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

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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.