptions on regional storage deployment towards 2050. For comparison to the default model setting, please see Figure A6.8.

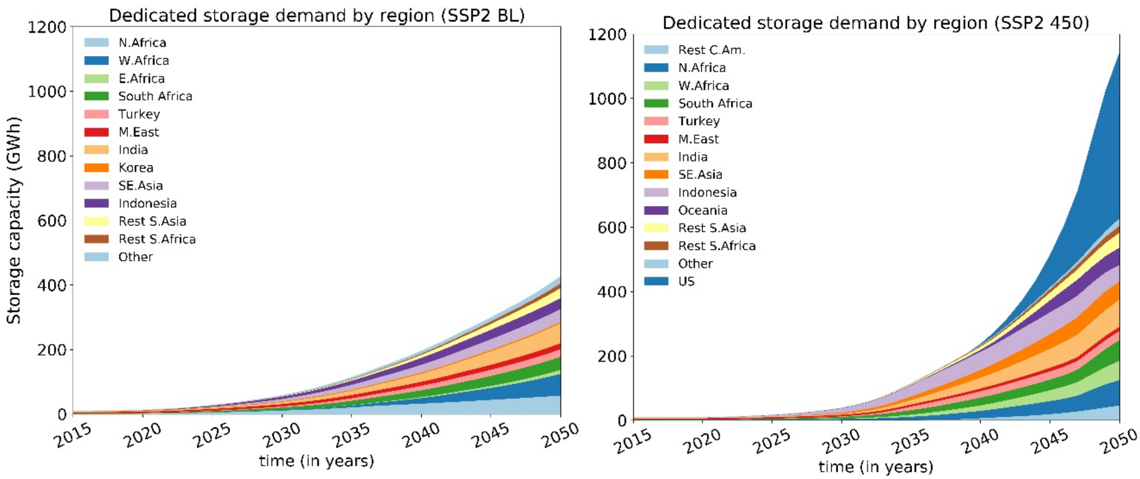

Figure A6.12. *Regional deployment of dedicated storage under the ‘high storage’ sensitivity variant. Results are given for the ‘high storage’ sensitivity variant of the SSP2 baseline and the ‘high storage’ sensitivity variant of the SSP2, 2-degrees climate policy scenario (right).*

A6.5.1.2 Sensitivity variant 2: high transmission expansion

Under the high transmission expansion assumptions we implement a slightly different growth of the high voltage (HV) electricity transmission network, while maintaining the default lengtht of the Medium and Low voltage levels. We choose to do so, because most available studies only elaborate on the expansion of HV (interregional) transmission capacity, see for example [89,92]. Based on these two studies with quanititative indications on the additional transmission line length in renewable energy scenarios for Europe (Figure A6.13), we conclude that our default assumptions on the expansion of HV transmission line lengths might be on the high side in the SSP2 Baseline scenario, while in the SSP2 2-degree scenario it might be on the low side.

