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

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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.