The material side of the energy transition: analyzing flows and stocks of critical and other metals

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Chapter 3

Increase in demand for critical materials under IEA Net-Zero Emission by 2050 scenario

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Abstract

Increasing the deployment of low-carbon technologies on a global scale is critical for mitigating climate change and achieving net-zero emissions (NZE) by 2050. Implementing such technologies requires a rapidly increasing supply of both critical and non-critical materials. We developed a scenario-based dynamic material stock flow model to calculate the critical material requirements of major low-carbon technologies under the newly released International Energy Agency (IEA) NZE by 2050 scenario. Our results show that most of the metal demand related to photovoltaics would reach its peak around 2035 and then gradually decline, whereas the demand for rare earth elements (REEs) continue to surge. Over the past decade, wind turbines have mainly been responsible for the consumption of neodymium iron boron (NdFeB) magnets containing REEs; however, this will soon be superseded by electric motors (EMs) primarily used in for electric vehicles (EVs). In the short term, increased recycling will have a relatively low impact on the demand for primary resources. With current recycling rates, the secondary supply of REEs will contribute <1% to the demand in 2050, however, aggressive recycling strategies could increase the contribution to 35%. Furthermore, we contend that alternative technologies based on non-critical materials could address the mismatch between supply and demand to resolve the issues presented by material scarcity.

3.1 Introduction

As the global clean energy transition accelerates, solar photovoltaic (PV), wind turbines, and EVs, which are considered the three major low-carbon technologies, are being increasingly deployed [217]. One of the critical issues for energy transition is accessing the necessary raw materials [146,147,185,218–221]. The IEA published a flagship report in which the global mineral demand until 2040 was quantified primarily based on the Sustainable Development Scenario (SDS) and the Stated Policies Scenario (SPS) in 2021 [19]. This report indicates that the current supply of and investment in many minerals are insufficient to support the rapid deployment of these low-carbon technologies. Widespread low-carbon technology deployment represents an extraordinary economic opportunity for associated mining industries, however, it could cause substantial material concerns [106,110]. High geographic concentration, long lead times for new mines to become operational, and a decline in resource quality exacerbates the supply demand imbalance, critically challenging energy and resource security [19,222]. Furthermore, political turmoil could cause considerable price swings for critical materials, exacerbating the situation of material constraints [223]. The analysis provided by IEA helps understanding the key role of materials in energy transition and provides a quantitively baseline for related research.

Moreover, the IEA published a landmark report on the NZE scenario within the framework of the Intergovernmental Panel on Climate Change (IPCC) Special Report [224]. The IEA report provides an ambitious and possible pathway for the energy sector to achieve Net-Zero Emissions by 2050 without relying on non-energy sector emission reduction [225]. According to the NZE scenario, the installed capacity of renewable energy will increase by a factor of nine compared to the capacity in 2020. Furthermore, electricity will become the primary energy carrier by 2050, with 88% of electricity generated from renewable sources, 8% generated from nuclear power, and 2% generated from hydrogen, with wind and PV providing two-thirds of the renewable energy [111]. According to the IEA NZE report, the electrification of road transportation will accelerate, internal combustion engine vehicles (ICEVs) will cease to be sold globally starting in 2035, and the PV and wind power installed capacity in 2040 will be roughly twice as large as it is in the SDS [107,111]. Consequently, this scenario will be accompanied by a considerable increase in mineral demand. The IEA also warned that under the NZE scenario, 1.5 times more minerals will be required in 2040 compared with the SDS [19].

Numerous studies have investigated material requirements in relation to various climate mitigation scenarios [226,227], like the Shared Socioeconomic Pathways (SSP) Scenarios [98,228,229], and other scenarios proposed by IEA [230,231]. Nevertheless, the quantification of material requirements for specific technologies under the NZE scenario is inadequate, making it the primary focus of this study.

Herein, we aim to answer whether metal demand can be scaled up to match the low-carbon technologies required in the aggressive IEA NZE scenario. The analysis applies a dynamic material stock-flow model to the NZE scenario of technology-specific critical materials demand on a global scale. We compared the demand results for various materials with IEA SDS scenario. In addition, by conducting sensitivity analyses, we assessed the impact of key parameters such as material intensity and lifetime on the results. Ultimately, we discuss and provide insights that can be used to address the material challenges that will arise from the aggressive policies required to tackle climate change.

3.2 Methodology

3.2.1 Model framework

We used a dynamic material stock-flow model to propose the critical material requirements for major technologies in energy generation and road passenger transportation applications conforming to the NZE scenario. Our stock-flow model predicts the future material demands of various low-carbon technologies as well as the potential of recycled end-of-life (EOL) materials. It comprises a technological (component) level and a material level, accounting for relevant technical and socioeconomic factors in each level (**Figure 1**).