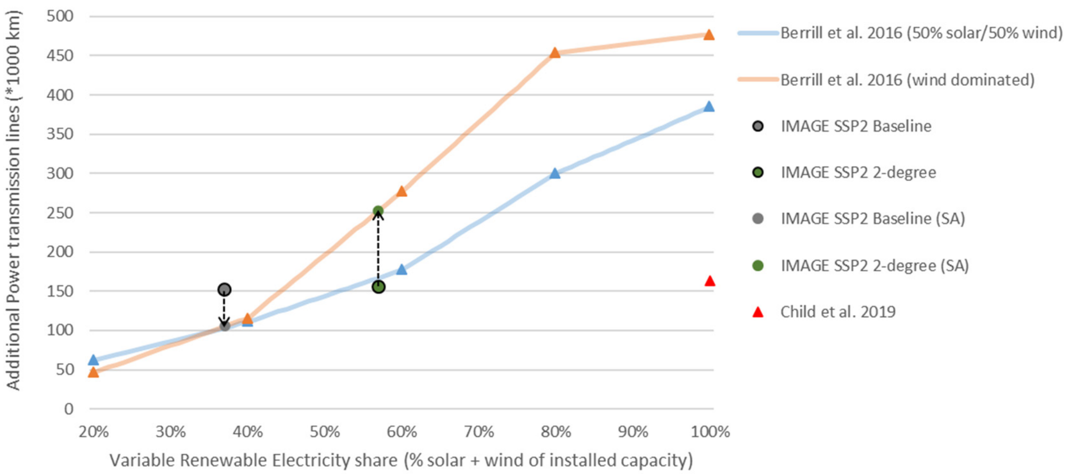

Figure A6.13. *European High Voltage transmission line expansion (in 1000 km) under different renewable energy shares. Shown are results from two studies compared to our own assumptions using the SSP2 scenario based on the IMAGE model baseline and the 2-degree climate policy assumptions. The arrows indicate the consequences of the sensitivity variant 2, which make the model more sensitive to the adopted levels of variable renewable electricity generation.*

To explore the effects of a model with a HV line length that is a little more sensitive to the penetration levels of variable renewable energy, we adjust our growth assumptions so that variable renewable electricity generation (PV Solar & Wind) will lead to a 100% larger demand for grid expansion, while other baseload technologies require 70% less grid expansion towards 2050. As such a 100% growth of a fully fossil-based generation capacity would lead to a 30% increase in the HV line length, but a 100% growth in a fully renewable-based generation capacity would lead to a 200% increase in HV transmission line length in the end of the scenario. Though these assumptions should be verified with data on other regions, it can be seen in Figure A6.13 that for Europe this would lead to an additional HV line length that seems comparable to the range found in [92].

Together, the two sensitivity variants describe an alternative development of the drivers of material demand in electricity storage and HV grid lines, as displayed at the global scale in Figure A6.14.

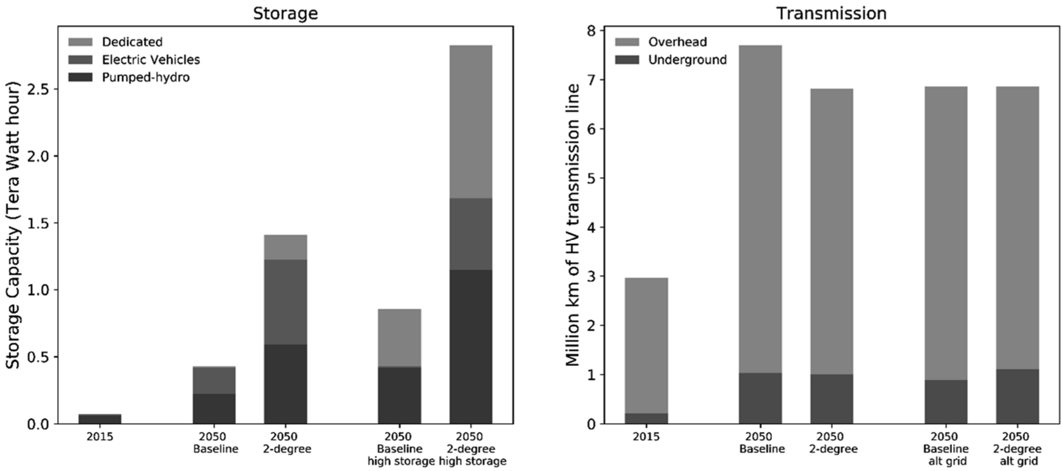

Figure A6.14. *Alternative assumptions on storage capacity and transmission line length under two sensitivity variants (high storage & alt. grid). These panels show the assumptions used in the sensitivity analysis. While the higher storage demand ('high storage') mostly affects the 2-degree scenario, the baseline is most affected by the alternative assumptions on grid expansion ('alt. grid'). Even though the differences between the basline and the 2-degree scenario seem small when implemeniting the alternative grid settings ('alt. grid') the 2-degree scenario now has a larger HV grid, despite much lower generation capacity, which was a consequence of higher efficiency improvements under stricter climate policy assumptions in the IMAGE SSP2 scenario.*

