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Self-sufficiency of the European Union in critical raw materials for E-mobility

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ABSTRACT

Widespread adoption of electric vehicles poses challenges due to critical raw material (CRM) requirements. The European Union (EU) is now dependent on other countries for supply of these materials, but wants to increase self-sufficiency for primary extraction to 10 % in 2030. Here we map and quantify Europe's raw material reserves and resources, revealing promising deposits for most minerals. Our analysis indicates that, assuming a high development scenario, for lithium, nickel and copper the planned extraction in Europe is sufficient to meet at least 10 % ofdemand for E-mobility in 2030, as the EU's proposed target dictates. The projected extraction of cobalt, natural graphite and REE, will probably not reach 10 % of the demand in 2030. For REE there is no European production projected. To meet these targets and increase the EU's self-sufficiency, CRM extraction in Europe needs to increase, in parallel with implementing circular economy efforts to reduce material demand.

1. Introduction

Mobility plays an important role in our daily lives, with people covering increasingly greater distances over the centuries. Transport causes 25 % of the European Union's (EU) total greenhouse gas (GHG) emissions, of which road transport accounts for 80 %. The transport sector is the only European sector where GHG emissions increased over the past three decades (European Parliament, 2023a). Since the EU aims to reduce transport emissions by 90 % in 2050, a sharp increase in the number of zero-emission vehicles on European roads is necessary (European Commission, 2019, 2020). Passenger cars and vans, responsible for 15 % of the EU's total CO2 emissions, are the primary focus (European Parliament, 2023b).

Zero-emission vehicles or electric vehicles (EVs) can be divided into battery-electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV), and non-electric e-fuel cars. In 2023, around 25 % of passenger cars sold in the EU was electric, and adoption of commercial EVs is expected to increase in the coming years as well (McKerracher, 2024). Also compared to the rest of the world EV demand in the EU will increase considerably in relation to its population size (Carrara et al., 2023).

EVs require more and different raw materials than conventional internal combustion engine vehicles. Even though the energy transition as a whole will require substantially less mining than the current fossil-based system (Nijnens et al., 2023), up to six times more minerals may need to be extracted for EVs compared to internal combustion engine vehicles (IEA, 2021). Many of these materials are classified as Critical Raw Materials (CRMs), which means they are economically important but associated with supply risks at the same time (Grohol and Veeh, 2023). The projected demand in EVs combined with the higher CRM requirements of the vehicles will lead to a considerable growth in CRM demand (Tang et al., 2021).

Multiple studies assess the rise in material demand due to EV adoption. Watari et al. (2020) review 88 critical metal outlook studies and project a considerable increase through 2030 and 2050 on a global scale. In a subsequent study, Watari et al. (2021) find considerable demand growth rates for copper (140 %) and nickel (140 %). Especially under the IEA Net Zero Emissions scenario, demand for CRMs is expected to increase (with 16 times in 2050 compared to 2020, according to Liang et al. (2023))

The IEA Global EV Outlook (IEA, 2024a) shows EV batteries are driving demand for critical metals such as lithium (EV batteries being responsible for 85 % of total demand), cobalt (70 % of the total demand), and nickel (10 % of demand). While current supply needs

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demand, mining and refining have to grow quickly to meet future demand and prevent supply chain bottlenecks. The Global Critical Minerals Outlook (IEA, 2024b) endorses this message, indicating demand growth has remained robust over the past years and EVs are the largest consuming application of many CRMs. Significant future supply gaps may emerge, especially for copper and lithium (for which current projected supply meets only 70 % and 50 % of demand respectively). For nickel and cobalt supply and demand are relatively equal, but supply risks could be limited further if potential future projects are developed. For graphite and REEs the high market concentration poses risks instead of supply volume (IEA, 2024b).

Gregoir and Van Acker (2022) emphasize the need for higher imports or increased domestic mining and refining for Europe. They find that metal supply and demand are most likely to deviate in the decade between 2020 and 2030, with major supply risks for copper, lithium, nickel, cobalt and REEs. Metal demand will peak between 2030 and 2040. In these decades, supply is expected to come mainly from primary sources, since larger volumes of secondary supply are only expected from 2040 onwards (Gregoir and Van Acker, 2022). This conclusion is endorsed by Liang et al. (2023), who find that for REEs secondary supply will be negligible at current recycling rates, while recycled supply can cover 35 % of the demand with high recycling rates. For battery materials, they find that lithium, cobalt and nickel demand can also partly be offset by recycling, but not on the short term and only if recycling rates increase significantly. Primary production will thus still be necessary in the coming decades.