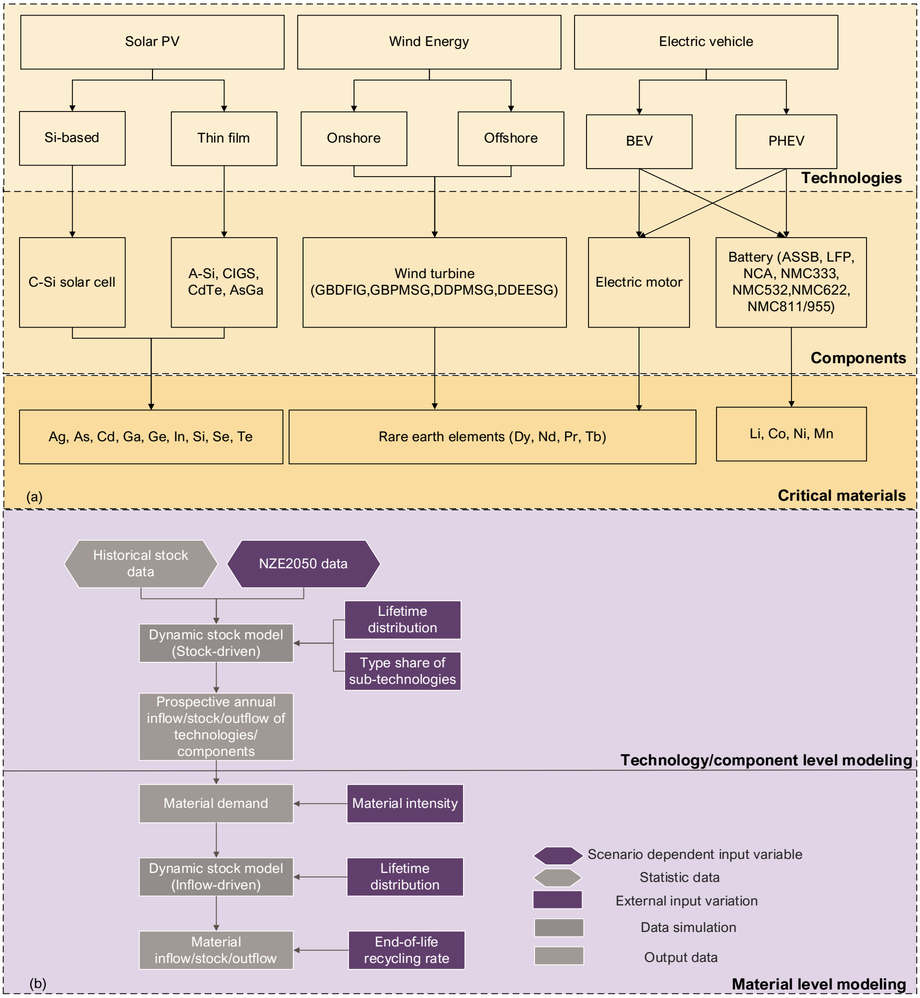

Figure 3.1 Overview of the calculations, (a) technologies, components, and materials included herein, and (b) the specific calculated steps of material flow and stocks.

(1) Technology/components level modeling

Based on the stock-flow model framework, the target installation data of wind power and PV under the NZE scenario is regarded as the "stock (GW)" [215,232]. The stock-driven model is then applied to calculate the inflow (newly installed capacities) and outflow (decommissioned capacities) during the yearly cohort according to **Equations (1)** and **(2)**, based on the principle of mass balance. The EV on-road fleet (stock) calculation is based on the total passenger car stock [233,234] and the market share of EVs under the NZE scenario [111]. We used the EV stocks to calculate the annual EV sales (inflow), as well as the stocks of motors and the corresponding batteries (GWh). The details of the total passenger car stock calculation and the survival function based on the lifetime distribution for each technology are provided in the **Supporting Information** (**SI)** (**Table A3.1** and **Figure A3.3**).

$$Inflow_c(t) = Stock_C(t) - \sum_{n=t_0}^{t-1} Inflow_c(n) \times Survival(t-n) \tag{1}$$

$$Stock_C(t) = Stock_c(t-1) + Inflow_c(t) - Outflow_c(t) \tag{2}$$

where c represents the category of different technologies; and Survival (t) refers to the complementary cumulative distribution function (cdf) of the lifetime distribution of the technologies, which decreased from 1 to 0, based on the initial stock ($Stock_C(t_0)$) being equal to the inflow ($Inflow(t_0)$) . The details of lifetime distribution are shown in the **SI**.

(2) Material-level modeling

The results from **Equations (1) and (2)** are subdivided based on sub-technologies and further translated into relevant materials flows and stocks. The annual newly added capacities (inflow) are multiplied by the corresponding material intensity (MI) to calculate the primary demand ($Inflow(t)$) of different materials. Subsequently, based on a flow-driven model,[235] the material stock and annual outflow are calculated using **Equations (3) -(5)**.

$$Inflow_m(t) = \sum_k [Inflow_m(t) \times MI_m(k,t)] \tag{3}$$

$$Stock_m(t) = \sum_{n=t_0}^{t} Inflow_c(n) \times Survival(t-n) \tag{4}$$

$$Outflow_m(t) = Inflow_m(t) - [Stock_m(t) - Stock_m(t-1)] \qquad (5)$$

where $MI_m(k,t)$ (t/GW or kg/kWh) represents the material intensity of material m in sub-technology k, at the time t.

