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

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Projected material requirements for the global electricity infrastructure – generation, transmission and storage

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Abstract

We analyze how the global material stocks and flows related to the electricity sector may develop towards 2050. We focus on three electricity sub-systems, being generation, transmission and storage and present a model covering both bulk and critical materials such as steel, aluminium and neodymium. Results are based on the second Shared Socio-Economic Pathway scenario, with additional climate policy assumptions based on the IMAGE integrated assessment framework, in combination with dynamic stock modelling and an elaborate review of material intensities.

Results show a rapid growth in the demand for most materials in the electricity sector, as a consequence of increased electricity demand and a shift towards renewable electricity technologies, which have higher material intensities and drive the expansion of transmission infrastructure and electricity storage capacity. Under climate policy assumptions, the annual demand for most materials is expected to grow further towards 2050. For neodymium, the annual demand grows by a factor 4.4. Global demand for steel and aluminium in the electricity sector grows by a factor 2 in the baseline or 2.6 in the 2-degree climate policy scenario.

We show that the combination of rapid growth of capital stocks and long lifetimes of technologies leads to a mismatch between annual demand and the availability of secondary materials within the electricity sector. This may limit the sector to accomplish circular material flows, especially under climate policy assumptions. We also highlight the potential for electric vehicles to curb some of the material demand related to electricity storage through adoption of vehicle-to-grid services.

6.1 Introduction

Demand for electricity has been increasing rapidly worldwide, by over 4% per year in the 1990-2015 period (IEA 2019), and will likely continue to grow due to trends such as continued economic development (Steinbuks 2017), electrification (Blonsky et al. 2019) and climate change (van Ruijven et al. 2019). Consequentially, the amount of materials contained in the infrastructure required to generate and deliver the electricity to end-users is increasing as well. There are several reasons to explore the effect of increased electricity demand on the demand for materials. First of all, previous research has pointed out that material scarcity could be a limiting factor to the expansion of renewable energy systems (de Koning et al. 2018; Valero et al. 2018; Månberger and Stenqvist 2018; Harmsen et al. 2013; Elshkaki et al. 2018). Secondly, the material demand of infrastructural stock development could be relevant for energy demand and related carbon dioxide emissions (Müller et al. 2013; Pauliuk and Müller 2014; Baynes and Müller 2016). A better representation of materials in infrastructural stocks could therefore contribute to more realistic scenarios on the energy system, while at the same time improving the understanding of its environmental impacts (Södersten et al. 2018; Chen and Graedel 2015). Currently, however, very few models that are used to generate global emission scenarios capture such explicit linkages between material demand and industrial energy use (Pauliuk et al. 2017). A key reason is that it requires detailed insights in the demand for individual materials that contribute to the formation of capital stocks in economic sectors, for example in buildings and vehicles (Hertwich et al. 2020; Habib et al. 2020; Deetman et al. 2020). The electricity sector specifically, comprises of large infrastructural stocks, but its size and the implications of its growth on material demand have been poorly understood from a global perspective.

Existing literature has addressed the development of material demand in relation to the electricity sector, but often reported results using a regional focus (Elshkaki and Shen 2019; Li et al. 2020a), or a broadly defined end-use category (such as ‘construction’), making it difficult to strictly distinguish materials used in the electricity sector alone (Wiedenhofer et al. 2019; Langkau and Tercero Espinoza 2018; Krausmann et al. 2017). Others have considered parts of the electricity sector such as only the electricity generation (Elshkaki and Graedel 2013; Deetman et al. 2018). Some studies also looked at the material use in the electricity sector using a life-cycle or a material footprint approach (Watari et al. 2019; Mostert et al. 2018; Kleijn et al. 2011; Hertwich et al. 2015; Luderer et al. 2019; Berrill et al. 2016) or with a narrow focus on reserve depletion (Capellán-Pérez et al. 2019; Jacobson and Delucchi 2011). Such studies are all valuable in highlighting the issues related to material demand in the electricity sector. However, they do not encompass a global perspective of all the physical infrastructure involved in providing electricity to consumers. In particular, developments towards higher shares of renewable electricity will require a combination of electricity storage and grid expansion to guarantee a reliable and affordable electricity supply (Laugs et al. 2020; Koskinen and Breyer 2016; Child et al. 2019).

Here, we address the knowledge gap by focusing on the materials used in the electricity sector, as defined by the infrastructure used to generate, transport and store electricity. We explore how the global material stocks and flows related to the electricity sector will develop, by introducing a model with a long-term perspective that provides comprehensive coverage of material stocks as well as the annual material flows related to the electricity sector towards 2050. The model covers bulk materials such as steel, concrete, aluminium, glass and copper, as well as some specific metals used in lower volumes, such as cobalt, neodymium and lead, but coverage of materials is often based on data availability and could be expanded in the future.

As a scenario background, we use a ‘middle-of-the-road’ scenario, i.e. the Shared Socioeconomic Pathway (SSP2) as implemented by the IMAGE integrated assessment framework (Stehfest et al. 2014; van Vuuren et al. 2017), which ensures that we consistently account for the regional development of important drivers such as population, affluence and electrification. We also look into the derived climate policy scenario consistent with the 2°C Paris Climate target (UNFCCC. Conference of the Parties (COP) 2015). This scenario includes a rapid increase of renewable energy use. Our analysis requires an elaborate set of assumptions on material intensities, lifetimes and the future development of the electricity infrastructure, which are documented in Appendix 6 and the associated model code (available via Github). The transparent approach allows to support future model improvements and facilitates the integration of material-energy feedbacks in integrated assessment models such as IMAGE.

6.2 Method

This section describes the approach and the assumptions in the calculation of the materials used in the electricity infrastructure, i.e. 1) electricity generation capacity, 2) the electricity transmission grid and 3) the required electricity storage, as summarized in Figure 6.1. With regards to the electricity sector, we define the system boundaries of our model to only include the stationary infrastructure that strictly functions to reliably provide electricity to end-users. For storage technologies this means that pumped-hydro dams and other dedicated electricity storage technologies are accounted as part of the electricity sector, while electric cars and their batteries (though available as a form or storage) are not.

However, we do reflect upon the importance of electric vehicle batteries to support a renewable energy system in the discussion.

