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

Deetman, S.P.

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8.

Synthesis

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

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

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

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

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

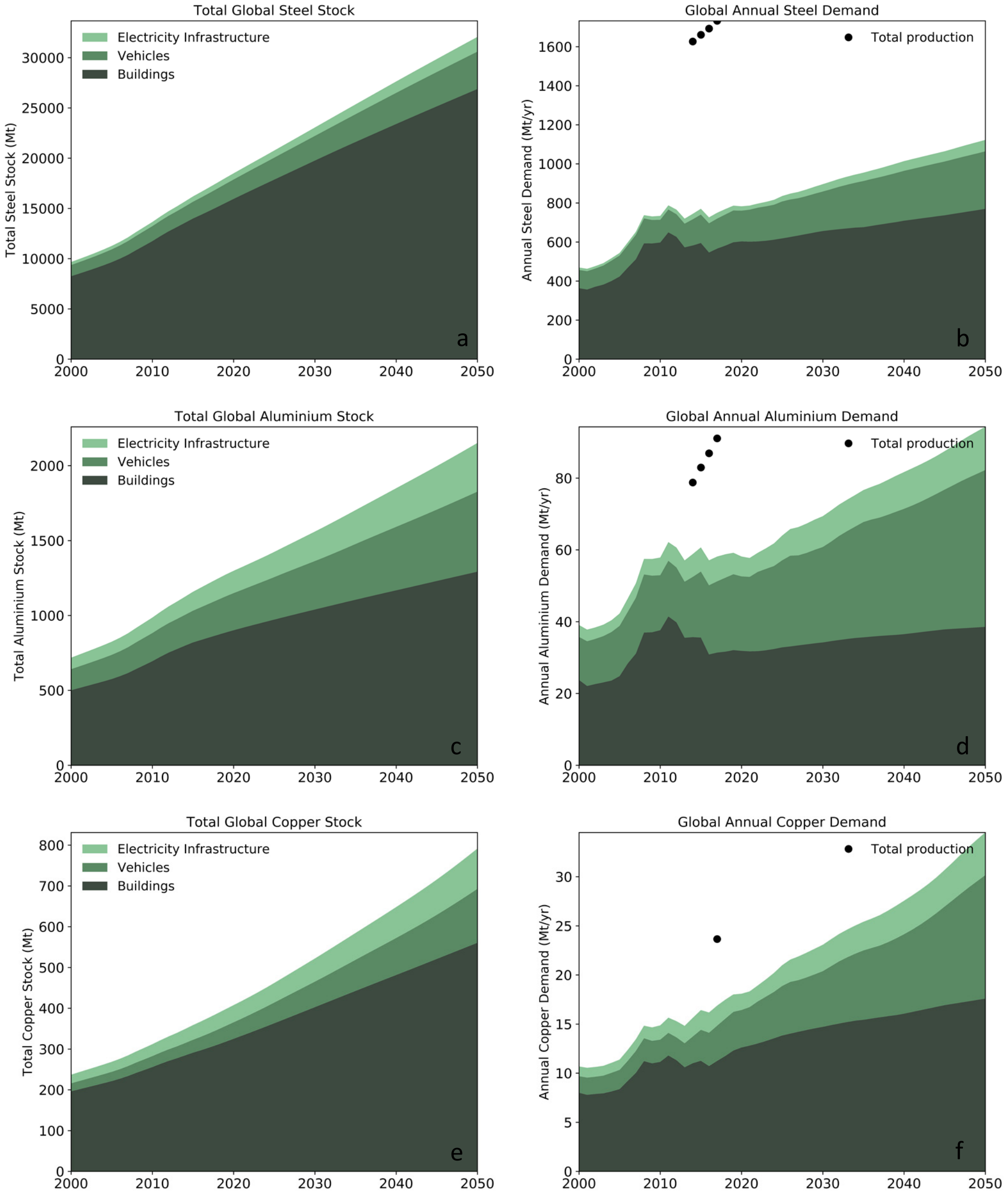

Figure 8.1a-f. *Overview of results on stocks and annual demand for steel, aluminium and copper in buildings, vehicles and in the electricity sector towards 2050 under the SSP2 baseline scenario. The dots in the plots on the right show the current total global annual production of materials based on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