3.2.2 Scenario description and data sources

The penetration rate of various sub-technologies is consistent with the IEA report [19], and some related research [37,236]. WebPlotDigitizer was used to extract certain data that was provided only in the figures in the IEA report [237]. Owing to the lack of reliable sources for battery chemistry data from 2040 to 2050, we conservatively assumed a constant market share after 2040. The market share of each technology is detailed in **SI** (**Figure A3.4(a-d)**). The historical installed capacity data of wind power and solar PV from 2000 to 2020 were gathered from the International Renewable Energy Agency (IRENA) [238], and the historical EV stocks data were obtained from the Global EV Outlook 2021 and 2022 [239,240]. The installed capacity of wind and solar PV up to 2050 was obtained from the NZE report [111], and the future population and type share of EV stock were collected from World Population Prospects 2019 [241] and the IEA [19]. The installed capacity data of wind and PV were obtained from the IEA in intervals of five years [111,242]. A logistics curve fitting (**Figure A3.5)** was used to fit each age cohort (one year) as a unit, and each sub-technology installed capacity was calculated based on the corresponding type of share. The average service lifetime was assumed to be 20 yrs for wind power [36,37,155,243]. and 25 yrs of PV [60,244–246]. For simplification, we assumed that the battery in EVs is generally not replaced until the EOL, specifically, the battery and EV lifetimes are the same (15 yrs) [41,122,247–249]. We assumed that motors containing permanent magnets (PMs) still dominate the market in the future,[19] and that all plug-in hybrid electric vehicles (PHEVs) and 90% of battery electric vehicles (BEVs) have motors containing PMs [19,95]. The average battery capacity data for BEVs and PHEVs [95]. are listed in **Figure A3.6**. We considered the reduction of MI per unit of energy in the future caused by technology learning, and the specific intensity data of all materials in each technology [36,39,211,236,250], are detailed in **Tables A3.3-3.4**. The end-of life recycling rate (Eol-RR) of different materials was mainly sourced from the literature [39,122,251–254]. The recycling rate here comprehensively considers the collection, separate, and other recycling processes, and refers to the final Eol-RR that can be achieved. The details are listed in **Table A3.5**.

3.2.3 Sensitivity analysis

The given models as well as the assumptions about future scenarios considered include inherent uncertainty regarding possible future developments. To assess the sensitivity of the model results to the main assumptions, we performed a sensitivity analysis of the changes in material demand using two alternative sensitivity variants.

First, we changed the lifetime assumptions, reducing the lifetime of the 20% EV and increasing the lifetimes of wind and solar power, by 5 yrs. These adjustments were based on literature [254–256], and the findings demonstrate that a longer lifetime for both wind and PV will likely cause a decline in the primary demand for all relevant materials, however it will reduce the materials' potential for secondary supply in the future by slowing the social metabolic rate of materials.

Second, we assumed a constant MI to examine its effect on the total material requirements. For batteries, we considered future innovations in battery chemistry and assumed the impact on material demand of an increase in the average battery capacity (to 70 kWh) by 2050.

3.3 Results

We quantified the stocks and flows of various low-carbon technologies and their components in Section **3.1**. The potential for recycling critical materials used in these technologies is determined in Section **3.2**. The material requirements for the NZE and SDS scenarios are compared in Section **3.3**, and the sensitivity of our assumptions to the results is discussed in Section **3.4**.3.3.1 Developments in stocks and flows of installed electricity generation capacity and electric vehicles

