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Research paper

May material bottlenecks hamper the global energy transition towards the 1.5 °C target?

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ABSTRACT

Potentially scarce materials play an important role in many current and emerging technologies needed for a sustainable energy and mobility system. This paper examines the global demand for 25 potentially scarce materials that would result from an energy system that is compatible with the 1.5 °C target. It further analyses the risk for short- and mid-term material shortages. To determine the material requirements, an extensive prospective database was built up on the specific demand of these materials in key technologies. A second database describes the potential development of sub-technology market shares within a technology class. A material flow analysis model was used to determine the annual and cumulative material requirements as well as the recycling potential in the underlying scenario. The results show that production of all materials has to increase, in some cases significantly, in a short period of time to meet the demand for the energy and transportation system. In addition, the cumulative demand for some materials significantly exceeds current reserves and even resources. In particular, lithium (demand increase (DI) more than factor 10, cumulated demand (CD) exceeds reserves up to factor 2), cobalt (DI/CD: <7/<3), and nickel (CD/DI: <2.4/<1.4) for batteries, dysprosium (DI < 8) and neodymium (DI < 1.5) (for permanent magnets (wind turbines and electric motors), and iridium (DI < 2.9) as well as platinum (DI < 1.8) (fuel cells, electrolyzers) are affected. The construction of battery electric and fuel cell electric vehicles thus represents a major driver of the material demand. Depending on the material, shortages can be reduced or delayed by technology substitution, material recycling, technology lifetime extension, increased material efficiency, and a smaller future vehicle stock, but not entirely avoided. Hence, it can be expected that material bottlenecks will result in increasing material prices, at least in the short to medium term.

1. Introduction

The mitigation of the man-made climate change is one of the most pressing issue of our generation. To potentially limit the global temperature increase to under 1.5°, a swift and decisive transformation of the global energy and transport sector towards renewable energy technologies is necessary (Teske, 2019). To stay within the global CO_2 emission budget this transition must take place in the next decades and will pose significant technical, political, economic and social challenges. One of those challenges is the availability of resources to enable the rapid switch to renewable technologies: Renewable power generation technologies, but also energy storages and new propulsion technologies in the transport sector require different and a wider range of materials in comparison to 'classic' power generation technologies (Watari et al., 2018), some of which are rare (e.g. platinum-group metals, PGM) (European Commission, 2017) or difficult to mine (rare earth elements, REE) (Zhou et al., 2017).

In order to estimate the raw material demand associated with a transformation of the energy system, energy system models and energy scenarios can be coupled with material flow analyses (Kullmann et al., 2021). Watari et al. (2020) summarized the state of the debate on resource demand in connection with the transformation of the global energy system, which has gained a lot of attention especially in the last 5–10 years.

Published studies on resource demand for the energy transition differ greatly in their scope of technologies and resources considered. The most comprehensive studies consider a wide range of resources and technologies in the context of the global energy transition, while some studies focus on regional analysis, e.g. the European Union (Moss et al., 2013) or specific countries (Viebahn et al., 2015; Elshkaki and Shen, 2019). In addition to these more comprehensive studies there are a variety of studies focusing on the resource demand of one or two specific technologies, often wind power and photovoltaic (Blagoeva et al., 2016; Carrara et al., 2020), as these two technologies are expected

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to be the backbone of future power supply (International Energy Agency, 2019). Many studies also address the issue of material demand for electric vehicles (Watari et al., 2020). Especially the resource demand for batteries in electric vehicles has been a point of discussion over the last 10–20 years (Andersson and Råde, 2001; Kushnir and Sandén, 2012; Olivetti et al., 2017; Jones et al., 2020). The material demand of technologies necessary for a hydrogen based economy, fuel cells and electrolysers, as well as more niche technologies like CSP have been studied to a lesser extent (Watari et al., 2020). These technologies are mostly studied within the more comprehensive studies with few specialized exceptions; Kleijn and van der Voet (2010) assess potential resource constraints in a hydrogen economy, Wittstock et al. (2019) examine the demand for critical materials for stationary and mobile fuel cells, Kiemel et al. (2021) the demand for water electrolysis and Pihl et al. (2012) published a detailed analysis of material constraints for CSP.

The studies analysed in Watari et al. (2020) deal most frequently with the rare earths dysprosium and neodymium required for permanent magnets in wind mills and electric motors (see Zhou et al., 2017; Hoenderdaal et al., 2013; Habib and Wenzel, 2014; Li et al., 2020 on global and Fishman and Graedel, 2019; Imholte et al., 2018 on national levels). Lithium and, to a lesser extent, cobalt are also among the elements most commonly analysed (Watari et al., 2020). Both elements are required in many battery technologies. Other materials that are of the focus are copper, indium and tellurium. While indium and tellurium are considered almost exclusively in studies on PV systems, copper is used as a (bulk) material in almost every technology and is therefore investigated in a wide range of studies (Watari et al., 2020).

While many studies focus on a few materials and technologies, there are numerous papers that take a broader view: Kleijn and van der Voet (2010) assessed potential resource constraints in a hydrogen economy based on renewable energies. They focus on PV and wind power generation, the transmission grid, hydrogen production (electrolysers) and end-use technologies (FCEV and stationary fuel cells). They conclude that neodymium, platinum and the thin-film PV elements (Cd, Te, Se, Ga, In, Ge, Ru) prevent the necessary upscaling of the respective technologies to the level needed for a sustainable transition to a hydrogen economy. Kleijn et al. (2011) assessed the metal requirements to decrease the CO_2 emissions of the power generation sector using life cycle assessment (LCA) data for the low-carbon technologies carbon capture and storage (CCS), nuclear and renewable. They focus on the demand for bulk materials. The analysis shows that metal demand will increase regardless of whether the CCS or non-fossil path to emission reduction is chosen. The non-fossil path, however, results in a higher demand. An approach to circumvent the problems based on the use of scarce materials in the global energy transition was investigated in García-Olivares et al. (2012), who suggest a renewable energy system with technologies using only little potentially scarce minerals. However, they conclude that the demand for lithium and platinum in the transport sector still poses significant challenges and, to decrease the neodymium demand, wind turbine types without permanent magnets should be focused in the large-scale deployment of wind power. Moss et al. (2013) examined the risks for metal bottlenecks for the deployment of strategic energy technologies in the European Union up to 2030 in detail. Five elements (dysprosium, neodymium, gallium, indium & tellurium) out of over 50 were identified as critical. Elshkaki and Graedel (2013) used dynamic material flow analysis to assess the global metal flows and stocks of 19 different resources in renewable energy generation technologies. They conclude that the supply of resources is not a problem for wind power in any of the scenarios considered. For photovoltaics however, bottlenecks may arise for silver, tellurium, indium, and germanium. Grandell et al. (2016) assess the demand for 14 critical materials due to the global transition towards renewable energies. Silver, mostly used in PV and CSP, is identified as most critical. Indium and tellurium which are also metals necessary for specific PV panels also exceed global reserve values considerably. In addition, platinum group metals (PGM) and rare earth elements (REE: neodymium, dysprosium and lanthanum) are identified as critical resources. Tokimatsu et al. (2017) and Tokimatsu et al. (2018) assess the metal requirements to reach the 2 °C target in different energy scenarios. They conclude that – depending on the scenario analysed – material bottlenecks could arise for nuclear, PV and electromobility and identified 11 materials (Se, In, Te, Dy, Ni, Zr, Pt, Y, V, Li & La) as critical, with vanadium identified as distinctly. de Koning et al. (2018) conclude that, despite the dramatic increase in the annual demand for indium, neodymium, dysprosium and lithium in the energy and transport sectors, the availability of the considered resources (Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li Zn, Pb) is unlikely to be a bottleneck for transforming the global energy system but that a delay of the necessary expansion of production capacities for these resources could lead to imbalances in demand and supply in the future. Tokimatsu et al. (2017) explore the effects of recycling and the usage of different sub-technologies on global metal flows in the transition towards renewable energy technologies. The analysis shows that material bottlenecks for specific sub-technologies are foreseeable, e.g. thin-film PV and Li-based batteries, and – under certain sub-technology scenarios – neodymium (wind power and electro motors). Valero et al. (2018) identified 13 resources that have a high risk of generating bottlenecks due to their necessity for the future development of renewable energy technologies up to 2050. The transport sector will presumably have the highest demand for critical materials with constraints mainly affecting lithium, cobalt and nickel for mobile batteries. In the PV sector the metals indium, silver, selenium, tin and tellurium may exceed current reserves and for wind power the rare earths neodymium and dysprosium seem to have the highest risk. Moreau et al. (2019) examine the requirements of 29 metals for renewable energy technologies in different energy and technology scenarios and compare it with known reserves. The reserves for eight metals (Cd, Co, Au, Pb, Ni, Ag, Sn, Zn) are likely to be depleted before a renewable energy system is fully deployed in 2050, independent of the energy or technology scenario. Depending on the scenario, lithium demand in the long term (second part of century) could also exceed reserves. Watari et al. (2019) examine the total material requirement for the global energy transition to 2050 focusing on transport and energy generation technologies. The results indicate a drastic increase in total material requirements. This increase is mainly driven by the demand for copper, silver, nickel, lithium, nickel and steel. Junne et al. (2020) analyse the demand for Li, Co, Nd, and Dy (in wind power, mobile and stationary batteries, electromotors) in six global energy system scenarios. They showed that the selection of different sub-technologies within a technology class can have significant impact on the demand for critical materials.