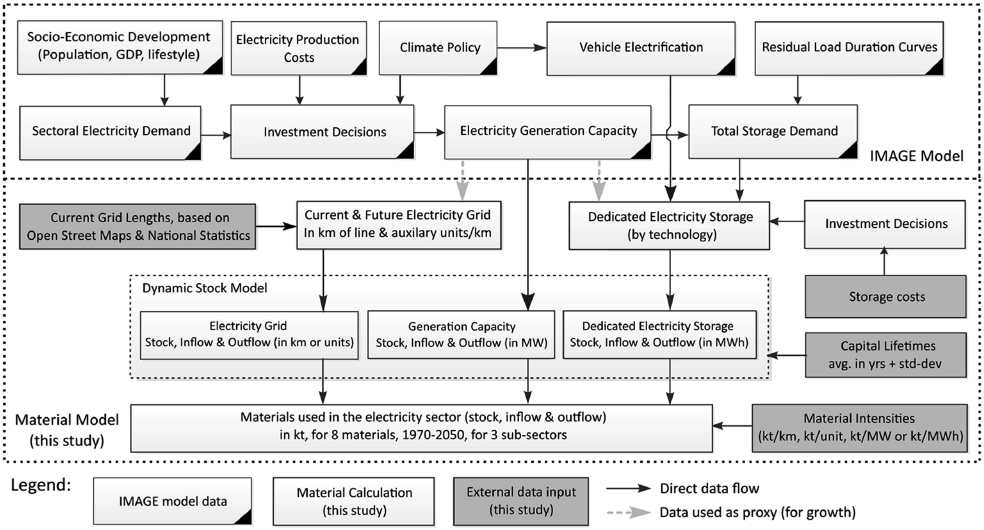

Figure 6.1. *Overview of the calculations. The top box indicates information within and from the IMAGE model. In the lower box, the calculations performed in this study are presented in black and external data input is indicated in the blue boxes.*

For each of the three parts of the electricity sector, we use a similar approach. The electricity grid, generation capacity and storage capacity are all described by an infrastructural stock model. They are driven by the actual demand. In the case of generation, this is provided by the IMAGE model, which accounts for trends in population, affluence and electrification. For the electricity grid and storage, we model the required capacity consistent with these IMAGE projections. Subsequently, new capacity is calculated by the difference between existing and required capacity, while depreciated capacity is determined using assumed technical lifetimes and a dynamic stock model (Pauliuk and Heeren 2019). The total capacity in stock, the newly installed capacity and the depreciated capacity is subsequently used to calculate the stock, the annual inflow and the annual outflow of materials by using a set of material intensity data, established through elaborate literature review. Below, we briefly describe the methods for each of the three infrastructural parts and subsequently discuss the key characteristics of the SSP2 scenarios used to generate the results.

6.2.1 Model description

6.2.1.1 Electricity generation capacity

In a previous study (Deetman et al. 2018), we presented a method to calculate the demand for metals in electricity generation technologies. The method used data on the material intensity for different metals expressed in kg per MW of installed generation capacity. Which were combined with the IMAGE model projections for the growth of installed generation capacity of 28 technologies, including those based on wind, solar, nuclear, hydro, biomass and various fossil power plants (with or without combined heat/power installations or carbon capture and storage capabilities). The method is summarized in equation 1 as follows:

$$GenMat_{flow,tech,reg,yr} = GenCap_{flow,tech,reg,yr} * MI_{tech} \qquad (1)$$

Where, for any given year (yr), the material use in electricity generation (GenMat) in kg is a product of Material Intensity (MI) as expressed in kg/MW and the Generation Capacity (GenCap) expressed in MW. Flows are represented by inflow, outflow or stock, and a full list of the 26 regions (reg) and the 28 generation technologies (tech) can be found in the Appendix 1 & 6 respectively.

In this study, we use the same method, but we expand the list of materials covered by including several bulk materials, such as steel, aluminium and concrete and glass. We incorporated 27 studies in our review (Öhrlund 2012; Elshkaki and Graedel 2013; BBF Associates; Kundig 2011; Moss et al. 2011; Sullivan et al. 2011; Ehtiwesh et al. 2016; Crawford 2009; Dones et al. 2007a; Haapala and Prempreeda 2014; Bonou et al. 2016; Marimuthu and Kirubakaran 2013; Guezuraga et al. 2012; Habib 2015; Wilburn 2012; Energinet 2015; van Exter et al. 2018; Vici Ventus 2020; Flury and Frischknecht 2012; S&T2 consultants 2006; Albers et al. 1977; Dones 2007; Weitzel et al. 2012; Dones et al. 2007b; Singh et al. 2015; Jungbluth 2007; Faist-Emmenegger et al. 2007; Moss et al. 2013; Bauer 2007) to come up with the overview of material intensities (in ton/MW) as presented in Table A6.2 in Appendix 6. By default, these material intensities were assumed to remain constant over time, but the effects of foreseeable changes in material composition where analyzed as part of the sensitivity analysis. The material intensities were then applied to the stock and the in/out-flows of the generation capacity in the IMAGE elaboration of the SSP2 baseline and the SSP2 2-degree climate policy scenario. We then calculate the inflow and outflow using a stock-driven dynamic stock model (Pauliuk and Heeren 2019) and the individual lifetimes of the electricity generation technologies ranging from 25 years (solar PV & wind turbines) to 80 years (hydro dams), as elaborated in Appendix 6.

6.2.1.2 Current and future electricity grid

In short, the size of the transmission and distribution grid is calculated using an estimate of the current high-volage (HV) grid size and a growth factor based on the indexed growth of the installed generation capacity as in equation 2:

$$HVGrid_{reg,yr} = HVGrid_{reg,2016} * \frac{GenCap_{reg,yr}}{GenCap_{reg,2016}} \tag{2}$$

Where the in-use stock of High Voltage grid (HVGrid) is expressed in kilometers of transmission line and the generation capacity (GenCap) in MW as before. The grid size of lower voltage levels (Medium & Low voltage) is derived using a fixed ratio with the HV grid length. The material use is then calculated based on these line lengths, multiplied with voltage-specific material intensities (MI) for various sub-elements of the grid, such as lines & poles, and substations with their transformers, as follows:

$$HVGridMat_{reg,yr} = HVGrid_{reg,yr} * MI_{lines} + HVGrid_{reg,yr} * \frac{Units_{trns.\&\,sbst.}}{km} * MI_{trns.\&\,sbst.} \tag{3}$$

Where the HV line length (in km) is multiplied with the material intensity (MI) in kg/km of lines to get the materials in the lines, which is then summed with the materials in transformers and substations to yield the materials in the HV grid (HVGridMat) in kg. The stock of transformers and substations is expressed in units by multiplying the grid length (HVGrid) in km by the units per km based on literature (Harrison et al. 2010; Turconi et al. 2014). The material intensity (MI) for transformers and substations (trns. & sbst.) is thus expressed in kg/unit. The same equation is applied to get the materials in the medium- and low voltage levels, but with material intensities specific to the voltage level. Below, we elaborate on the current grid size calculation, followed by some more in-depth discussion on the assumed grid growth and the used material intensities.

We estimate the current size of the global electricity transmission and distribution network based on two sources. We use our own data based on the OpenStreetMap database for the year 2016, available from (OpenStreetMap contributors 2016) and a second dataset for the year 2019 based on (Arderne et al. 2020). We used Geographic Information System (GIS) software to extract the available grid-related infrastructural elements, such as electricity poles and transmission lines, to determine the length (in kms) of the High Voltage grid for each of the IMAGE model regions. Where possible, we correct and compare these findings with available national statistics as can be found in Table A6.4 in Appendix 6.