3.3.1.1 Electricity generation

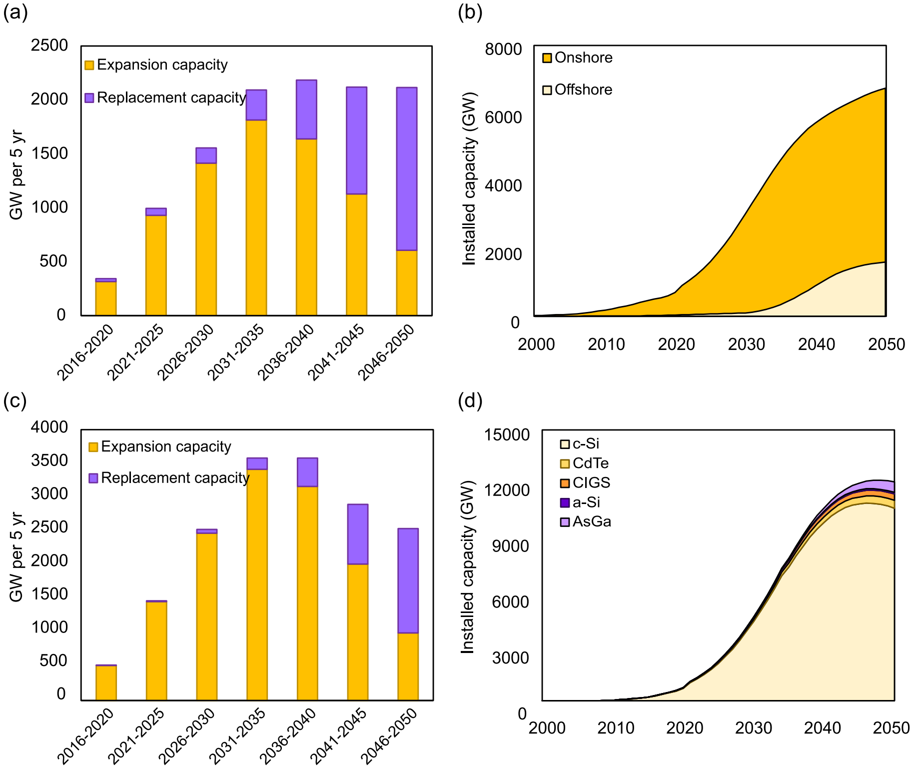

Figure 3.2 Newly installed capacities every five years (inflow for capacity expansion and replacement) of wind (a), and PV(c). Global installed capacities (stock) of wind power (b), and PV (d).

As illustrated in **Figure 3.2**, both wind power and PV capacity additions are considerable until 2035, averaging ~580 and 1020 GW every 5 yrs, respectively, and those additions are mainly for capacity expansion. Before 2030, >90% of the annual inflow will be used for capacity expansion and accumulation of in-use stock. The main driving force of the added annual capacity between 2046 and 2050 will be the replacement of the currently decommissioned capacity; 71% and 61% of the entire replacement capacity comes from wind and PV, respectively. The share of offshore wind power in the total stock gradually increases, and silicon-based PV cells still dominate the market. The in-use wind and PV stocks increase over the entire period, whereas the newly added capacity decreases after 2040, slowing the rate of in-use stock builds.

3.3.1.2 Electric vehicles and batteries

Our results show that under the NZE scenario, with ~2 billion EVs on the road, annual global EV sales will increase up to 160 million in 2050. During the transition to rapid electrification, annual PHEV sales on average account for >40% of the total EVs sold in the previous decade, and BEV sales will continue to increase, occupying >95% of the EV market after 2035 (**Figure 3.3**). Meanwhile, the annual sales capacity of different batteries will increase sharply, reaching 10 TWh in 2050, which is ~80 times that in 2020 (**Figure 3.3(c)**). For different market shares in battery chemistries, nickel manganese cobalt oxides (NMC) batteries still dominate the market.[19] It is estimated that the innovation of low/zero-cobalt all-solid-state batteries(ASSB) will show their advantages in the battery market after 2030, occupying 30% of the market share in 2040.

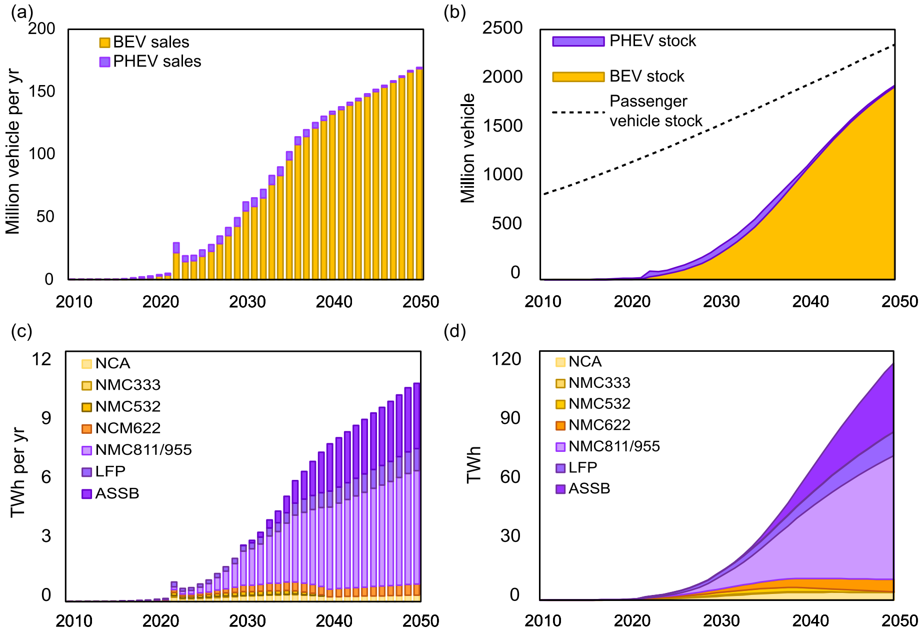

Figure 3.3 Annual sales (a,) and stocks (b) of EVs. Annual battery sales capacity (c) and stocks (d) of different types of batteries.3.3.2 Material demand calculation