Many of the studies cited provide valuable individual contributions to the question of the extent to which the scarcity of certain materials might impede rapid transformation of the energy system. In doing so, they are generally based on scenarios for the energy transition that are not in line with the current targets from the Paris Agreement to limit global warming to less than 1.5 °C and not always consider the entire energy and transport system. Furthermore, approaches to mitigate the bottlenecks (such as increasing material efficiency, extending the lifetime of technologies, technology substitution and recycling) are not or only marginally considered. This paper fills this gap by addressing the following research questions:

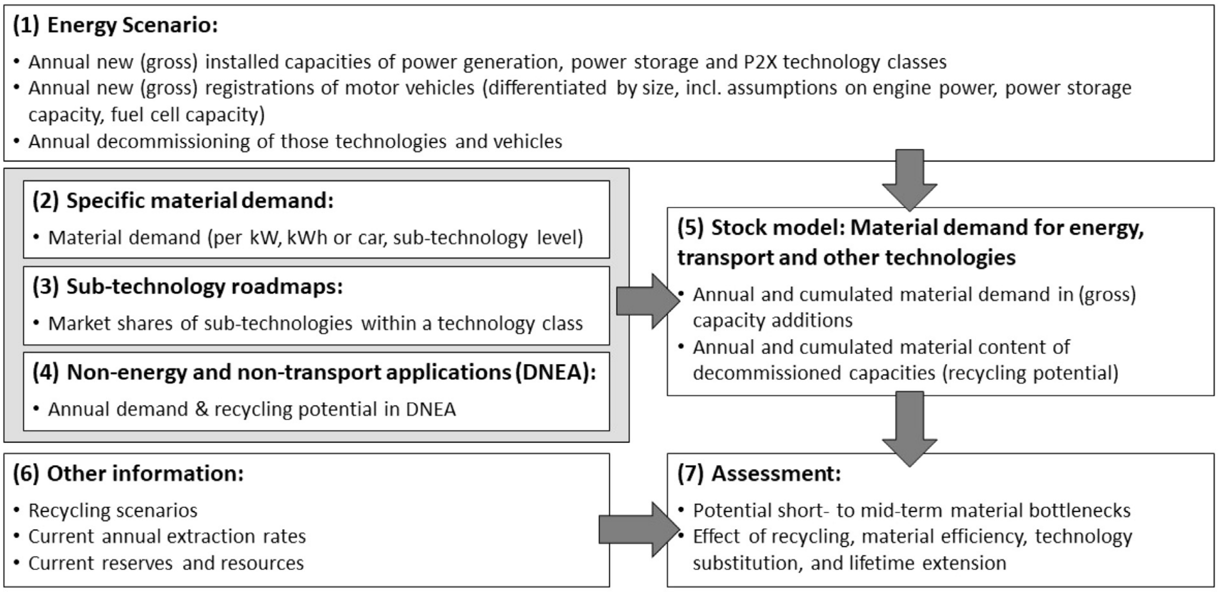

Fig. 1. Overview of the workflow.

– How will the demand for potentially scarce materials develop over the next decades as a result of the energy transition in agreement with the 1.5 °C goal of the Paris Agreement?
– How much do current annual production capacities for certain materials need to be expanded and to what extend will new deposits have to be exploited in order to meet the additional material demand from the energy and transport system?
– How much can sub-technology substitution, lifetime extension, material efficiency and material recycling help reduce potential material shortages?

The analysis considers the most relevant technologies for the energy transition and 25 different materials (see Table 1). It is based on a comprehensive literature review of the specific material demand in energy and transport technologies as well as potential future development of sub-technology market shares within each technology class. The data bases used for the calculation are published in the supplementary material.

2. Materials & method

2.1. Overview of the workflow

The method used in this paper is a further development and expansion of the method from Junne et al. (2020) and is depicted schematically in Fig. 1:

In a first step, the materials considered in this study are selected based on criteria described in Section 2.2. The resource demand analysis is carried out on the basis of a selected transformation scenario for the global energy system (Section 2.3) as well as two databases set up on the basis of literature research and expert interviews. The database 'Specific Material Demand' (SMD, Section 2.4) includes data for 25 materials and over 50 (sub-) technologies on the development of specific material demand (e.g. per kW installed capacity, per kWh storage capacity, per car etc.). In each technology class (e.g. PV) different sub-technologies (e.g. c-Si, CIGS, …) are differentiated. This is necessary as the specific demand of a given material might differ considerably between sub-technologies. The database 'Sub-Technology Roadmaps' (Section 2.5) describes scenarios how the market shares of the various sub-technologies within a technology class could develop until 2050. The calculated demand in the energy and transport sector is complemented by the demand for each material in non-energy (and non-transport) applications (DNEA, see Section 2.6). A stock model is used to calculate the annual resource demand and recycling potential (Section 2.7.) Sensitivity tests (Section 2.8) allow estimating the effects of sub-technology substitution, material efficiency, lifetime extension, and recycling. Demand results are compared with current extraction rates and known reserves and resources (Section 2.9) in order to assess potential short- and mid-term material bottlenecks.

Differences to the method of Junne et al. (2020) are primarily the consideration of the expected decrease of the specific material demand until 2050 (material efficiency). Furthermore, the calculation of new and decommissioned capacities has been improved. In addition, significantly more materials and technologies are considered in the present paper. Technology roadmaps for technologies already considered in Junne et al. were updated on the basis of more recent literature and expert interviews.

2.2. Selection of materials analysed in this study

In order to determine the materials to be investigated, the first step was to compile a list of materials that are considered to be potentially scarce (limited global production capacities and/or low deposits) from the literature (e.g. Li et al. (2019) and European Commission (2020)). Materials considered critical *only* because of geopolitical risks were not included. In a second step, literature on renewable energy and transport technologies were examined with regard to the required materials (e.g. Watari et al. (2020), Li et al. (2019) and Marscheider-Weidemann et al. (2021)) and the intersection between the potentially scarce materials and materials in energy and transportation technologies was identified. Potentially scarce elements are mainly required in photovoltaics (PV), wind power and concentrating solar power

Table 1
Current production, estimates on reserves and resources, and current recycling rates for all selected materials.