Subsequently we assume a fixed ratio between High Voltage lines and lower voltage distribution such as Medium Voltage (MV, 1-130 kV) and Low Voltage (LV, <1 kV) distribution. If no national data is available, we use a ratio of 2.85 km of MV network per km of HV lines and assume 17.4 km of LV distribution network per km of HV transmission lines, based on the sources detailed in Table A6.5 in Appendix 6. A further distinction is made between the fraction of the network that is underground versus the part of the network that is aboveground. Based on data from Eurelectric (Eurelectric 2013) as elaborated in Figure A6.2 Appendix 6. This leads to a total global electricity line length of 3 million km HV line, 10 million km MV line and 51 million km LV distribution line in 2016.

To derive the development of the stock of grid infrastructure towards 2050, we apply the indexed growth of the installed electricity generation capacity over the same period, according to the IMAGE-TIMER SSP2 scenario (van Vuuren et al. 2017) as indicated in equation 2. We feel that this is currently acceptable as a pragmatic approach given that there is no research or database describing the grid length and transmission capacity over time at the global level. This approach captures the most important drivers for network expansion, given that the IMAGE model accounts for a rising peak capacity as the average load drops in a renewable electricity scenario. By expanding the transmission network according to the growth in the generation capacity, we account for at least some of the additional demand for grid infrastructure in a system with high variability in the supply (Child et al. 2019). Additionally, the sensitivity analysis deals with alternative assumptions on the growth of the grid.

In order to assess the relevant stock dynamics, we applied a lifetime based dynamic stock model in python (Pauliuk and Heeren 2018) to calculate the inflow and the outflow as a result of the given infrastructural stock. Here, we used average lifetimes of 30 years for transformers and 40 years for all other elements (lines, stations), based on (Harrison et al. 2010; Turconi et al. 2014), in combination with a standard deviation based on (Balzer and Schorn 2015).

To complete the assessment of material requirements for electricity transmission and distribution, we calculate the requirements for auxiliary grid elements such as transformers and transformer sub-stations on a per km basis, based on detailed life cycle assessment studies (Jorge et al. 2012) on Great Britain (Harrison et al. 2010) and Denmark (Turconi et al. 2014) as given in Tables A6.6-9 in Appendix 6. Finally, we apply the material intensities to derive the materials contained in the global grid infrastructure. An example of the material intensities for transmission and distribution lines is given in Table 6.1.

6.2.1.3 Electricity Storage Capacity

For the estimation of materials required in electricity storage, we use the total amount of storage required according to the IMAGE model (see Figure 6.1). This is calculated using regionally specific residual load duration curves (RLDCs) as described by (Ueckerdt et al. 2017) and implemented into the IMAGE model as described by de Boer et al (de Boer and van Vuuren 2017). Using this method, ensures an optimal deployment of electricity storage capacity, given the changing levels of penetration of wind and solar energy as variable renewable energy sources. As wind and solar energy have different intermittency profiles, the specific combination of wind and solar shares results in a different demand for storage as elaborated in Figure A6.4 in Appendix 6.

Table 6.1. *Material Intensities on High, Medium and Low Voltage network lines (ton/km) based on* (Jorge et al. 2012; Turconi et al. 2014; Harrison et al. 2010)*, for details on the composition of auxiliary grid elements (transformers and substations), please see Appendix 6.*

	High Voltage		Medium Voltage		Low Voltage	
	Over-head	Under ground	Over-head	Under-ground	Over-head	Under-ground
Steel	52.3	-	0.80	-	-	0.18
Aluminium	12.9	-	-	0.82	0.98	0.53
Concrete	209.1	17.5	-	-	-	-
Copper	-	11.7	1.49	0.66	-	-
Glass	1.1	-	-	-	-	-
Lead	-	14.1	-	-	-	-

Given the total demand for electricity storage capacity over time, we apply a tiered approach to determine which technologies will be deployed to supply the actual storage capacity (please see the sensitivity analysis for alternative assumptions):

1) First, pumped hydro storage will be deployed according to the projections from (Rogner and Troja 2018)
2) Then, vehicle-to-grid (V2G) capacity is used, based on regional electric vehicle availability
3) Finally, dedicated (stationary) electricity storage capacity is built, using various technologies

Given that pumped hydro is the cheapest form of electricity storage (IRENA 2017), we simply assume that this is always deployed first and will therefore supply a considerable part of the required electricity storage capacity. However, the potential for deployment of pumped hydro storage is very region and site-specific (Carneiro et al. 2019), which is why we used the projections on availability of pumped hydro-storage capacity based on (Rogner and Troja 2018). Though these projections provide data only for a few regions and only until 2030, we used a regional disaggregation and assumed a continued growth of pumped-hydro storage capacity in accordance with the regular hydropower availability in the IMAGE model.

The second tier of storage capacity is the battery capacity of idle electric vehicles that is (partially) available to provide grid backup & stability through discharging from vehicle-to-grid (V2G). Though the concept of vehicle-to-grid is currently technically feasible (Lauinger et al. 2017), it is not yet a mainstream practice for most electric vehicle owners, due to barriers such as battery degradation or charger communication protocols (Noel et al. 2019). We assume that beyond 2025, provided the right incentives (Jian et al. 2018), battery electric cars will start to be available as a means for electricity storage, growing to large scale adoption towards 2040. In our model we assume that only privately owned cars are available for V2G, and that only a percentage of the battery capacity is available. The number of privately owned electric vehicles (plugin or full electric) is derived from a previous study (Deetman et al. 2018) and we assume a partial availability of 5% of the battery capacity of plugin-hybrid electric vehicles and 10% availability of the larger battery capacity in full electric vehicles. The total available battery capacity per car changes over time, as we assume that due to falling prices and an increase in energy density, the limiting factor to the battery capacity will be the weight of the battery pack in the vehicle. We use currently available car models for 2019-2020 to derive a current average battery capacity and use a fixed battery weight assumption, leading to an EV battery capacity that grows from about 60 kWh now, to roughly 120 kWh by 2040; see Appendix 6 for an elaboration.

The final tier of so called ‘dedicated’ (i.e. stationary) electricity storage technologies is the remainder between the storage demand and the available supply from pumped hydro storage and electric vehicles (tier 1 & 2).

To find the relevant technologies for dedicated (stationary) electricity storage capacity we elaborate a market-share model based on price and storage performance indicators for 17 electricity storage technologies, including various battery-types as well as mechanical storage technologies. The assumptions on the performance of storage technologies for dedicated electricity storage are based on an elaborate review of 23 studies (Majeau-Bettez et al. 2011; Wikipedia 2019; IRENA 2017; Batteryuniversity.com 2019a; Berg and Zackrisson 2019; Xu et al. 2017; Yang et al. 2014; Gür 2018; Van den Bossche et al. 2010; Rydh 1999; Batteryuniversity.com 2019b; Li et al. 2016; Patel 2016; Deng et al. 2017; Yu et al. 2019; Albertus et al. 2018; Collins and BloombergNEF 2019; Gerssen-Gondelach and Faaij 2012; Zackrisson et al. 2016; Tan et al. 2017; Zhu et al. 2016; Gallagher et al. 2014; Luo et al. 2015; Gardiner 2014), which were summarized in a table with indicators on energy density, cycle-life, efficiency and price, as given in Appendix 6 (Table A6.13).