A6.5.2 Alternative assumptions on material intensities

The use of static material intensities in our default model assumptions is not just a convenient modellers choice. There is an inherent uncertainty about technological developments into the future, which simply makes it impossible to model the expected changes in material intensity towards 2050 for all of the 28 generation technologies, the 17 storage technologies, the materials invovled in the infrastructure of 6 different line types as defined in this study. Instead, we explore the impact of three foreseeable changes in the material composition of a few of the technologies used for generation, transmission and storage based on sparesely available literature. The details are discussed below, followed by an elaborate discussion on the outcomes of the sensitivity analysis based on the three different sensitivity variants.

A6.5.2.1 Sensitivity variant 3: dynamic material intensities

First of all, we model the potential impacts of reduced cobalt content in lithium-ion batteries after a recent study by [93]. This sensitivity variant enforces a continually decreasing cobalt content of NCA & NMA battery types between 2020 and 2050, effectively eradicating cobalt from these battery types in new batteries by 2050. Mind that this battery composition change is enforced simultaneously with the battery density improvements that are part of the default assumptions. Given that we do not assess the demand for nickel, we are unable to fully assess the trade-off in terms of additional demand for substituting materials.

Secondly, we explore the possible impact of an increasing share of transmission lines being High Voltage Direct Current (HVDC lines) between 2020 and 2050. Though the default model does not strictly distinguish between Alternating Current (AC) or Direct Current (DC) transmission and bases the material intensities of underground cables on a mix of both AC & DC lines found in [43], the sensitivity variant addresses the possible increase in the share of new HVDC lines (especially in intercontinental transmission) [90] by increasing the copper content of underground HV lines, which is notably higher in HVDC lines [43], to represent 75% of the additions to be HVDC by 2050 (up from 50% in the default scenario). In terms of material intensity, this represents a 13% increase in the copper content (in kg/km).

Finally, we implement an annual material efficiency improvement of the structural use of steel and aluminium in solar- and wind based generation technolgies between 2020 and 2050. Given that these technolgies are still in development, we address the posibility of ongoing improvements in material efficiency of the newly installed generation capacity, by assuming an annual material efficiency improvement of 1%. Over the 2020-2050 period this would lead to a 26% decrease in the material intensity (kg/MW) for wind and solar technologies. This could for example be achieved through the development of lighter solar panels [94] or through the increased substitution of materials in windmills by composites [95] or even wood [96].

A6.5.3. Results of the sensitivity analysis

Figure A6.15 shows the results from the sensitivity analysis in terms of total stock for the four materials that are affected by each sensitivity variant. Table A6.15 shows more details regarding the deviation from the reference scenarios (the SSP2 Baseline & 2-degree scenario) towards 2050, including the consequences on material inflow, outflow and the resulting ratio. Table A6.16 shows some additional details with regard to the material use in dedicated storage applications.

The alternative assumptions explored in the three sensitivity variants do not have a large effect on the amount of materials contained in the stock. For the period 2045 to 2050, the largest increase compared to the default assumptions is a 9% increase in cobalt stocks under alternative storage assumptions in the 2-degree scenario. The largest decrease in material use found for the same period is 7.7% less steel as a consequence of the dynamic material intensities (due to a 1% annual material efficiency improvement in solar- and wind-based electricity generation).