Material	Production [t/a]	Ref.	Reserve [kt]	Ref.	Resource [kt]	Ref.	Current recycling rate	Ref.
Cadmium	25.000	Geological Survey (2020)	7.500	Geological Survey (2020)	57.000	Geological Survey (2020)	15%	Graedel et al. (2011)
Cerium	80.900	Zhou et al. (2017) and Geological Survey (2020)	46.240	Zhou et al. (2017) and Geological Survey (2020)	106.540	Zhou et al. (2017)	1%	Graedel et al. (2011)
Cobalt	140.000	Geological Survey (2020)	7.000	Geological Survey (2020)	25.000	Geological Survey (2020)	68%	Graedel et al. (2011)
Dysprosium	1.647	Junne et al. (2020) and Geological Survey (2020)	544	Zhou et al. (2017) and Geological Survey (2020)	1.255	Zhou et al. (2017)	1%	Graedel et al. (2011)
Gadolinium	1.822	Zhou et al. (2017) and Geological Survey (2020)	1.040	Zhou et al. (2017) and Geological Survey (2020)	2.400	Zhou et al. (2017)	1%	Graedel et al. (2011)
Gallium	320	Geological Survey (2020)	5.2	Månberger and Stenqvist (2018)	100	Geological Survey (2020)	1%	Graedel et al. (2011)
Germanium	130	Geological Survey (2020)	119	Frenzel et al. (2014)	440	Sverdrup et al. (2014)	1%	Graedel et al. (2011)
Indium	760	Geological Survey (2020)	47.1	Månberger and Stenqvist (2018)	96	Geological Survey (2020)	1%	Graedel et al. (2011)
Iridium	8	Alison (2020)	0.44	Geological Survey (2020) and Sverdrup and Ragnarsdottir (2016)	0.64	Geological Survey (2020) and Sverdrup and Ragnarsdottir (2016)	25%	Graedel et al. (2011)
Lanthanum	44.319	Zhou et al. (2017) and Geological Survey (2020)	25.330	Zhou et al. (2017) and Geological Survey (2020)	58.370	Zhou et al. (2017)	1%	Graedel et al. (2011)
Lithium	77.000	Geological Survey (2020)	17.000	Geological Survey (2020)	80.000	Geological Survey (2020)	1%	Graedel et al. (2011)
Manganese	19.000.000	Geological Survey (2020)	810.000	Geological Survey (2020)			53%	Graedel et al. (2011)
Neodymium	29.169	Junne et al. (2020) and Geological Survey (2020)	16.070	Zhou et al. (2017) and Geological Survey (2020)	37.040	Zhou et al. (2017)	1%	Graedel et al. (2011)
Nickel	2.700.000	Geological Survey (2020)	89.000	Geological Survey (2020)	130.000	Geological Survey (2020)	60%	Graedel et al. (2011)
Platinum	180	Geological Survey (2020)	44	Månberger and Stenqvist (2018)	47.4	Geological Survey (2020) and Sverdrup and Ragnarsdottir (2016)	70%	Graedel et al. (2011)
Potassium	34.000.000	Geological Survey (2020)	3.000.000	Geological Survey (2020)	5.800.000	Geological Survey (2020)	0%	Graedel et al. (2011)
Scandium	11	Geological Survey (2020)			1.150	Weng et al. (2015)	1%	Graedel et al. (2011)
Selenium	2.800	Geological Survey (2020)	99	Geological Survey (2020)			5%	Graedel et al. (2011)
Silver	27.000	Geological Survey (2020)	560	Geological Survey (2020)	1.025	Sverdrup et al. (2014)	40%	Graedel et al. (2011)
Strontium	220.000	Geological Survey (2020)	2.980	Geological Survey (2020)	438.800	Geological Survey (2020)	1%	Graedel et al. (2011)
Sulphur	79.000.000	Geological Survey (2020)					0%	Graedel et al. (2011)
Tellurium	470	Geological Survey (2020)	31	Geological Survey (2020)			1%	Graedel et al. (2011)
Vanadium	73.000	Geological Survey (2020)	22.000	Geological Survey (2020)	63.000	Geological Survey (2020)	1%	Graedel et al. (2011)
Yttrium	9.448	Geological Survey (2020)	3.120	Zhou et al. (2017) and Geological Survey (2020)	7.165	Zhou et al. (2017)	0%	Graedel et al. (2011)
Zirconium	1.036.500	Geological Survey (2020)	45.900	Geological Survey (2020)			1%	Graedel et al. (2011)

(CSP), hydrogen technologies (fuel cells, electrolysers), electromobility and stationary power storage. Potentially scarce elements required for the energy transition are listed in Table 1. Although copper is often considered as potentially scarce and plays an important role in the power system (Watari et al., 2020), it was excluded from this analysis as it is not possible to quantify the large copper demand in power lines, which is expected to dominate the copper demand in the energy system. An overview of which material is used in which technology can be found in Fig. 3 in the supplementary material.

2.3. Energy scenario

The basis for the analysis here is a global 1.5 °C scenario from European Commission (2020). The scenario describes a very ambitious pathway in which global energy related CO_2 emissions are cut down to zero by 2050 and the cumulated energy related CO_2 emissions for the period 2015–2050 are limited to 450 Gt. Details on the scenario and the necessary processing of scenario results can be found in Section 1 in the supplementary material.

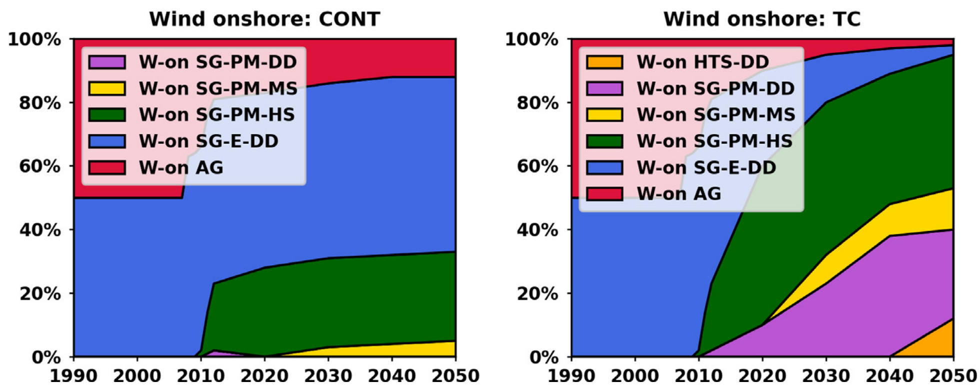

Fig. 2. Development of the market shares of different sub-technologies in total new installations in a given year ("roadmap"), here exemplarily for the technology class wind onshore and the roadmaps "CONT" (left) and "TC" (right).

2.4. Specific material demand

The 'Specific Material Demand'-database is based on a comprehensive literature research of specific material demand (SMD) of energy generation, conversion and storage technologies and electric motors in vehicles. It comprises data for 25 materials (see Section 2.2) and over 50 sub-technologies. If SMD data for (then) current technologies are reported in the analysed literature, the year of publication was chosen as the reference year for this data. Reference years are also usually given for estimates of the future potential development of SMD. Reference years were chosen for the database in 5-year increments and the reference year from the literature was assigned to the next reference year in the database. Ideally, this will result in multiple data points per reference year in the database, allowing an estimate of the uncertainties of the SMD. In the case where no estimates are available for 2050, the SMD for 2050 was assumed to be the same as the SMD for the last available reference year. For the further calculations, linear interpolation was performed between the reference years of the database. A detailed description and documentation as well as the data itself can be found in the supplementary material.