Subsequently, a review of the material composition for each of the 17 storage technologies was based on 15 additional studies (Majeau-Bettez et al. 2011; Cusenza et al. 2019; Nelson et al. 2019; Dakota Lithium 2019; Olofsson and Romare 2013; Chen et al. 2015; Rydh 1999; Sullivan and Gaines 2010; Van den Bossche et al. 2010; Deng et al. 2017; Zackrisson et al. 2016; Axpo 2018; Eller et al. 2018; Liu and Chen 2015; Azo Materials 2020; Werfel et al. 2008; Moss et al. 2013) and is summarized in an overview of the material composition as given in weight percentages in Table A6.14 in Appendix 6. By default, the material composition (in wt%) of battery technologies is assumed to be static, but the energy density of storage technologies was assumed to change between 2018 and 2030, mostly based on projected changes according to (IRENA 2017). As a consequence, the weight per kWh of storage capacity will go down over time, and the material demand per unit of storage capacity will drop accordingly. In the sensitivity analysis we also explore the effects of a changing material composition of some battery types. With regards, to costs, we apply a decline in the storage costs (in US$/kWh) based on the projections by (IRENA 2017). Even after 2030, we assume a continued decline in the costs towards 2050, be it with a lower annual cost decline than before. We use the development of the storage costs to determine the market share of the newly installed storage capacity, by means of a multi-nominal logit function:

$$MS_{tj} = \frac{e^{-\lambda C_{tj}}}{\sum_{k=1}^{J} -\lambda C_{tk}} \qquad \text{for } j=1,\ldots,J \qquad (4)$$

Where the market share of a technology *j* (MS_{tj}) is determined by its cost C_{tj} (in US$ per kWh delivered back to the grid), the costs of other technologies C_{tk} , and the multi-nominal logit parameter λ, which is calibrated against historic values according to the International Energy Agency (IEA 2017), see Appendix 6 for details. Figure 6.2 shows the resulting market shares of grouped electricity storage technologies.

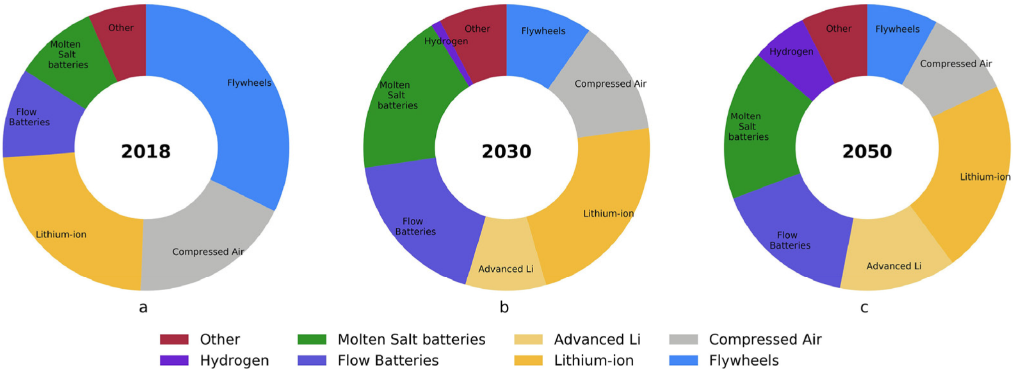

Figure 6.2a-c. *Assumed development of market shares for dedicated electricity storage technologies.*

6.2.2. Scenario assumptions

The model as described above can be applied with different scenario settings by changing the IMAGE data on generation capacity and electricity storage. We present results for the second shared socio-economic pathway (SSP2). The SSP2 scenario is commonly referred to as a middle-of-the-road scenario when it come to the development of population (towards 9.2 Billion people by 2050) as well as affluence (growing by a factor 3.4 between 2010 and 2050) (O'Neill et al. 2017; Riahi et al. 2017). In the results section we show outcomes for the material use in the electricity sector for the SSP2 baseline as well as the SSP2 2-degree scenario, which accounts for decarbonization efforts to limit global warming below 2-degrees above pre-industrial levels. Figure 6.3 shows the development of the drivers for the material model for the SSP2 Baseline and the 2-degree scenario. Here, total global generation capacity and total electricity storage are derived from the IMAGE model (see Figure 6.1). The development of the global grid and the disaggregation of electricity storage categories (also shown in Figure 6.3) are calculated in this study.

Figure 6.3a shows that the total electricity generation capacity in the SSP2 Baseline is expected to grow beyond 10 TW by 2050. A number that is expected to be slightly lower under climate policy assumptions of the SSP2 2-degree scenario, as a consequence of lower electricity demand due to strong energy efficiency measures. Given that we assume transmission growth to be in line with generation capacity, this influences the development of the transmission grid in a similar way as can be seen from panel 6.3c, however, in the following section we explore the effects of alternative assumptions on the expansion of transmission lines as part of the sensitivity analysis.

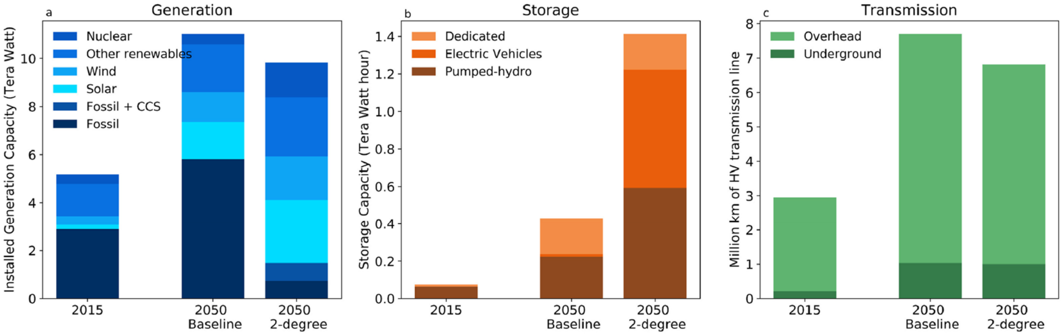

Figure 6.3a-c. *Global infrastructural components in the electricity sector, in the SSP2 Baseline and 2-degree scenario. Panel a) Generation Capacity in TW, b) Storage capacity in TWh c) High-Voltage Transmission line length in km. For regional details on the model drivers (generation & storage) please see Figure A6.3 and A6.8 in Appendix 6.*

The middle panel, Figure 6.3b, shows that the storage capacity is expected to grow, especially in the 2-degree scenario, but the availability of pumped hydro storage and battery capacity from electric vehicles would be nearly sufficient to provide the required storage capacity. As a result of our tiered modelling, we foresee a surplus storage capacity in electric vehicles in many regions if Vehicle-to-Grid technology becomes available, as elaborated in Figure A6.7 of Appendix 6. However, we do explore the effects of alternative assumptions on storage deployment, as part of the sensitivity analysis, in the following section.