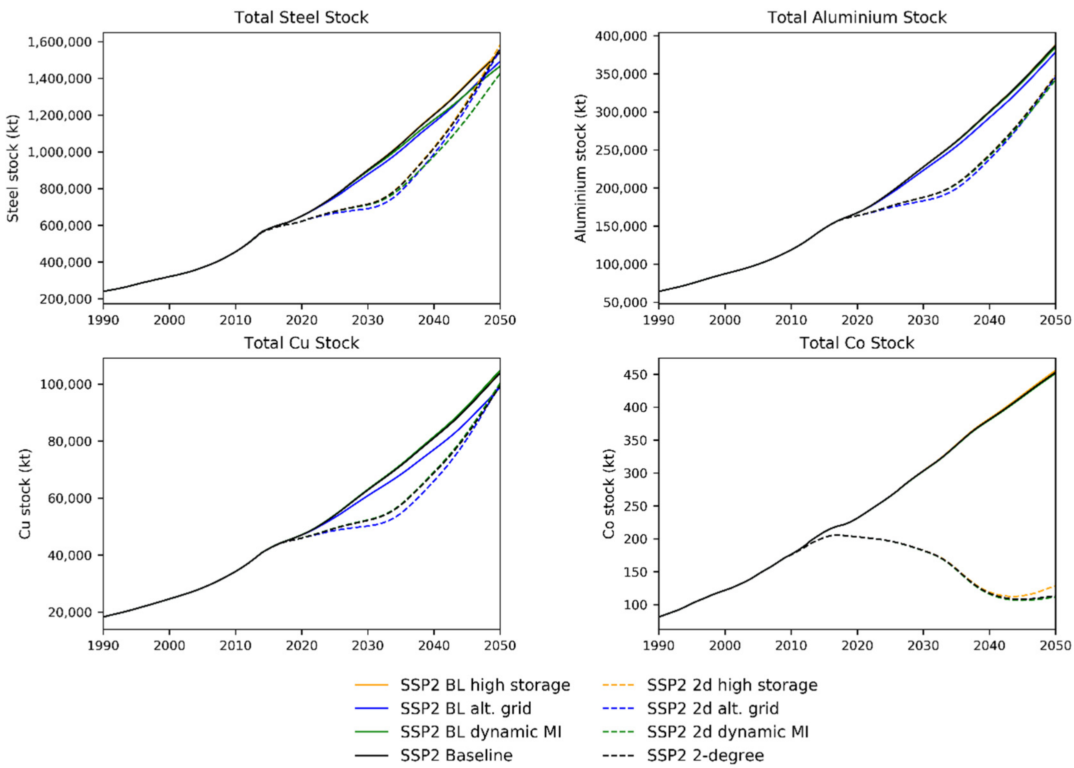

Figure A6.15. *Results of the sensitivity analysis on the stock of steel, aluminium, copper (Cu), and Cobalt (Co). Dashed lines describe the SSP2 2-degree scenario and its sensitivity variants. A solid line refers to the Baseline.*

The effects of the sensitivity analysis on the inflow indicators are larger. For the inflow, the largest increase related to the sensitivity variants is also found for cobalt and steel. However, the roughly 13% decrease of annual steel demand (i.e. inflow) and the roughly 60% increase in annual cobalt demand show a larger effect of the sensitivity analysis on the inflow indicators. The large increase of cobalt demand in the 'high storage' variant of the 2-degree scenario can be explained by the assumed doubling of the storage capacity, and an increase of the share of dedicated electricity storage in a period that other uses of cobalt (such as high-temperature steel in electricity generation) are no longer expanding their stock.

Table A6.15. *Results of the sensitivity analysis: percentage deviation of the three sensitivity variants compared to the default model outcome by the end of the scenario period (average of 2045-2050). Shown are the deviations in terms of total stock and in terms of inflow, for those materials that are affected by the three sensitivity variants, being: 1) alternative growth of the high voltage grid ('alt. grid'), 2) High storage demand combined with pessimistic assumptions on the availability of pumped hydro storage and vehicle-to-grid tehcnolgy ('High storage') and 3) implementing a dynamic material intensity based on foreseeable shifts in technologies of material efficiencies ('dynamic MI'). Readers guide: the 'dynamic material intensity' variant, which implements a 1% annual steel efficiency improvement in solar- and wind-based electricity generation, causes a 4.2% decrease in the steel contained in stocks over the last five years of the SSP2 Baseline, compared to the last five years of the default Baseline explored in Chapter 6 (e.g. Table 6.2).*