2.5. Sub-technology roadmaps

The specific material requirement may vary significantly from sub-technology to sub-technology within a technology class. Sub-technology roadmaps describe the development of the market shares of each sub-technology in the total new capacity within a technology class over time. Two different roadmaps were defined for each technology class which describe different "narratives" of market development and innovation:

- **Continuity (CONT):** Existing market trends continue; no sudden jumps regarding the market shares of the different sub-technologies occur.
- **Technological Change (TC)**: Due to a rapid increase of market shares for newer sub-technologies the established sub-technologies lose market power and are in some cases even completely pushed out.

Sub-technology market shares for the years 1990–2020 were taken from industry reports and similar studies. Future market shares were estimated based on industry reports, expert interviews and own assumptions. The concept of the roadmaps is illustrated in Fig. 2, which shows the CONT and TC roadmaps for onshore wind turbines. A detailed documentation of all roadmaps, plots and data sheets can be found in the supplementary material.

2.6. Demand in non-energy and non-transport applications (DNEA)

The selected materials are also required in non-energy and non-transport applications (DNEA). To get a comprehensive overview of the future demand for each material it is necessary to also include estimates on DNEA in the assessment. In this study, DNEA is estimated (Junne et al., 2020), which in principle extrapolates current DNEA with estimates on global GDP growth. Details on the calculation can be found in the supplementary material.

2.7. Material flow analysis (MFA) model

In the material flow analysis (MFA) model, the annual and cumulative resource demand, as well as the annual and cumulative material content from decommissioned capacities, is calculated using the data from the selected scenario, the two DLR databases and the demand beyond the energy and transport sector. The MFA model is described in detail in the supplementary material.

The annual new installations of the respective capacities of the technology classes are broken down to the sub-technology level using the sub-technology roadmaps. These values are multiplied by the specific material demand of the individual sub-technologies in the corresponding years (derived from the 'Specific Material Demand' database). The values of the individual sub-technologies are then added up, either per year or over the entire time period. Based on the lifetime of each technology class (defined in the LDF scenario Teske, 2019) the stock model also calculates the amount of decommissioned capacities and the resulting material content that could potentially be recycled and reused (recycling potential of the energy and transport sector). By adding the, either yearly or cumulated, resource demand/recycling potential of the non-energy applications we get the complete resource demand and recycling potential.

2.8. Sensitivity tests

The effect of **recycling quotas** on the primary material demand was assessed in three different sensitivity tests:

- "moderate recycling": recycling quota for all minerals are held constant at current levels (Table 1)
- "ambitious recycling": recycling quota for all minerals increase linearly to 80% in 2050
- "100% recycling": To assess the minimum amount of primary material required for the transformation scenarios, calculations with a recycling rate of 100% were performed.

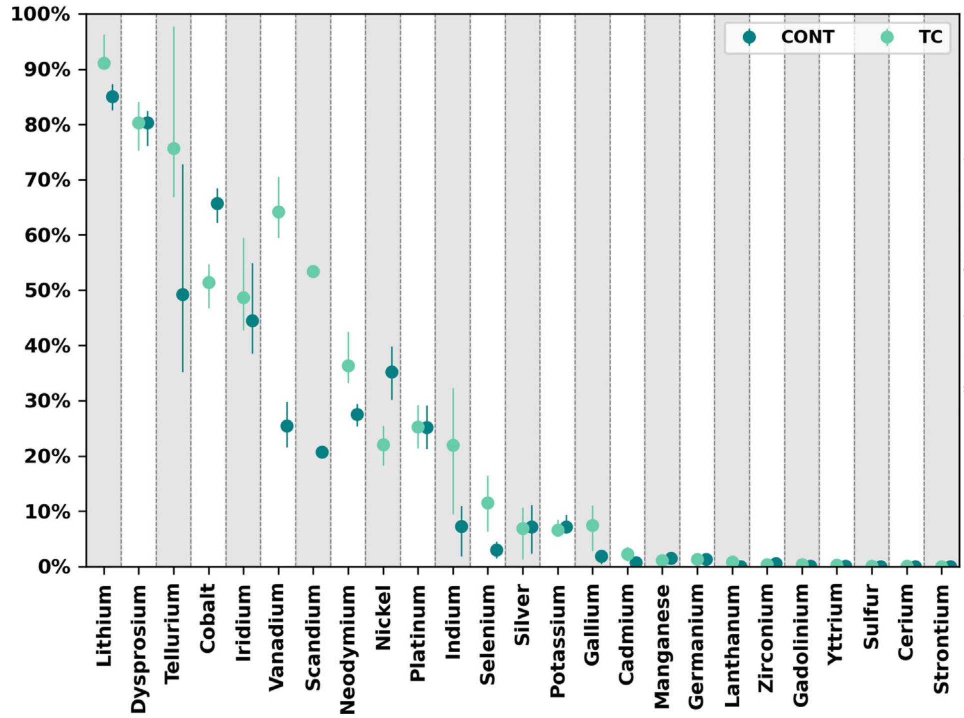

Fig. 3. Share of energy and transport technologies in total cumulated material demand (2015–2050) in the CONT and TC roadmaps. The error bars indicate uncertainties only due to uncertainties in the specific material content for energy and transport technologies (i.e. not DNEA).

The effect of **increasing material efficiency** was estimated by comparing mineral demand in the standard setup (which includes material efficiency) with a run where the specific material demand is held constant at the 2020 level for each material and technology.

The effect of a **longer technical lifetime** was estimated by comparing mineral demand in the standard setup (technical lifetimes documented in the supplementary material) with calculations where the lifetime of each technology was increased by 25% (and rounded up to the next integer).

Furthermore, the effect of **technology substitution** can be analysed by comparing the results for the different roadmaps (see Section 2.5).

2.9. Assessment of potential resource bottlenecks

In order to assess potential short- and long-term bottlenecks, the calculated resource demand is compared to geological limiting factors on a global level:

- **Short-term bottlenecks**: Is the current global **production** capacity sufficient to meet the increasing annual demand?
- **Mid- to long-term bottlenecks**: Is the capacity of currently economically mineable and/or potentially feasible global deposits (**reserves/resources**) sufficient to meet the cumulative demand in the timeframe of 2015 to 2050?

Reserves are defined as those deposits that could be economically extracted or produced at the time of determination (Geological Survey, 2020). It does not imply that extraction facilities are in place and operative. Resources are defined as the known deposits for which economic extraction is currently or potentially feasible (Geological Survey, 2020).

Reserve and resource estimates are not definite, clear and unchangeable limits. Higher demand for certain materials (potentially resulting in an increase in price), as well as technical progress in the mining sector, can significantly increase the proportion of economically mineable reserves. The same applies for resources; price increases and technical progress can lead to the exploration of new potentially economically mineable deposits.

Data on current production as well as estimates of reserves and resources are summarized in Table 1.

3. Results

The following sections examine the share of energy and transport technologies in the global demand for the materials studied (Section 3.1). Section 3.2 shows which energy and transport technologies contribute to the cumulative material demand and to what extent. In a third step, the demand is compared with current production volumes and known reserves (Section 3.3). Section 3.4 analyses the impact of technology substitution. The results of the other sensitivity tests are presented in Section 3.5. Additional detailed results (e.g. time series plots for annual and cumulated demand and recycling potential, results of the sensitivity tests) can be found in the supplementary material.