6.2.3. Sensitivity analysis

The assumptions underlying the described model and the used scenarios encompass inherent uncertainty about possible developments into the future. To assess the sensitivity of the model outcomes to some of these assumptions we perform a sensitivity analysis by using three sets of alternative assumptions (i.e. three sensitivity variants) with regard to the development of storage, grid expansion and material efficiency. More information on the sensitivity analysis can be found in Appendix 6.

First, we define a ‘high storage’ sensitivity variant, in which we double the demand for storage towards 2050 (originally defined by the IMAGE model), while we halve the availability of storage in electric vehicles. Furthermore, the pumped hydro storage capacity does not grow beyond 2030, and of the remaining storage demand (after PHS) 50% is deployed as dedicated storage, loosely based on reflections by (Child et al. 2019; Laugs et al. 2020). Effectively, this means that we discard the tiered approach for storage deployment in this somewhat pessimistic sensitivity variant.

In the second sensitivity variant on ‘alternative grid’ developments we adjust the assumptions on the growth of the high-voltage (HV) grid to make the model more sensitive to the penetration of variable renewable energy sources (solar and wind). This is based on views in the literature that expanding HV transmission capacity could be a way to improve reliability as well as costs of electricity supply in regions with high levels of solar and wind (Koskinen and Breyer 2016; Laugs et al. 2020; Child et al. 2019; Berrill et al. 2016). Practically this means that we double the demand for grid lines in relation to generation capacity from solar and wind, while lowering the growth of the HV grid in relation to the other (baseload) generation technologies.

The third sensitivity variant aims to explore the effects of foreseeable changes in material content of some of the technologies used by adjusting the material intensities (up or down) towards 2050. In this ‘dynamic material intensity’ variant, we explore the effects on material use as a consequence of the following changes: 1) reducing cobalt content to zero in selected lithium-batteries, based on (Li et al. 2020b), 2) increasing the copper content of underground HV transmission lines by 13% to represent a possible increase in the adoption of high voltage direct current (HVDC) transmission, after (Chatzivasileiadis et al. 2013), 3) implementing an annual material efficiency improvement of 1% for steel and aluminium used in generation capacity based on wind and solar.

6.3 Results

The model presented in the Method section allows us to explore the amounts of different materials in stocks as well as inflow and waste flows for the electricity system as a whole; comprising of the electricity generation capacity, the transmission grid as well as electricity storage applications. In this section, we discuss the results for three selected materials, being steel, aluminium and neodymium. However, the full range of results on all eight materials is available in the Supplementary Information provided with the original publication, which covers both the SSP2 baseline as well as a 2-degree climate policy scenario.

Figure 6.4 shows the resulting global in-use stock of steel, aluminium and neodymium in the grid, the generation capacity and in electricity storage applications, under the SSP2 Baseline. It shows a steady increase of materials in stock for each of the three sub-sections of the electricity sector. However, the relative contribution of elements to the stock varies for the materials shown. Steel and aluminium use in the electricity grid is in the same order of magnitude, but the substations are responsible for a large fraction of the aluminium use, while transformers require more steel. In the electricity generation, the use for steel is widespread in all technologies, while the aluminium stock is projected to be dominated by solar PV applications and neodymium is mostly found in windmills.

Finally, the use of steel and aluminium in electricity storage applications is of much less importance in absolute terms, but here the Pumped Hydro dominates the steel stocks, while aluminium and neodymium stocks are dominated by mechanical storage like compressed air and flywheel technologies (where neodymium is used in permanent magnets).

The materials stocks contained in generation capacity displayed in Figure 6.4 and 6.5 continue to expand, even under the climate policy assumptions of the 2-degree scenario, despite lower installed capacities (see Figure 6.3a). This can be explained by the higher material intensities of renewable energy technologies. For example, the (global average) steel intensity of electricity generation would increase from 65 tons of steel per MW of generation capacity in 2015 to 101 tons of steel per MW of generation capacity (in-use, or stock) by 2050 under the 2-degree scenario. The material intensity of the generation capacity is expected to go up towards 2050 for most materials, however a few materials will have a lower material intensity per MW by 2050, as can be seen in Appendix 6 (Table A6.3).

Corresponding to the growth of total stocks, Figure 6.5 also details the resulting total annual inflow and outflow of steel, aluminium and neodymium at the global level. Here, the inflow relates to the total annual demand for these materials in the electricity sector, and the outflow indicates the corresponding availability of scrap materials resulting from decommissioned infrastructure.

As a consequence of the projected expansion of electricity infrastructure, the annual outflow of steel, aluminium and neodymium for the electricity sector will not be enough to cover the sectoral raw material demand through recycling alone. In fact, the mismatch between annual inflow & outflow towards the year 2050 indicates a serious challenge for establishing a circular economy when it comes to the electricity infrastructure.

Furthermore, the challenge of closing material cycles seems to be amplified under climate policy conditions of the SSP2 2-degree scenario, which causes an initial drop in annual material demand as a consequence of lower electricity demand due to energy efficiency measures, but subsequently leads to higher annual material demand due to the expansion of storage and generation capacity towards 2050. For steel specifically, the annual outflow in the 2-degree scenario increases at first, as a consequence of early retirement of fossil-based generation capacity. However, this development is offset by the expansion of renewable generation capacity, with higher material intensities, towards 2050. Though these results are highly dependent on scenario dynamics and assumptions on timing, the climate policy scenario seems to worsen the perspectives on circular material flows in the electricity sector by 2050, because it increases the annual material demand, while lowering the availability of scrap materials in the same period. Detailed results for all materials are shown in Table 6.2 as well as in Appendix 6.

Table 6.2 shows the total global stock, inflows and outflows of materials in the electricity sector for recent years, compared to the same indicators by the end of the scenario period, for both the SSP2 baseline and a 2-degree climate policy scenario. It shows that the stock as well as the annual demand for materials used in the electricity infrastructure is expected to rise between now and 2050 and that despite a slightly smaller stock in the 2-degree scenario, the continued expansion of renewable electricity generation likely adds to the annual material demand for most materials.

Table 6.2 also shows that the ratio between outflow and inflow of materials indicates that a relative shortage of secondary materials to fulfill the new demand for materials in the electricity sector continues to exist towards 2050 as a consequence of continued growth of the electricity demand, and a corresponding expansion of both grid infrastructure as well as generation and storage capacity. For most materials, the 2-degree scenario increases this gap towards a more circular use of materials in the electricity sector.