		Sensitivity Analysis: Difference in 2045-2050 results					
		SSP2 Baseline			SSP2 2-degree scenario		
		Alt. grid	High storage	Dynamic MI	Alt. grid	High storage	Dynamic MI
Stock	Steel	-3.4%	0.4%	-4.2%	-1.0%	1.1%	-7.7%
	Aluminium	-2.6%	0.1%	-0.6%	-0.9%	0.3%	-1.3%
	Cu	-5.0%	0.1%	0.9%	-0.5%	0.4%	0.9%
	Co		0.6%	-0.3%		9.0%	-1.5%
Inflow	Steel	-1.3%	0.7%	-8.6%	3.3%	2.3%	-12.8%
	Aluminium	-0.8%	0.2%	-1.3%	2.9%	0.9%	-2.1%
	Cu	-2.7%	0.2%	1.3%	7.6%	1.0%	1.4%
	Co		2.8%	-1.5%		60.3%	-6.4%

Based on the sensitivity responses of the 'high storage' and the 'dynamic material intensity' variants, it seems fair to conclude that the uncertainty regarding the analysis of the material use in the electricity sector seems to increase when looking at a climate policy scenario and may be even more pronounced when focusing on inflow indicators. The only case where this doesn't seem to hold is in the variant exploring 'alternative grid' expansion rules under baseline conditions, this has to do with the timing of the deployment of generation capacity and, consequentially, the lower grid size. Here, the inertia of the stock composition causes a lag between changes in the materials inflow and the materials in in the stock.

The 'high storage' sensitivity variant specifically, could have large consequences on the demand for materials in dedicated storage applications, as shown in Table A6.16. Compared to the default model settings, the materials contained in the in-use stocks is more than doubled. Differences between materials occur due to the dynamic deployment of different storage technologies, each with their own material composition. While in-use stocks for steel and copper grow by a factor 2.1 in the 2-degree scenario, cobalt stocks grow by a factor 5.2. This effect is higher than expected based on the doubling of total storage demand alone. Therefore, the future availability of vehicle-to-grid storage capacity (and to a lesser extent that of pumped hydro), could play an important role in lowering material demand for dedicated storage applications.

Table A6.16. *In-use material stocks for dedicated electricity storage under the 'high storage' sensitivity variant by 2050 (in kt). Similar to Table A6.15, results are shown for the SSP2 baseline and the SSP2 2-degree scenario and values refer to an average of model outcomes (2010-2015 & 2045-2050).*

		Default settings		'high storage' sensitivity variant	
		Baseline	2-Degree	Baseline	2-Degree
	2015	**2050**	**2050**	**2050**	**2050**
Steel	1566	6943	14400	12800	29600
Aluminium	63	302	375	597	1230
Glass	0.4	6.1	7.7	13	30
Cu	35	161	334	300	711
Nd	1.8	8.3	10	17	35
Co	0.1	1.9	2.4	4.4	12
Pb	11.7	98	126	217	537

A6.6 Detailed results & model code

Detailed results with respect to other materials can be found in the supplementary information for the original article. Furthermore, the pyhton code used for the analysis is made available for review and future improvement online, via github.com/SPDeetman/ELMA This repository also contains the raw output data. In case of future improvements or corrections, updates will be posted and managed there.