3.1. Share of material demand for energy and transport in total material demand

Fig. 3 shows the share of the energy and transport sector in the cumulated material demand (i.e. including demand for non-energy applications, DNEA) for both roadmaps and for each selected material. It can be seen that the cumulated demand for lithium, dysprosium, tellurium, and cobalt is clearly dominated by energy and transport technologies, which contribute more than 50% to the total demand. Energy and transport technologies also contribute significantly to the total demand of vanadium, scandium, neodymium, nickel, platinum, indium, selenium, silver, potassium, and gallium, with shares generally between 5 and 50%. For the other materials analysed here – cadmium, manganese, germanium, lanthanum, zirconium, gadolinium, yttrium, sulphur, cerium, and strontium, the contribution of the energy and transport sectors to total demand is very small (5% or less). Note that for some minerals (e.g. tellurium, vanadium, scandium), the

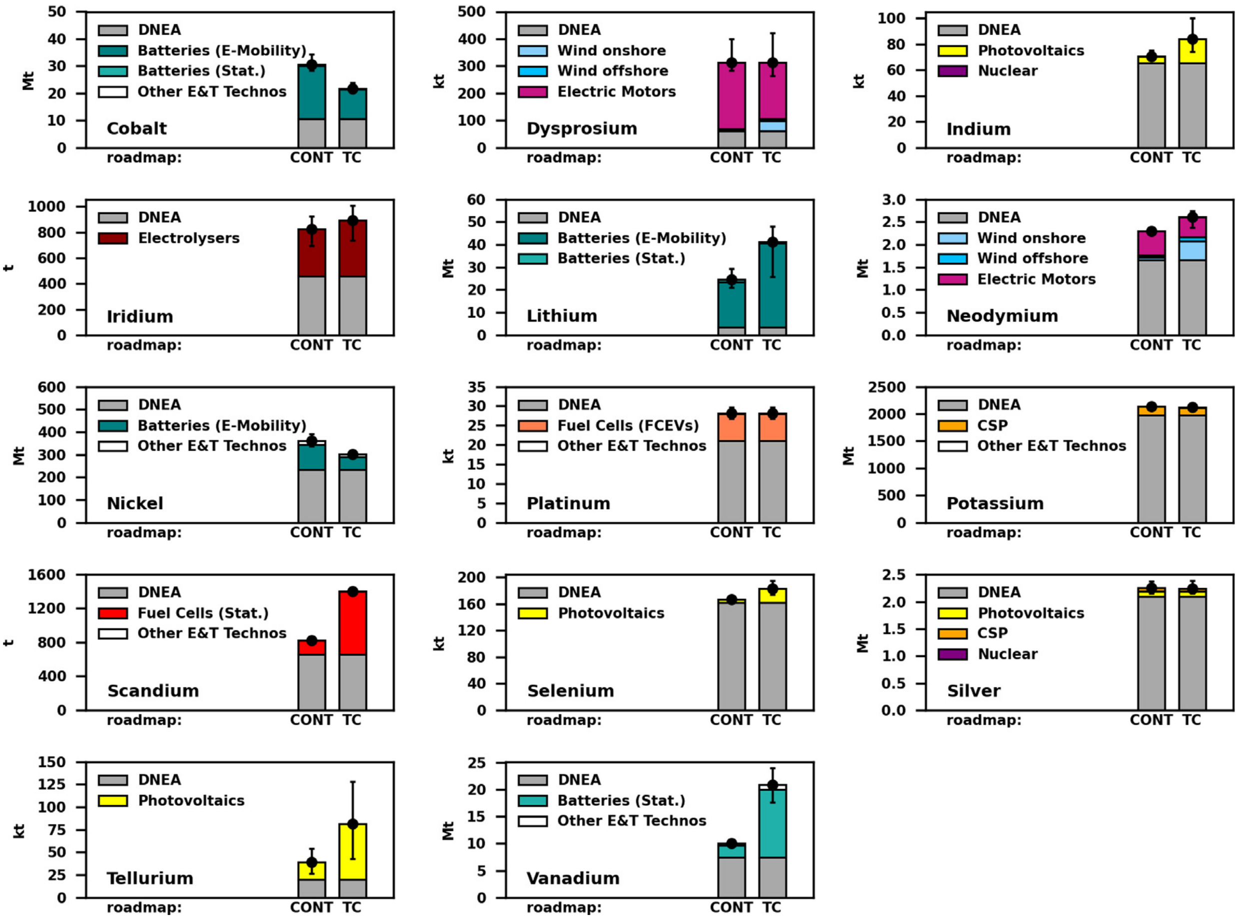

Fig. 4. Cumulated material demand (2015–2050) per technology and roadmap for selected elements. The error bars indicate uncertainties due to uncertainties in the specific material demand in energy and transport technologies (without DNEA).

share depends strongly on which sub-technologies are used in the relevant technology classes (see differences between CONT and TC roadmaps in Fig. 3).

3.2. Technologies contributing to the total demand

In Fig. 4 the cumulated material demand per technology class and roadmap for those materials for which the energy and transport sector has a significant impact are shown. Furthermore, it illustrates how the choice of sub-technology roadmaps affects the cumulated material demand.

The demand for **cobalt** is clearly dominated by batteries in electric vehicles: battery electric vehicles (BEV), plugged-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV), and (mild) hybrid electric vehicles (HEV). The cobalt demand for stationary batteries or other energy and transport technologies (fuel cells and electrolyzers) is small. In a similar manner, **lithium** and **nickel** are mainly used in mobile batteries. The demand for nickel and lithium in stationary batteries is comparatively low. The small amounts of nickel required for other energy technologies (wind turbines, PV, CSP, fuel cells, electrolysers, conventional power plants) are of no significance.

Dysprosium and **neodymium** are used in permanent magnets in electric motors and wind turbines. Depending on the roadmap used, the demand for Dy and Nd in wind turbines can be neglected compared to the demand for electric mobility.

Indium, **selenium** and **tellurium** are only used in thin-film PV technologies (indium to a small extent also in nuclear power plants). **Silver** is required for electrical contacts in PV systems and for silver-plating the mirrors of concentrating solar power plants (CSP). **Platinum** is almost exclusively required for fuel cells, in the case of this scenario mainly for fuel cell electric vehicles (FCEVs). The platinum demand for stationary fuel cells and electrolysers is negligible in this scenario. **Iridium** is used only in electrolysers. **Scandium** is required for certain types of stationary fuel cells, but also to a much lesser extent in electrolysers. **Vanadium** is mainly used in a special type of stationary batteries, but to a lesser extent also in wind turbines, PV, CSP and nuclear power plants, fuel cells, and electrolysers. The demand for Vanadium depends strongly on the selected roadmap for stationary batteries.

As a summary it can be seen that the transport sector is directly or indirectly the main driver for the demand of many these minerals: cobalt, lithium, nickel, and platinum are almost exclusively used in electric vehicles, dysprosium and neodymium to a large extent. As the H_2 demand in the scenario is driven by the demand for FCEVs, also the iridium demand for stationary electrolysers is mainly (although indirectly) caused by the development of the propulsion technologies in the transport sector. The other elements selected here (indium, scandium, selenium, silver, tellurium, vanadium) are mainly required for power generation or power storage. Only potassium is required in thermal storages (however, in CSP plants, and thus indirectly also for power generation and storage).

3.3. Comparison of material demand with production and reserves

Fig. 5 compares the cumulated material demand *in energy and transport applications alone* with known reserves (x-axis) and