3.3.2.1 Material flow of PV-relevant material

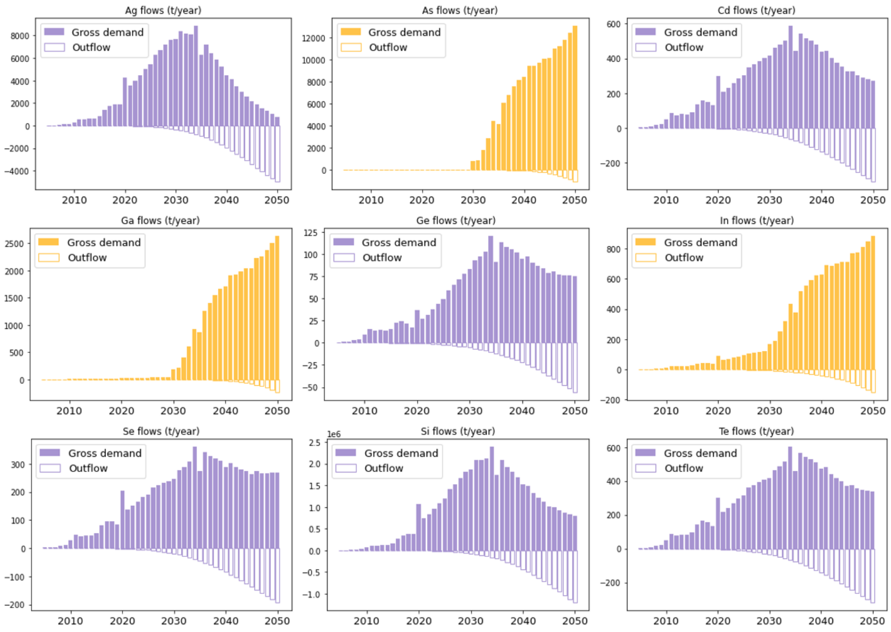

Figure 3.4 Gross demand (positive values) and outflow (negative values) of PV-relevant materials from 2005 to 2050.

Figure 3.4 demonstrates the various material requirements of PV cells. The results show that the In, Ga, and As requirements spike, because the emergence of GaAs PV cells in the market after 2030 stimulates the increase in demand for these materials. Aside from those three commodities, the peak demand for other materials will emerge in the middle of the 2030s, and after 2040, it is anticipated that the secondary supply of silver will outpace the primary demand. The reduced demand for Te, Cd, and Ge is mainly driven by the reduction in MI. Our results in Section 3.3.4 show that at constant material content, the primary demand for these materials does not decrease (the details of the dynamic materials intensity are shown in **Table A3.3**).

3.3.2.2 Rare earth demand for permanent magnets

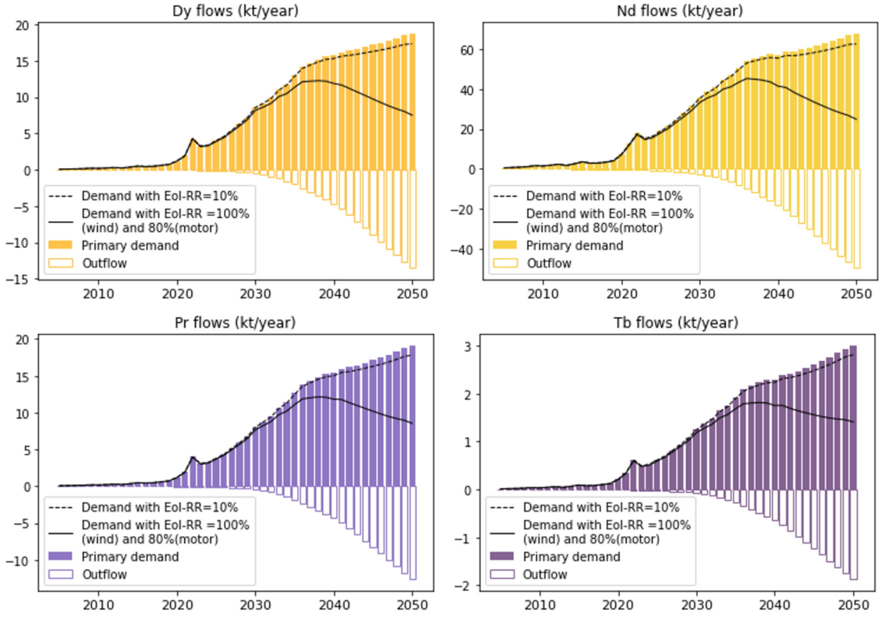

Figure 3.5 Global REE flows of wind turbines and EMs during 2005-2050 (positive values represent the gross demand, negative value represent the potential secondary supply from retired magnets during 2010-2050 (after accounting for a 10% magnet recycling rate, heoretically 100% recycling of magnets in wind turbines and 80% recycling of magnets in EMs), and the black dashed and solid lines show the net material required).