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

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

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

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

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

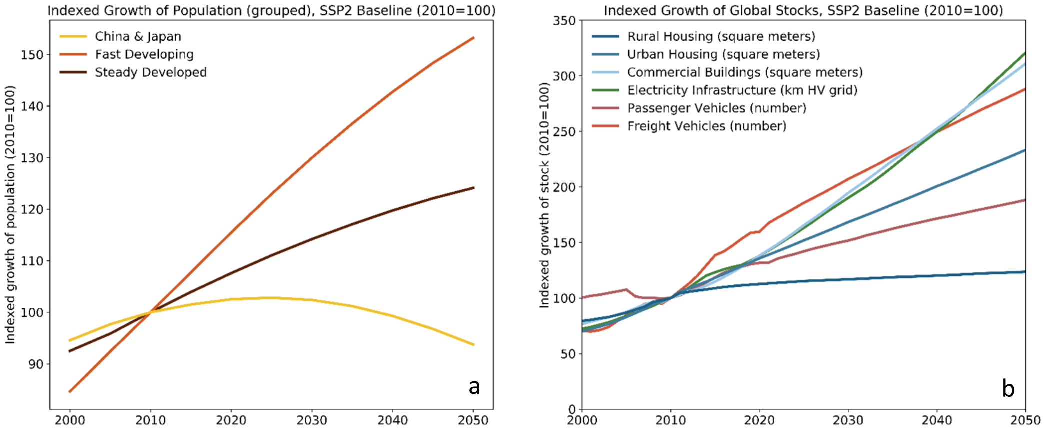

Figure 8.2a-b. *Indexed development of global population (a) based on* (KC et al. 2017)*; and indexed development of in-use stocks as drivers of material demand (b) based on the IMAGE model elaboration of the SSP2 Baseline* (van Vuuren et al. 2017) *and calculations in chapters 4 to 7. The regional aggregation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

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

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

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

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

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

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

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

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

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

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

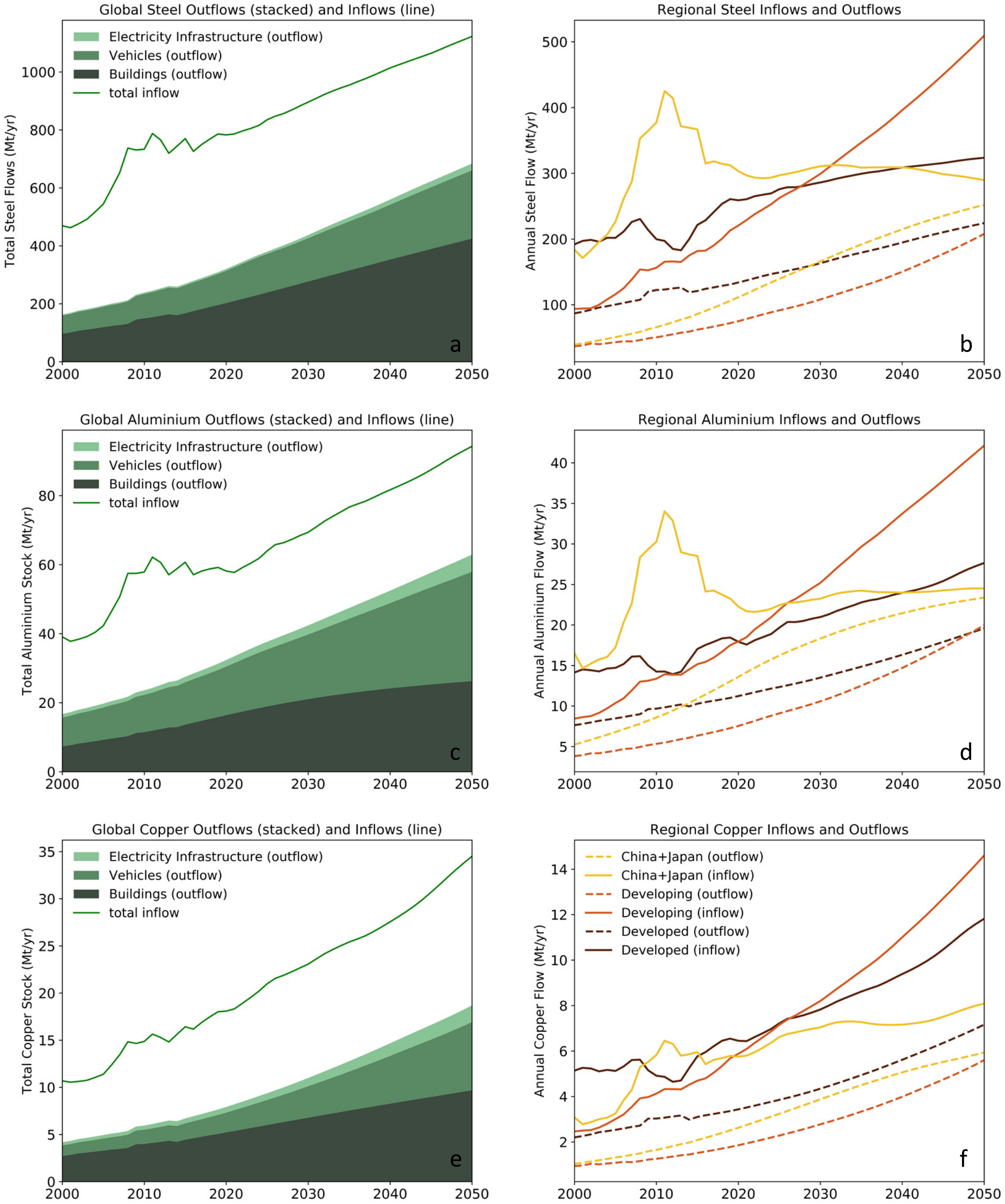

Figure 8.3a-f. *Overview of global and regional results on inflow and outflow of steel, aluminium and copper. The global total inflow (line in the left-side panels) is similar to the sum of the right-side panels in Figure 8.1. Regional grouping in the right-side panels is the same as used in Chapter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