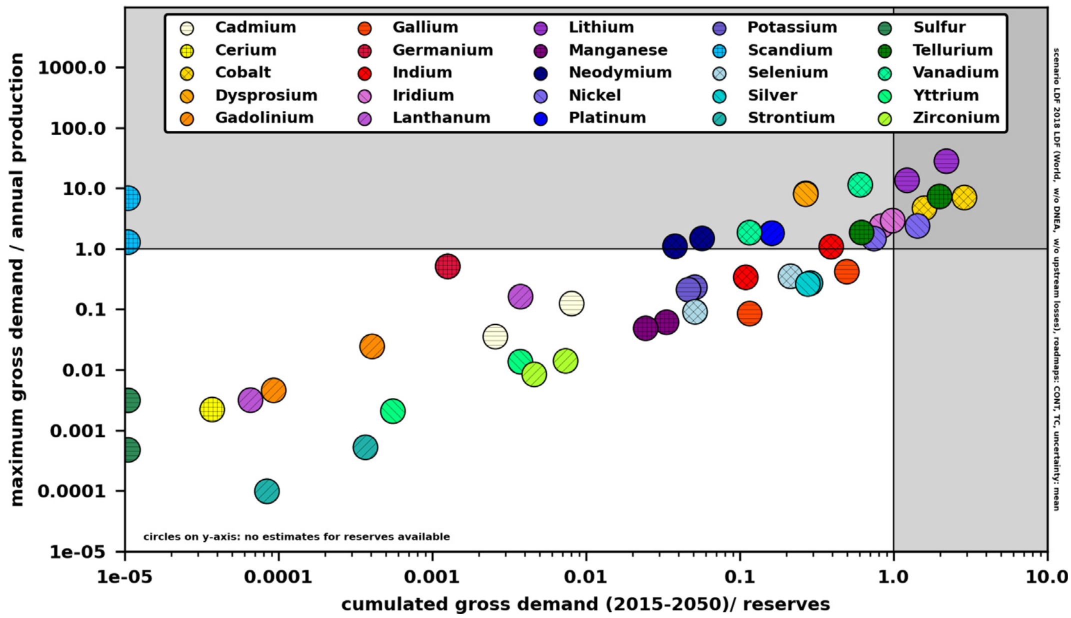

Fig. 5. X-axis: ratio of cumulative material demand (2015–2050) and actual reserves for both roadmaps. Y-axis: ratio of maximum annual material demand and actual production, also for both roadmaps. Demand estimates for energy and transport technologies only.

the maximum demand within the period 2000–2050 with the actual production of each mineral (the corresponding years of the maximum demand are documented in the supplementary material). Fig. 6 shows similar results, but in this case demand estimates include the demand in non-energy applications (DNEA).

The cumulated demand in energy and transport technologies alone exceeds actual reserves for cobalt (ratio cumulated demand/reserves: 1.6–2.9, depending on roadmap) and lithium (1.2–2.2), as well as – depending on the roadmap – also for tellurium (0.6–2.0), nickel (0.7–1.4), and iridium (0.8–1.0).

For all those minerals, the maximum demand for energy and transport technologies alone is higher than the actual production (cobalt: ratio maximum demand – actual production: 5–7, iridium: ratio 2–3, lithium: ratio 14–28, nickel: ratio ca. 2, tellurium: ratio 2–7). Other minerals, for which the production has to be expanded very quickly on order to meet the demand for energy and transport technologies are vanadium (ratio 2–11), dysprosium (ratio ca. 8), scandium (ratio 1–7), nickel (ratio ca. 2), platinum (ratio ca. 2), and neodymium (ratio: ca. 1).

The situation looks even more serious when the additional demand for non-energy and non-transport applications (DNEA) is taken into account, as depicted in Fig. 6: Although large uncertainties in the DNEA must be assumed, it turns out the current production for all the analysed minerals must significantly be expanded in order to meet the demand from transport, energy, and other technologies. In this scenario, the lithium production must be increased by a factor of 15–30, dysprosium by ca. a factor of 9, tellurium: 3–9, cobalt: 7–9, iridium: ca. 4, Vanadium: 6–16, scandium: 4–10, neodymium ca. 3, nickel: 4–6, platinum ca. 6, 5. For the other elements the share of energy and transport in total demand is low (<20%, see Fig. 3). In this case, the uncertainties of the DNEA estimates dominate the estimate of the total maximum demand. However, for all these minerals, short-term supply bottlenecks due to a delay in the necessary expansion of production capacities cannot be excluded.

The cumulated resource demand including DNEA exceeds current reserves by a factor of 3–4 for cobalt (depending on the roadmap), nickel (factor 3–4), lithium (1–2), tellurium (1–3), iridium (ca. 2), and indium (ca. 2). The ratio of cumulated demand and reserves is ca. 0.5–1 for vanadium, ca. 0.3 for dysprosium, 0.1–0.2 for neodymium, and ca. 0.6 for platinum. For scandium, no reserve estimates are available. A high ratio (>1) between cumulated demand and known reserves is also found for gallium, silver, strontium, manganese, selenium, zirconium, and yttrium. However, the demand for these minerals is driven by applications beyond energy and transport (see Fig. 3). For all minerals where the ratio between cumulated demand and reserves exceeds one, mid- to long-term supply bottlenecks and/or price increases cannot be excluded, as new deposits have to be developed to meet demand, which may entail higher production costs. Interim shortages can as well lead to scarcity prices. With respect to resources, the cumulated demand for nickel, iridium, and (depending on the roadmap) cobalt even exceeds current resource estimates. The corresponding plot can be found in the supplementary material. Note that the results presented in Figs. 5 and 6 do not include upstream material losses between mining and manufacturing of technologies. If these losses, some of which are very high (Wang et al., 2020), were included in the analysis the identified material bottlenecks would be further aggravated.

3.4. The effect of technology substitution on cumulated material demand

The potential effect of technology substitution can by analysed by comparing the results for the cumulated material demand in both roadmaps, CONT and TC, as presented in Fig. 4.

As shown in Section 3.2, the transport sector clearly is one of the main drivers of material demand: The electrification of the transport sector will greatly increase the demand for Li-Ion **batteries** in electric vehicles, which will lead to a significant demand for **cobalt**, **lithium** and **nickel**. Fig. 4 also shows that the demand for those three minerals clearly depends on the chosen sub-technology roadmap. However, a dilemma is emerging her: In order to reduce the high demand for cobalt in the CONT roadmap, it would in principle possible to partly replace those battery types in the CONT roadmap which have a high specific demand in cobalt and nickel (e.g. NMC-811, which dominates the CONT roadmap for mobile batteries after 2030) with battery types with a lower (or no) cobalt and nickel content per unit of storage capacity (e.g. LiS8, which is expected to increasingly

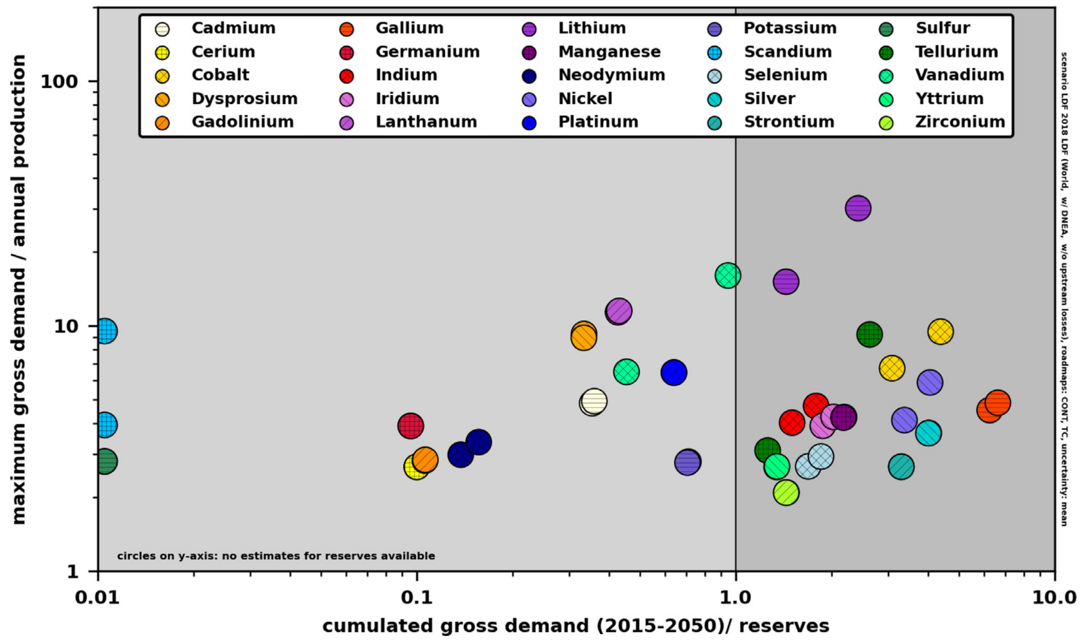

Fig. 6. X-axis: Ratio of cumulative material demand (2015–2050) and actual reserves for both roadmaps. Y-axis: ratio of maximum annual material demand and actual production, also for both roadmaps. Estimates include demand for non-energy and non-transport applications.

dominate the market for mobile batteries in the TC roadmap). However, as LiS8 batteries have a much higher specific lithium demand (0.36 kg/kWh) than NMC-811 (0.11 kg/kWh), a reduction of the cobalt and nickel demand through a shift from NMC-811 batteries to LiS8 batteries increases the lithium demand – and vice versa. Thus, the results suggest that there is a trade-off in simultaneously reducing lithium, cobalt, and nickel demand in mobile batteries through technology substitution. Overall, the total demand for cobalt, lithium and nickel exceeds the known material reserves in both roadmaps (see Fig. 6).