In order to get a feeling for the magnitude of the annual material demand of the electricity sector compared to other sectors, we compare these results to the current production (CP) globally of materials, based on (USGS 2017; Butler and Hooper 2019; Morimoto et al. 2019).

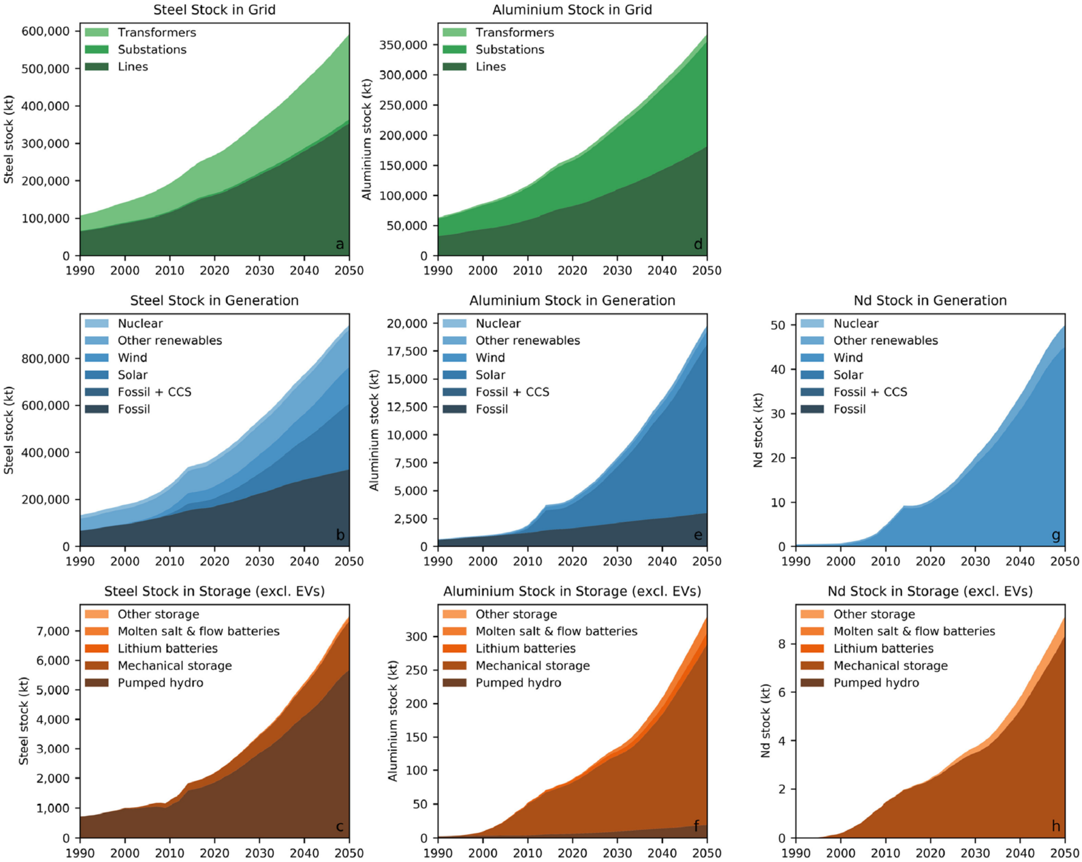

Figure 6.4a-h. *Steel, aluminium and neodymium (Nd) stock in the electricity sector between 1990 and 2050, in kt. The panel shows the SSP2 Baseline scenario results regarding the stock of Steel (left, a-c) and Aluminium (middle, d-f) and Neodymium (right, g-h) in the three sub sectors of the electricity sector, being: generation capacity (top), the transmission grid (middle) and electricity storage (bottom). Mind that the materials required for storage in electric vehicles are not displayed here because they are not strictly part of the electricity sector. The plateau in the material stocks for generation capacity around the year 2015 has to do with the IMAGE model adjusting to historic over-capacity. Panels for other materials and for the 2-degrees climate policy scenario are available in the supplementary information provided with the original publication.*