The rapid increase in wind capacity and the exponential implementation of EVs contribute to a continuous increase in the demand for REEs. The secondary supply potential from scrapped magnets will continue to rise in the next 30 yrs (**Figure 3.5**). The demand for REEs in NdFeB magnets during 2040-2050 will increase by two orders of magnitude compared with the previous decade (2011-2020); EMs will soon be the main driver of NdFeB applications. The Sankey diagrams in **SI (Figure A3.6)** compare the 2020 and 2050 changes in demand for REEs for wind turbines and EMs; the growing stream of EOL PMs is expected to incentivize a recycling industry. Our calculations show that until 2050, the secondary supply will be negligible at the current recycling rates (<1%); however, in a high recycling rate scenario (100% recovery in wind turbines, and 80% recovery in motors), secondary supply can satisfy 35% of the primary demand. EMs account for roughly 70% of the total REE demand throughout the period of 2021–2050, compared to only 17% in the previous 10 yrs (2011-2020).

3.3.2.3 Battery metals demand and scrap generation

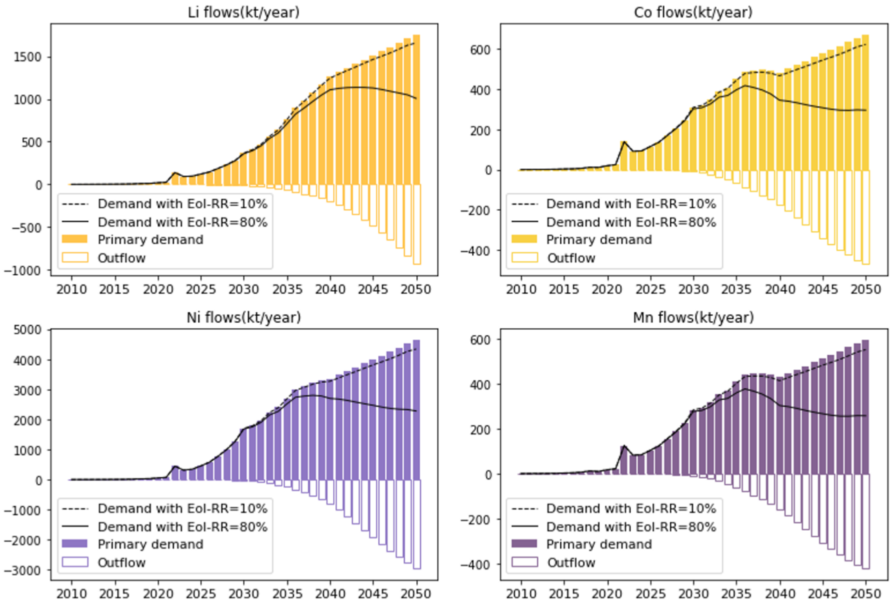

Figure 3.6 Global material demand associated thedeployment of new EVs (positive numbers denote total demand, negative values denote the possible secondary supply of retired EVs from 2010 to 2050, and the solid and dashed black lines denote the net material demand after accounting for recycling rates of 10% and 80%, respectively).

Figure 3.6 shows the primary demand and outflow of EV battery-relevant metals. The demand for various cathode materials shows a continuous growth trend caused by the explosive deployment of new EVs. The battery chemistry determines the proportions and forms of the materials required. Technological advances in battery chemistry, such as NMC811 or ASSBs (*e.g.*, Li metal and Li-S batteries), will considerably reduce the MI of Co and Mn, although more Li and Ni will be required. The cumulative Li and Ni demand in 2041-2050 will increase nearly 300 times compared to the previous decade, much more than Co and Mn. The materials retrieved from EOL batteries start increasing after 2030. With a low recycling rate of 10% in 2050, the secondary supply will meet <7% of the entire demand, however, if recycling rates rise to 80%, the secondary supply could meet ~50% of the primary demand.