Li-ion batteries are also used in stationary batteries. Here, battery types that do not require lithium, cobalt, or nickel (such as lead acid or vanadium redox flow batteries) could be used. However, in the scenario, the storage capacity of stationary batteries is very low compared to battery capacity in electric vehicles. As a consequence, the demand for lithium, cobalt, and nickel in stationary batteries is – in absolute terms – only very little affected by the choice of the roadmap.

The selected roadmap for stationary batteries heavily affects the demand for **vanadium**. Vanadium is only used in redox flow batteries, which achieve significant market shares only in the TC roadmap. Thus, a focus on lithium-based stationary batteries (or lead acid batteries) in the stationary segment could help to reduce potential vanadium (short-term) shortages, albeit at the cost of higher lithium, cobalt and nickel requirements.

The need for the rare earth elements (REE) **dysprosium** and **neodymium** can in principle be reduced if electric motors are installed that do not require permanent magnets. This is the case in the roadmap TC, in which the market shares of electric motors without permanent magnets increase to 50% by 2050 (2020: 10%). However, in the TC roadmap, there is a counteracting effect for wind turbines: In this roadmap, market shares of wind turbines with permanent magnets (which require dysprosium and neodymium) increase compared to today, resulting in an increasing demand for these two elements for wind power generation. It should be noted, however, that a combination of the roadmaps TC for electric motors and CONT for wind turbines would be quite possible. In this case, the neodymium and dysprosium demand in both electric vehicles and wind turbines would decrease compared to the CONT and TC roadmaps presented here.

Indium, **selenium**, and **tellurium** are mainly used in thin-film PV technologies. The need for these materials depends heavily on the extent to which thin-film PV technologies achieve greater market share in the future, which is the case in the TC roadmap. As a consequence, the demand for indium, selenium and tellurium is much higher in the roadmap TC than in the CONT roadmap, which mainly uses c-Si PV. A preference for silicon-based PV technologies can therefore help to reduce potential bottlenecks in these minerals.

The TC roadmap assumes a strong increase in the market share of **scandium**-based stationary SOFC fuel cells, resulting in a much higher scandium demand in TC than in CONT (where PEMFC dominate the market). Thus, a future focus on PEM fuel cells could reduce potential (short-term) shortages in scandium, but implies a higher demand for platinum.

The cumulated demand for **iridium** is only slightly affected by the choice of the roadmap. The same applies to **platinum**, **potassium** and **silver**.

3.5. The effect of recycling, material efficiency and lifetime extension on cumulated material demand

Recycling material from old plants is in principle an effective means of reducing primary material requirements and thus counteracting material shortages. However, the present analysis shows that even in the (unrealistic) case of complete recycling, the cumulative material requirement for energy and transport technologies can be reduced by a maximum of 50% until 2050. For some materials, the reduction potential is even less than 20%, as it is illustrated in Figure 7 in the supplementary material. This is due in particular to the fact that only a few recycling cycles can be completed for most technologies by 2050 and that a large part of the material will still be installed in the existing plant and vehicle stock in that year. However, the recycling potential strongly depends on the time horizon of the analysis: The more replacement cycles a technology has gone through, the more recycling can and must contribute to reducing the primary material demand.

An **extension** of the **lifetime** of the technologies by 25% results in a reduction in cumulative demand until 2050 of up to

20%, depending on the material (for details see Figure 8 in the supplementary material). The fact that an extension of the life time results in only a small reduction in cumulative demand for certain materials can be explained by the following factors (which are not mutually exclusive): (a) The technologies in which these materials are used have a long lifetime, so that an extension does not lead to significantly more replacement cycles within the period under consideration. (b) The corresponding technologies are mainly installed at the end of the period under consideration, so that the first replacement cycle would not be due until after 2050. In the very long run (when every technology has undergone multiple replacement cycles), a lifetime extension by a factor of *x* is expected to reduce material demand by a factor of 1/x for all materials.

The assumed **material efficiency** (reduction of the specific material demand) has very different consequences for the different materials (for details see Figure 8 in the supplementary material): (Cumulated) demand reductions range between 0% and 90%. For many materials, increasing material efficiency might reduce the cumulated demand between 25% and 50%. Conversely, this means that if the increase in material efficiency, as assumed in the standard calculations, cannot be achieved, the material requirements will increase by the corresponding values compared to Figs. 4 and 5. This is especially true for dysprosium and neodymium (permanent magnets in electric motors and wind turbines), indium, selenium, and tellurium (PV), silver (PV and CSP), iridium (electrolysers), and platinum (fuel cells).

4. Discussion

4.1. Uncertainties and limitations of this approach

The scenario on which the analysis is based represents only one possible development of the global energy system. A whole series of assumptions had to be made in order to derive the quantities necessary for calculating the material demand. In the future, it would be desirable if scenario studies could publish significantly more detailed results, especially on the development of the vehicle fleet and the stationary storage demand.

For some materials, especially in "new" or "emerging" technologies, data on the specific material demand is very limited – both for today, but to an even greater extent for its future development. The uncertainty in the data was partially accounted for by re-calculating all results using the minimum and maximum values from the literature (error bars in Fig. 4). However, estimates for the future specific demand might reflect current development goals and expectations, but these will not always be achieved in reality. On the other hand, the lack of prospective estimates for the specific material demand in some technologies might lead to an underestimation of achievable material efficiency and overestimation of global demand.

The sub-technology roadmaps represent potential market developments until 2050. However, the actual future development of the technology markets may look very different from what is described in the roadmaps. This holds in particular for the market shares of emerging technologies. Furthermore, it is not possible to reflect disruptive innovations, the effect of governmental technology support or regulatory restrictions regarding the use of certain technologies. It should be noted, that a combination of the roadmaps TC for electric motors and CONT for wind turbines would be conceivable. In this case, the global demand for neodymium and dysprosium would decrease compared to the CONT roadmap presented here.

The selected recycling scenarios are coarse and do not make assumptions on individual recycling rates of the materials, nor do they differentiate between individual technologies. An assessment of the economic viability or technical feasibility of the proposed recycling rates was beyond the scope of this study. However, it would be worthwhile to develop more realistic recycling scenarios, including estimates on the additional costs for a recycling-friendly technology design and the development of a recycling infrastructure in a global effective and efficient circular economy.

The calculation of demand beyond the energy and transport sector (DNEA) was carried out in much less detail than the calculations for energy and transport technologies. The resulting uncertainties are high. The values of the demand for non-energy and -transport applications should therefore represent only an estimate of the magnitude of demand.

The demand of the selected materials in steel alloys was not considered. This concerns (among others) cobalt, manganese and nickel. Unfortunately, it was not possible to estimate the magnitude of the resulting uncertainty.