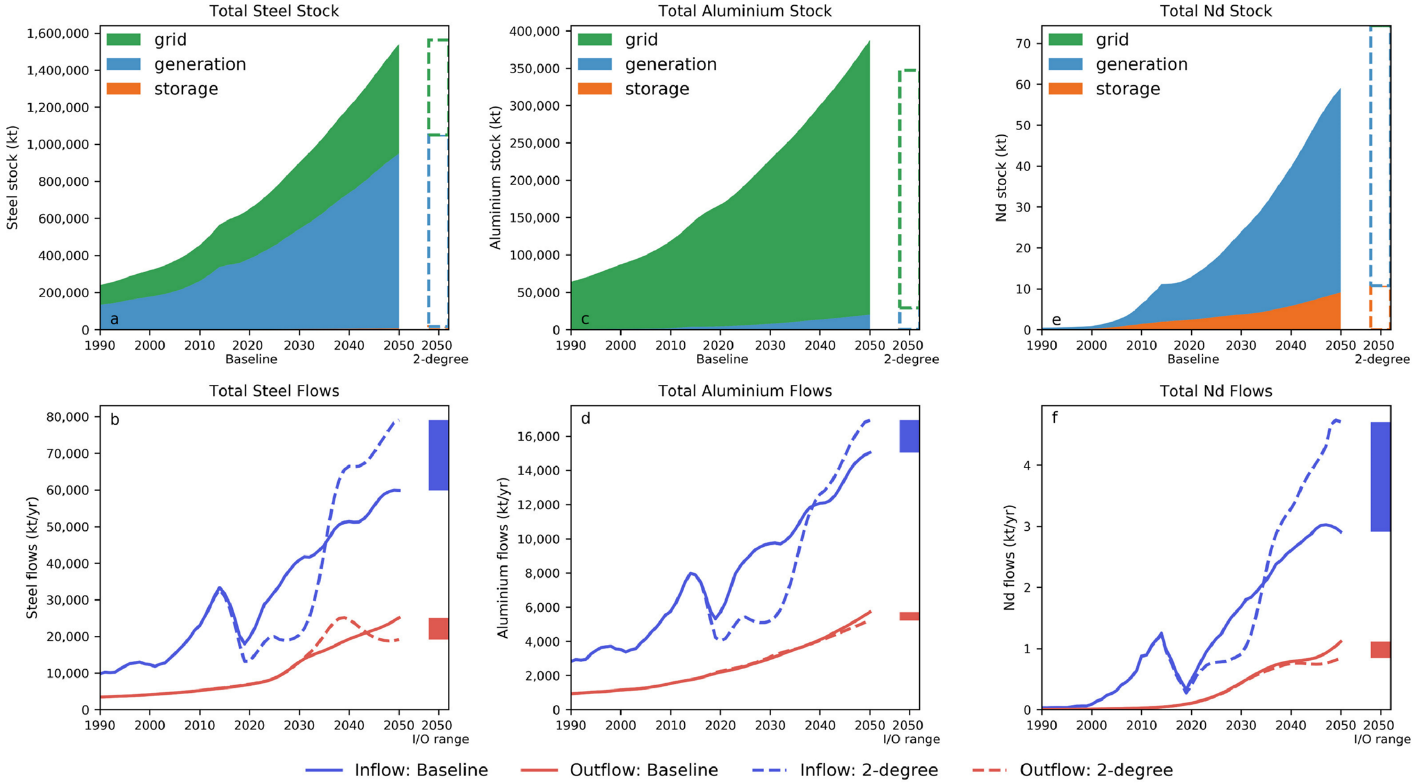

Figure 6.5a-f. *Total steel, aluminium and neodymium stocks (a,c,e) in the electricity sector and the corresponding material flows (b,d,f) in the SSP2 Baseline and the SSP2 2-degree scenario. Top panels display the stock in the SSP2 baseline as a stacked area chart and compare it to the size of the stock in the SSP2 2-degree scenario by 2050 (dashed bars). Lower panels display the inflow and the outflow of the materials under the SSP2 baseline (solid) and 2-degree (dashed) scenario. The range of the resulting inflow and outflow by 2050 is indicated by the blue and red bars respectively. Similar to Figure 6.4, the plateau in the material stocks for generation capacity around the year 2015 is a consequence of the IMAGE model adjusting to historic over-capacity, which also explains the drop in inflow for both the SSP2 baseline and the 2-degree scenario.*

This shows that the annual material demand (inflow) of the electricity sector is generally small compared to the current total global production for materials such as concrete, steel and glass, but for other materials such as copper and aluminium the electricity sector represents a considerable fraction of the total global demand. As the annual demand of the sector is expected to increase, so does the relevance with respect to the current production. Our estimates in Table 6.2 show that in a 2-degree scenario, by 2050 the electricity sector would represent up to 34% of the current global aluminium production and up to 28% of the current global copper production.

We find that by 2050, the annual copper demand in the electricity sector could exceed the copper involved in the construction of houses (Deetman et al. 2020). Even the speed at which the electricity sector expands may be larger than the growth in construction of housing (see Figure A6.11 in Appendix 6). So while the electricity sector is by no means the only cause for an increase in the global material demand (OECD 2019), it may play an increasingly important role in the demand for some materials such as copper and aluminium.

These outcomes are in line with other studies that provide projections on the material demand in the electricity sector, such as (Watari et al. 2019) who project a 2 to 9 fold increase in the demand for minerals associated with the electricity sector. Nevertheless, these outcomes are highly dependent on the timing of capital expansion. Our findings indicate the importance of developing suitable waste management practices for large infrastructural capital in the electricity sector. Our model results indicate a substantial rise in infrastructural waste flows is expected, and the expansion of the electricity sector could lead to an increased dependence on virgin raw materials. The combination of rapid growth of the capital stock and relatively long lifetimes (25-40 yr.) of technologies used in the electricity sector could lead to a mismatch between annual demand (inflow) for materials and the availability of secondary materials (scrap, or outflow) within the sector. The delay between increased material demand during stock expansion and the availability of scrap, decades later, would limit the potential for the sector to accomplish a circular flow of materials before 2050.

A general picture that emerges from these findings is that it depends on the material whether the electricity sector plays an important role in the global demand. However, mainly as a consequence of the use in the electricity transmission, the demand for copper and aluminium is considerable in comparison with other large demand categories such as residential buildings. Furthermore, the demand for most materials in the electricity sector is expected to grow rapidly, especially when accounting for the additional demand for materials under climate policy assumptions in the SSP2 2-degree scenario.

Table 6.2. *An overview of the stocks, inflows and outflows of materials in the electricity sector in 2015 and 2050, under the SSP2 baseline and the 2-degree climate policy scenario* (van Vuuren et al. 2017)*. Because inflow and outflow are volatile, the value indicated with 2015 is based on an average of the last historical model years (2010-2015) and the 2050 numbers are based on the average of the last years in the scenario period (2045-2050). The ratio column shows the outflow over inflow ratio and indicates the maximum percentage of the inflow that could be covered by the outflow of materials in the same year (when 100% of scrap would be recycled, without losses). The CP column indicates the inflow in the electricity sector as a percentage of total global current production according to* (USGS 2017; Butler and Hooper 2019; Morimoto et al. 2019).

	2015					**2050 Baseline**					**2050 2-degree**				
	Stock	**Inflow**	**Outfl.**	**O/I**	**CP**	**Stock**	**Inflow**	**Outfl.**	**O/I**	**CP**	**Stock**	**Inflow**	**Outfl.**	**O/I**	**CP**
	Mt	kt/yr	kt/yr	%	%	Mt	kt/yr	kt/yr	%	%	Mt	kt/yr	kt/yr	%	%
Steel	521	28,787	5,608	19%	1.8%	1,456	58,546	23,288	40%	3.8%	1,413	75,130	19,133	25%	4.8%
Aluminium	132	7,029	1,676	24%	14.7%	365	14,427	5,270	37%	30%	319	16,095	4,924	31%	34%
Concrete	4,772	184,782	31,173	17%	.69%	9,199	207,895	100,068	48%	.77%	8,396	227,571	85,347	38%	.85%
Glass	3	209	35	17%	.3%	23	1,257	255	20%	2%	41	2,662	263	10%	4%
Cu	38	2,086	571	27%	11.9%	98	4,256	1,828	43%	24%	91	4,934	1,611	33%	28%
Nd	0.009	1.0	0.04	3%	5.4%	0.055	3	1	32%	16%	0.064	4.4	0.8	18%	24%
Co	0.19	8	2.1	25%	7.9%	0.44	14	7	49%	13%	0.11	3.7	3.9	104%	3.4%
Pb	2.5	109	34	31%	2.1%	12.6	588	118	20%	11%	11.5	718	116	16%	15%

Even when total demand for electricity is expected to go down as a consequence of additional energy efficiency measures in a 2-degree scenario, the material intensity of renewable energy technologies leads to an increased demand for most materials used in electricity generation compared to the baseline. For more details on the outcomes of individual materials, and the full range of results for both the SSP 2 Baseline and the 2-degree scenario, please see the Supplementary Information provided with the original publication.

6.3.1 Results of the sensitivity analysis

Alternative model assumptions on the development of storage, grid expansion and material intensities as described in Section 6.2.3 only have a mild effect on the model outcomes for materials contained in the stock. The largest increase of in-use stocks is found for cobalt in the 'high storage' variant (+9%), while the largest decrease is found for steel (-7.7%) as a consequence of assuming a 'dynamic material intensity'. However, the effect of the three sensitivity variants on inflow indicators seems larger, in particular when implemented in a 2-degree scenario. This suggests that our model outcomes, especially results on annual material flows, are more uncertain for scenarios with rapid change and should therefore be interpreted with caution.