3.3.3 Comparison of material requirements under SDS and NZE

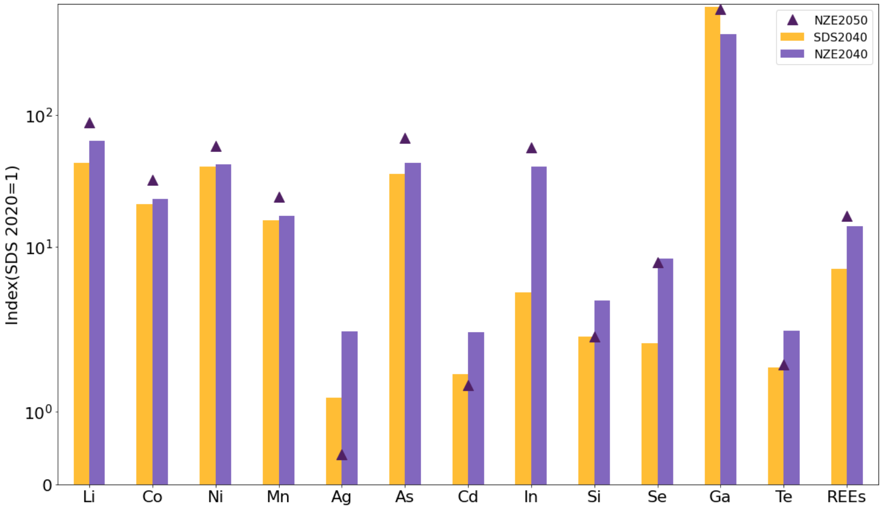

Figure 3.7 Demand growth for selected materials comparing the SDS 2020 (SDS 2020=1) and 2040 (SDS2040) with the NZE scenario 2040 (NZE2040) and 2050 (NZE2050).

Compared with the SDS, wind power and PV in the NZE scenario have more installed capacity in the same period and the mobility electrification is much faster. Therefore, in 2040, almost all material demand will be higher in the NZE scenario (**Figure 3.7**). The emergence of GaAs technology will considerably boost the Ga demand beyond 2030. The Ga demand in the NZE scenario is lower than that in the SDS owing to the difference between the Ga intensity data used herein [251] and that used by the IEA.

3.3.4 Results of sensitivity analysis

Alternate model assumptions about the MI and lifetime of the technology have a limited effect on the results of the model for material requirements, as discussed in Section 3.2.3.

Table 3.1 shows the outcomes of the sensitivity analysis, illustrating the influence of varying parameters on cumulated material requirements. The reduction in MI achieved through technological learning would provide substantial benefits to the cumulative material requirements of the PV sector, it should be noted that this would result in an approximate doubling of the cumulative demand for Ag, Cd, Se, and Te, based on the current constant MI. An consequence of a 20% reduction in the life of the vehicle is an increase of over 10% in the cumulative material demand of the battery and motor materials.

Table 3.1 Sensitivity analysis results for material cumulated demand from 2020 to 2050, considering lifetime (L) and material intensity/battery capacity (I) parameters.

Technologies	Elements	Cumulated demand change (L)	Cumulated demand change (I)
EV battery	Li	13.7%	7.3%
	Co	12.6%	6.9%
	Ni	13.3%	7.2%
	Mn	12.5%	6.9%
EV motor	REEs	12.8%	11.1%
Wind	REEs	-14.3%	19.0%
PV	Ag	-5.3%	96.5%
	As	-17.3%	0.0%
	Cd	-7.1%	134.1%
	In	-16.2%	19.9%
	Se	-13.7%	92.6%
	Si	-7.4%	36.3%
	Ga	-17.2%	1.6%
	Te	-7.5%	128.2%

In addition, by decreasing the social metabolic rate of wind turbines and solar panels, a longer lifetime (+5 yrs) may lessen the material potential for secondary supply in the future. For EVs, a reduction in lifetime (-20%) would cause a 12.3% rise in the total demand for battery materials during the ensuing 30 yrs (**Figure A3.9**). The primary demand for PV-related materials will rise by 36% and the primary demand for REEs will rise by

19% between 2020 and 2050 because of constant intensity. Simultaneously, if the average battery capacity of BEVs rises, the total primary demand for materials connected to batteries will rise by 7.6% from 2020 to 2050. Although there are no demand bottlenecks for some metals (such as Ag) in the energy sector, we do not account for the application of these materials in the entire economic sector when comparing the future demand with production in 2021. The sensitivity analyses of each element are presented in **SI** (**Figures A3.10-13**) with more information.

3.4 Discussion

Our findings demonstrate that the demand for critical metals is driven by a considerable share of wind and solar PV, along with the electrification of mobility. We also emphasize the increasing interconnectedness of material efficiency, technology innovation, and material demand. However, the NZE scenario and the model given here both have a built-in uncertainty. Below, we analyze the main presumptions, their potential impact on the findings, and the limitations of this paper.

3.4.1 Comparison of key results

Because it is unclear how many passenger cars will be on the road in 2050 under the NZE scenario, we referred to other studies, and herein, the authors thoroughly consider the reasons for the relatively conservative car fleet in 2050. We also compared with the results from other studies under different scenarios in **Figure A3.2**. In contrast to the NZE scenario, the low energy demand (LED) scenario would lead to a substantial decrease in the stock of electric vehicles (EVs) [257,258]. Assuming all other factors remain constant, this reduction would significantly decrease the material demands for batteries and motors. Nevertheless, based on the current findings, the demand for materials is bound to increase, and if there are more on-road car fleets in the future, much more will be required of the environment. There are slight fluctuations in annual demand for battery materials (*e.g.* lower annual demand in 2040 versus before and after), which may be result of linear interpolation used to obtain the annual battery chemistry market penetration between each decade.

