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

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**Citation**

Deetman, S. P. (2021, December 8). *Stock-driven scenarios on global material demand: the story of a lifetime*. Retrieved from https://hdl.handle.net/1887/3245696

# 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.