Finally, estimates on production capacities, reserves and resources are dynamic values: An increase in mineral prices or progress in mining technologies could increase the reserves of individual materials. Furthermore, estimates for production and in particular reserves and resources found in the literature vary, sometimes significantly. It is therefore important that the resource bottlenecks identified in this study are not expected to become a "showstopper" for the sustainable global energy system. However, they provide insights into where and why material bottlenecks could potentially occur and provide indications for future research needs.

4.2. Comparison with results from other studies

To put the findings of this paper into perspective the results are compared to recent other studies which are similar in scope, methodology, and/or focus.

Similar to the results here, Elshkaki and Graedel (2013) found out that some materials used in thin-film PV (indium, selenium, tellurium) are prone to potential bottlenecks if thin-film technologies contribute significantly to the overall PV installations. As they assume a much higher specific silver demand (per kW) in c-Si PV modules, they calculate a very high overall demand for silver. The energy scenarios used in Elshkaki and Graedel (2013) are much less ambitious (in terms of CO_2 emission reduction) than the scenario used here. This is reflected in the significantly lower power generation capacity. Furthermore, Elshkaki and Graedel (2013) do not consider the transport sector. As a consequence, their estimate of the demand for neodymium, nickel, and dysprosium is much lower than estimates here. H_2 technologies (fuel cells and electrolysers) and the corresponding demand for iridium, scandium, and platinum were also not considered.

Grandell et al. (2016) identify potential bottlenecks for silver, indium, tellurium, platinum-group metals (PGM) and some rare earth elements (REE). They estimate a much higher silver demand than in our assessment. This can partly be explained by the fact that the study here does not consider the silver demand in power electronics of electric vehicles. Thus it is well possible that the silver demand is underestimated in this study. Grandell et al. (2016) calculate a high demand for indium and tellurium (thin film PV) as well as neodymium and dysprosium (electric vehicles and wind turbines), which is in line with the findings of this study. The demand for the other rare earth elements (REE) is not comparable as materials in lightning technologies are not included in this analysis, but have a huge impact on the demand in Grandell et al. (2016).

Our results are in good agreement with Månberger and Stenqvist (2018). They also found out that the availability of specific materials could potentially limit the expansion of thin-film PV. The findings in the transport sector, specifically for batteries are also comparable to this study, where bottlenecks for lithium, cobalt, and nickel could occur, but also for neodymium and dysprosium.

The comparison of results with Moreau et al. (2019) is difficult, as they assess the material demand in less ambitious transformation paths and do not include the transport sector in their analysis. However, one striking difference is their estimate of the (cumulated) cobalt demand in stationary batteries (up to 7 Mt). This can partly be explained by the higher capacity of stationary battery storage systems in Moreau et al. (2019) compared to this study, but probably also due to higher specific cobalt demand in batteries and/or a higher share of battery types with a high specific cobalt demand in the study of Moreau et al. (2019).

The approach of Valero et al. (2018) does not consider a specific scenario for the global energy system, but estimates the future installed capacities based on expansion rates of each technology (which leads to significantly lower installed capacities than assumed here). Despite these differences (Valero et al., 2018) identified potential material bottlenecks for similar resources as identified in this study: Materials for thin-film PV (In, Te) and batteries (Co, Ni, Li). However, in contrast to Valero et al. (2018), Cd, Ga, and Mn were considered as less critical – at least from the perspective of the energy and transport system alone.

The study from de Koning et al. (2018) focusses more on bulk materials which were not examined in this study and also assesses scenarios (4 °C pathways) which are not early as ambitious as scenario used here. However, even in this case, the demand for indium, lithium, dysprosium and neodymium increases significantly in the scenarios with more renewable energies, with the ramping up of production capacities proving to be a potential bottleneck.

The comparison with the studies from Tokimatsu et al. (2017, 2018) and Moss et al. (2013) is difficult, as Tokimatsu et al. (2017) and Tokimatsu et al. (2018) calculate until 2010, whereas (Moss et al., 2013) only considers Europe. Despite the different scopes, the materials for thin-film PV are also highlighted here as particularly critical (Moss et al., 2013; Tokimatsu et al., 2018).

5. Summary, conclusion and outlook

This study presents an estimate of the global demand for 25 potentially scarce materials as it would be required for a very ambitious transformation of the global energy and transport system. It shows the following:

For materials such as lithium, dysprosium, tellurium, cobalt, iridium, vanadium, scandium, neodymium, and nickel, the transformation of the energy and transportation systems is the key driver of future demand. An increase in the current production volume is necessary for almost all of the materials studied here. Short-term material bottlenecks due to currently insufficient production capacities are to be expected for lithium, vanadium, cobalt, nickel, dysprosium and neodymium, among others. For those materials the expected annual demand for energy and transport technologies *alone* exceeds production volumes today. In the medium to long term, the cumulative material demand for energy and transport technologies exceeds current reserves, especially for cobalt, lithium, nickel, iridium and tellurium. The resulting challenges are in part significantly exacerbated by the fact that technologies beyond energy and transportation also require significant quantities of these materials and material losses between mining and end-use are not considered here. The potential material shortages primarily affect stationary and mobile batteries (lithium, cobalt, nickel), wind turbines and electric motors in electric vehicles (neodymium, dysprosium) and technologies for hydrogen production and conversion (platinum, iridium).

Research and development for ambitious material recycling, extending technology lifetime, further reduction of material intensity, and technology substitution should be fostered as it could help reduce or delay the bottlenecks without preventing them altogether. Since the transport sector is a major driver of demand for many materials, a future reduction in the number and size of electric and fuel cell vehicles could also reduce material demand. This would be conceivable, for example, if the expansion of public transport or attractive car-sharing concepts made it easier to do without one's own vehicle. Since there appears to be no single solution to avoid future material shortages, all of these levers should be pursued vigorously.

The production of many materials must be expanded as quickly as possible and new deposits must be developed in the medium term, if the transformation of the energy system is not to be delayed. In addition to the technical and economic challenges that have to be solved, it is important to ensure that the environmental and social impacts of this production expansion is as low as possible. Production expansion and their ecological and social compatibility could be supported by an appropriate political framework.

The combination of energy system modelling and material flow analysis is only in its infancy. Therefore, there are a variety of aspects for which further research would be important: It can be expected that the demand for materials like steel, aluminium, and cement, for which no shortages are expected, will increase due to the transformation of the energy system. The production of many of these "bulk" materials is energy and/or CO_2 intensive. Therefore, it is important to further investigate feedbacks between the transformation of the energy system, the provision of the necessary materials, and the resulting energy demand and CO_2 emissions (Kullmann et al., 2021).

Many energy system transformation strategies are based on results of cost-optimizing energy system models. In principle, therefore, material bottlenecks could be integrated in energy system models via assumptions about increases in the investment costs of the affected technologies. However, to our knowledge, there is currently no estimate of how the identified material shortages will affect technology costs. In addition, there is a lack of estimates of what proportion of technology costs are accounted for by material costs. Further studies in this direction would therefore be very helpful to better understand the impact of material shortages on the global energy transition.

In addition, it would be useful to include other aspects of the "criticality" of individual raw materials in an analysis of possible bottlenecks for transformation strategies. These include primarily geopolitical aspects (such as country concentration and the geopolitical reliability of the countries producing or further processing the materials), but also environmental and social aspects of mining and refining the materials.

The database and refined methodology published here for calculating the material demand of a sustainable energy system can serve as a basis for further research. The systematic compilation of current and prospective specific material values in this level of detail across a multitude of sub-technologies is a novelty in the field of energy system analysis. The corresponding databases in the Supplementary Material are publicly available. We therefore invite experts for individual technologies to review the assumptions for their technologies in the database and provide us with feedback. The possibilities presented for expanding this database even further open up new fields of research to better understand and support the upcoming transformation of the energy system.

CRediT authorship contribution statement

Simon Schlichenmaier: Conceptualization, Methodology, Validation, Investigation, Data curation, Formal analysis, Writing – original draft. **Tobias Naegler:** Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2022.11.025.

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