Stock-driven scenarios on global material demand: the story of a lifetime

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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.

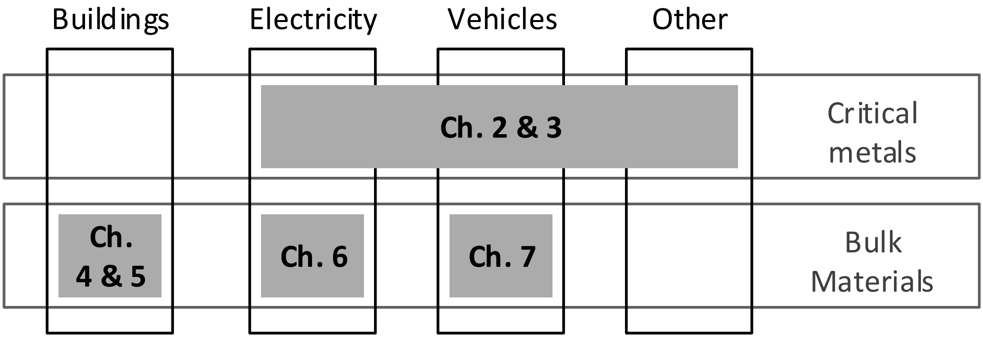

Figure 1.2 *Thesis overview, coverage of materials and end-use sectors throughout the chapters.*