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Appendix 7

A7.1 Material composition of vehicles

Table A7.1. *Material composition by type of vehicle bodies (including drivetrain & wheels)*

Cat.	Vehicle	Type	Steel	Al	Cu	Plastics	Glass	Ti	Wood	Rubber	Pb	Nd	Sources
Passenger	Car	ICE-HEV	63.2%	9.7%	1.8%	12.5%	2.7%			3.1%	0.8%	0.02%	1–5
		PHEV-BEV	47.8%	13.8%	7.4%	10.2%	2.4%		0.75%	2.4%	0.1%	0.09%	
		FCV	45%	24.9%	1.4%	8.5%	3%			4.3%	0.2%	0.25%	
	Bicycle		34%	46%		12%				7%			6–8
	Bus	Regular	55.3%	19%	0.25%	8.8%	2.2%			2.9%			9
		Midi	31.9%	36.5%	0.25%	14.9%	4.6%			2.6%			
	Train	Regular	60.5%	31%	0.14%	2.1%	0.37%						10,11
		HST	59.6%	25%	1.3%	3.3%	1.9%						
	Airplane	passenger	9%	68%	0.46%	5.3%		6%					12–15
Freight	Truck	LCV	65.6%	6.1%	1%	10.8%	0.6%			3%			9
		MFT	64.2%	0.9%	0.3%	19.6%	0.7%			5.6%			
		HFT	73.9%	3.6%	0.5%	5.6%	0.3%			5.8%			
	Inland ship		91%	1%	1%	2%	0.06%		1%				16–20
	Intern. ship	Small-XL	91%	1%	1%	2%	0.06%		1%				
	Airplane	Cargo	9%	68%		5.3%		6%					12–15
	Rail	Cargo	94.5%	5.4%	0.15%								10,11

A7.2 Dynamic fleet characteristics of international shipping

	Small Vessels		Medium Vessels		Large Vessels		Very Large Vessels	
	DWT	nr	DWT	nr	DWT	nr	DWT	nr
2005	373	23660	7985	29710	53057	5700	138632	2157
2006	378	25122	8078	34794	52920	6974	137670	2682
2007	378	25515	8095	36028	53052	7472	137751	2914
2008	379	26307	8104	37335	53097	7995	138184	3177
2009	379	27084	8077	36285	52912	8183	137611	3399
2010	380	27831	8170	37165	52947	8930	137797	3842
2011	378	28286	8265	36927	53111	9540	138851	4321
2012	374	28843	8196	36144	53324	9867	139949	4617
2013	375	29682	8118	36728	53364	10317	140816	4857
2014	374	31240	8167	37719	53399	10924	142568	5211
2015	374	32136	8170	38351	53285	11309	143482	5437
2016	373	33356	8175	39017	53228	11615	144916	5816
2017	374	33752	8212	39141	53100	11783	145851	6039
2018	375	34495	8215	39452	53051	11997	147805	6307

Table A7.2. *Development of international shipping fleet characteristics. Assumed DWT (Dead weight tonnage) and the total number of ships according to* [21,22].

A7.3 Additional assumptions for trains

Table A7.3. *Additional assumptions on trains in various regions. These sources were used to derive data in Table 7.2. Therefore, Table 7.2 does not compare all global trains, but only the indicated regions. Based on this data, i.c.w. sources stated in Table 7.2, an average of 1.5 locomotives per freight train was assumed.*

Source(s)	Country/ region	year	Regular passenger trains (coaches)	Freight Trains		HST (trains)
[23]	India	2016	55,500	11,500	locomotives	none
				278,000	wagons	
[24]	Canada	2017	512	2,842	Locomotives	none
				55,357	wagons	
[25,26]	China*	2018	52,399	21,482	Locomotives	2600
				839,213	wagons	
[27,28]	US	2018	18,314	29,031	Locomotives	20
				1,690,396	wagons	
[29–33]	Europe	2015/ 2018	88,790	40,000	Locomotives	N.A.
				880,000	Wagons	
[23,34–36]	Japan**	2017	31,319	N.A.		N.A.
[37,38]	Russia	2014	N.A.	20,300	Locomotives	N.A.
				1,229,200	Wagons	

Notes: * In Chinese national statistics the total number of coaches is stated, including high-speed coaches. The World Bank states that Chinese HST usually have 8 coaches per train; therefore, 2600*8 = 20800 is subtracted from the stated 73199 based on the indicated sources. **own estimation based on the stated sources.

References to Appendix 7

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