3.4.2 Discussion of the parameters and limitations

- Longer lifetime

By extending the lifetime of the product, the material remains as in-use stock longer, thereby partially alleviating the primary demand and delaying the peak demand for these materials. We considered the lifetime extension of wind and PV in the sensitivity analysis. Notably, there is often a mismatch between the technical lifetime and economic lifetime [256]. Power transmission facilities typically have a lifespan of >40 yrs for wind or solar power plants [93,259], which is a substantially longer lifespan than wind turbines and PV cells. The trade-off between dismantling maintaining or extending the lifetime of wind turbines and PV cells is complicated. It involves many aspects such as technology, cost, and policy to determine the optimal lifetime; however, these issues are not within the scope of this study. According to research, batteries last 6–10 yrs on average [260–262], necessitating battery replacement over the lifespan of EV. However, the service life of battery is gradually increasing with technological innovation. In a recent study, only 5% of EV battery replacements were considered [39]. Another study indicated that the optimization of battery technologies, the improvement of the cooling system, and more effective battery management will enable a longer battery life, thus, a lifetime of 15 yrs will be more in line with future conditions [263]. A longer lifetime would reduce the battery's retirement rate, reducing the potential for battery reuse as an energy storage facility [178,264,265]. Like stationary batteries, these effects are beyond the scope of this study and are thus not discussed in detail.

- Trade-offs of alternative technologies

Demand forecasting is subject to huge variations depending on how the technology evolves. For this reason, seven alternative scenarios constructed in the SDS of the IEA report for wind, PV, and EVs. The market share in our model is consistent with the likeliest of the IEA’s base scenarios.[19] An alternative scenario assumes that perovskite PV cell would become a dominant technology. Experimentally, the efficiency of perovskite solar cell is highly promising. Additionally, they require fewer resources and probably have a lower production cost [24,266,266]; however, one drawback is their use of lead which is toxic [267–269]. Furthermore, contrast to NMC technology, lithium iron phosphate (LFP) batteries do not require nickel, manganese, or cobalt, which has attracted considerable interest from automobile manufacturers recently [270,271]. The next generation of low/zero-cobalt, nickel-rich automotive battery is often considered to be at the forefront to enable higher energy densities and a longer drive range as well as reduce risks to cobalt supply. They are expected to enter the market after 2030 [19,272,273], and will shift demand pressure to lithium [127]. Battery technologies replacing lithium with sodium are in the early stages of development [128]. Another technology-based assumption is that PM motors will dominate the market. However, if there is an extreme imbalance between supply and demand, induction motors that are mainly copper-containing and REE-free can be a reasonable PM-free alternative, although at the cost of efficiency.

- Scale-up recycling efforts

Recycling could lower the demand for raw materials. Currently, the recycling of batteries and REEs is difficult, and the technology is still in its infancy; hence, we have roughly assumed different recycling rates (**Figures 3.5 and 3.6**). We have calculated specific total material requirements for PV based on the current recycling rates (**SI**, **Figure A3.7**), although we did not calculate the recycling of silicon-based on the current situation. Although AsGa technology will enter the market after 2030, the corresponding recycling system will not be mature and a large number of these cells will be in the service life cycle in 2050; thus, As, Ga, and In contained in AsGa cells are not considered for recycling. For a robust supply of secondary materials, an effective recycling rate of minor materials (such as REEs) is essential [274], *e.g.*, the PMs used in wind turbines are bigger and have greater recycling potential than EMs [275]. By designing products and alloys with recycling in mind, (*e.g.*, avoiding combinations of metals that are difficult to separate during refining), recycling losses and contamination can be minimized. Improper disassembly of vehicle batteries may cause dangers such as explosion accidents; therefore, stringent standards are crucial to the battery recycling industry [276,277].

- Other potential remedies for supply and demand imbalances are required

Faster improvements in renewable energy technology and the electrification of transportation are crucial for achieving NZE, however electrification levels alone are not a panacea. Whilst supply-side modeling was not included in our analysis, it is noteworthy that the global average lead time from the mineral discovery to production is 17 years, which will even be longer for cobalt [19]. To fulfill the demand under the NZE scenario for critical materials, it is imperative to swiftly expand processing facilities and adopt low-carbon production process. [110] Even in the case of sufficient geological reserves, the surge in demand in the short term might cause bottlenecks of resource supply [278], and geopolitical tensions will make this even more difficult [185]. The demand for materials will surely become more difficult as wind turbines and batteries get bigger, and the procedures or extracting and refining such materials are energy-intensive and potentially harmful to the environment [220]. The changes brought about by the progress of battery technology and the considerable increase in PV material efficiency are inspiring. Herein, we consider the possible reduction in unit MI that benefit from technological innovations. Although other actions through demand-side measures, such as in consumption [118] and behavior [111,116,257,279–281], are essential for achieving NZE, they are not explored here.