Though our model does not account for materials in vehicle batteries as these are not strictly part of the electricity sector, the sensitivity analysis does provide some insights into the importance of vehicle-to-grid services. The lower availability of storage capacity from pumped-hydro and battery electric vehicles in the 'high storage' sensitivity variant leads to an increased deployment of dedicated storage, which in turn leads to larger in-use stocks of materials by a factor 2.1 (for steel & copper) to 5.2 (for cobalt) compared to the default 2-degree scenario (See Table A6.16 in Appendix 6). This is higher than the expected increase from doubling the storage demand alone, and indicates that the availability of vehicle-to-grid storage capacity could help reduce the demand for materials in the electricity sector.

6.4 Discussion & conclusions

6.4.1 Discussion and model improvements

The key question of this chapter is how the global material stocks and flows related to the electricity sector will develop towards 2050. The model developed here is able to address this question, by showing the global stocks and flows of several materials related to the growing demand for electricity. These outcomes are relevant to a broader understanding of the societal metabolism (Pauliuk and Hertwich 2015) and its implications for curbing emission and attaining a more circular economy (Ghisellini et al. 2016). The model includes a number of key assumptions. Below we discuss the effect of these assumptions and how to possibly improve the model further.

First of all, we use our model in conjunction with outcomes of the IMAGE/TIMER model for the SSP2 baseline and 2-degree climate policy scenario. These scenarios prescribe the developments regarding the use of renewable electricity as well as the adoption of electric vehicles, for example. The outcomes of our model on resulting material stocks and annual demand are only valid in the context of this scenario selection. It would be interesting to explore the material implications of other scenarios with a higher penetration of renewable electricity and electric vehicles.

Secondly, we think that our work could benefit from an improved formulation of the development of the demand for transmission capacity of the electricity grid over time. Though we apply a set of alternative assumptions on grid expansion in a sensitivity analysis, ideally, our assumptions should be compared to scenarios from a spatially-explicit global transmission model, which unfortunately is not available at this time.

Thirdly, we should emphasize that our model assumes fixed material intensities for grid elements and generation technologies, by default. Even though our model accounts for a change in energy density of storage technologies, and the effects of some foreseeable changes in material composition are explores in the sensitivity analysis, we are unable to account for all relevant developments in the material composition of technologies. It would therefore be interesting to improve these assumptions in a future study, which may also expand the coverage of materials.

Finally, an integration of this type of work into integrated assessment models could be used to define an explicit feedback loop between material and energy demand, thus improving the modelling of long term emission scenarios (Pauliuk et al. 2017).

6.4.2 Conclusions

On the basis of the results is possible to derive several key conclusions.

The electricity sector will likely be responsible for a large increase in annual material demand towards 2050. Using the IMAGE/TIMER implementation of the SSP2 scenario and a scenario consistent with the Paris Agreement, we show that material demand for generation, transmission and storage is expected to increase. Most notably, we show that the electricity sector contributes substantially to the annual demand for materials such as aluminium and copper. While annual demand for steel and aluminium in the electricity sector is expected to roughly double in the SSP2 baseline, the aluminium demand in the 2-

degree scenario grows from 7 Mt in 2015 to around 16 Mt by 2050, and steel demand is expected to go up from 29 Mt in 2015 to 75 Mt by 2050. For Neodymium a growth factor of about 3 is found in the baseline, increasing to 4.4 in the 2-degree scenario. Copper demand grows from about 2 Mt now, to about 5 Mt by 2050. This means that by the end of the scenario period, the annual demand for copper and aluminium in the electricity sector may reach about 28% to 34% of the current annual global production (respectively).

The combination of rapid growth of the capital stock and relatively long lifetimes of technologies used in the electricity sector comprises a challenge to reaching a more circular economy. Given that the annual demand (inflow) of most analyzed materials will continue to surpass the availability of secondary materials (outflow) within the sector.

Climate policy could influence material demand in the electricity sector in different ways. In the analyzed scenarios the additional climate policies cause a higher annual energy efficiency improvement, which consequently requires a lower installed capacity of electricity generation technologies by 2050. In our study this leads to a lower amount of materials in infrastructural stock of the grid, but for the generation it still results in a larger stock as a consequence of higher material intensities of renewable generation technologies. In terms of annual material demand, climate policy seems to make it more difficult to reach circular material flows in the electricity sector by 2050.

6.4.3 Policy implications

While the electricity sector is by no means the only contributor to an increase in the global material demand in the coming decades, the expected rate of growth in the infrastructure required to generate, transmit and store electricity could mean it will be increasingly important in the demand for materials towards the year 2050. To mitigate some of the environmental impacts related to the production of these materials, regional policies could be aimed at adequate deployment of recycling capacity and stimulating material efficiency. Our analysis shows that material use in renewable energy systems is not only interesting from the perspective of the often-highlighted critical raw materials in storage applications. The demand for bulk materials in the infrastructure for the transmission and generation of electricity should also be accounted for in scenarios looking at the development of future energy systems. Higher material intensities for renewable generation technologies, and the required expansion of transmission and storage capacity in a renewable energy system imply a higher annual demand for most considered materials under climate policy ambitions. This seems to present an apparent trade-off between ambitions related to climate policy and circular economy policy, given that the long lifetimes of capital stock and the additional increase of the material demand resulting from a renewable energy system will make it more challenging (if not impossible) to achieve circular material flows in the electricity sector before 2050. However, this work does not encompassingly assess the material use implications of electrification in other sectors, which would be required to confirm such a trade-off. Nevertheless, the deployment of additional infrastructure in the electricity sector could ultimately enable the reliable production of low-carbon electricity at low costs. The enticement of this perspective could justify policies aimed at optimal timing of the deployment of transmission capacity, dedicated storage & vehicle-to-grid services, in order to limit the impacts of additional material demand from the electricity sector as much as possible.

Practically, our analysis highlights the potential of electric vehicles to provide electricity storage capacity to balance supply and demand on the grid. Though the concept of bidirectional charging or vehicle-to-grid (V2G) services is not yet applied on a large scale, it provides a promising opportunity to avoid demand of materials that would otherwise be required to install dedicated electricity storage towards 2050. Our analysis presents an optimistic picture in the sense that it assumes the availability of pumped-hydro storage as well as a slow adoption of storage in electric vehicles after 2025. Under these conditions, climate policy seems to provide a synergetic solution to its own problem as the additional demand for electricity storage could be fulfilled with a simultaneously growing battery capacity of the increased electric car fleet, in line with the SSP2 2-degree scenario. The increase in material demand under less favorable assumptions on storage demand in the sensitivity analysis emphasizes the importance of stimulating and governing the effective deployment of synergistic technologies such as vehicle-to-grid storage in a renewable energy system over the coming years.

Acknowledgements

Our model uses the open sousrce python Dynamic Stock Model as developed by Stefan Pauliuk and described by Pauliuk and Heeren (2019).

Appendix

More information regarding details of the analysis and assumptions made in this chapter are available in Appendix 6.