The studies mentioned above provide clear assessments of expected CRM supply and demand, and emphasize the high geographic concentration of extraction of these metals. Whether supply of these materials will be able to keep up with the growing demand is uncertain (Bobba et al., 2020; Gregoir and Van Acker, 2022). An elaborate overview of the status of CRM value chains, circularity and sustainability in relation to the EU can be found through the EC's Raw Materials Information System (RMIS) (RMIS, n.d.). The Critical Raw Materials Act (CRMA), proposed by the European Commission (EC) in 2023 and formally adopted in early 2024, aims to increase EU capacities for strategic and critical raw materials at each stage of the value chain through setting benchmarks for domestic extraction, processing and recycling. One of the set goals is the EU being 10 % self-sufficient in terms of mining of CRMs by 2030. For processing, the goal is to domestically process at least 40 % of the EU's annual consumption in 2030, while for recycling the target is 25 %. The ambition of the Act is to ensure a strong, resilient and sustainable value chain for CRMs, reducing strategic dependencies and improving circularity and sustainability (European Commission, 2023).

This paper conducts a comprehensive investigation of reserves and resources of these CRMs in Europe with their expected production plans, and compares it with the forecasted European demand. We explore the feasibility of meeting the goal of mining at least 10 % of the EU's annual consumption domestically for six CRMs required for E-mobility. We assess the potential European self-sufficiency for cobalt, copper, (natural) graphite, lithium, nickel and rare earth elements (REEs). These are key CRMs for EVs, particularly used in EV batteries and permanent magnets for traction motors (Carrara et al., 2023).

2. Methods

2.1. Terminology

In this paper we define mineral resources as a '*concentration or occurrence of solid materials of economic interest in or on the Earth's crust in such a form, grade, quality and quantity that there are reasonable prospects for eventual economic extraction*' (CRIRSCO, 2019, p. 19). These are categorized into inferred, indicated, or measured resources, in order of increasing geological confidence. Measured and indicated resources are combined and categorized as 'measured & indicated' or M&I resources. There are also 'non-compliant' resources, i.e. historic estimates or resources lacking classification support. These were not included in our analysis due to high uncertainty. See SI 1 for a table with the definitions of different resources and reserves.

Mineral reserves are '*the economically mineable part of a measured and/or indicated mineral resource*' (CRIRSCO, 2019, p. 25). This includes diluting materials and extraction losses. Reserves are determined through pre-feasibility and feasibility studies, which show whether extraction could be economically justified. Economics are the determining factor for reserves. When prices increase reserves do so as well, making it financially feasible to mine resources that are more difficult and thus more expensive to extract.

2.2. Mapping and quantifying of sources

This paper maps and quantifies the resources and reserves in Europe for cobalt, copper, natural graphite, lithium, nickel and REEs by country and development stage or level of confidence. We collected quantitative data, such as resource estimates and coordinates, and qualitative data about mining activities, project development stages and data reliability up to May 2023. The main source for project information was S&P Capital IQ Pro, while scientific papers provided additional insights into resource distribution, resource estimates and their certainty, coordinates and other information about mineral occurrences and deposits. An overview of the different data sources for the different minerals and locations can be found in Table 1.

When data quality for certain commodities or specific locations was insufficient, additional primary sources like company websites were used. Coordinates of projects, deposits or occurrences were primarily sourced from our main data sources but other sources like company websites or mineralogical databases were consulted if the main sources were lacking. All countries on the European continent were taken into account, plus Greenland and excluding Russia (collectively further referred to as 'Europe'). The 30 countries for which resources have been found are displayed in SI table 3. An absence of depicted occurrences in a certain country does not necessarily mean that there are no CRM resources in that country – this could also be due to a lack of data.

Extraction rates for current or future projects were rarely available in our main sources or in scientific papers. We obtained this data from company websites and reports, press releases, and news articles. We prioritized recency and validity of the data, and used meta studies to complement the data when relevant.

Resource and reserve tonnages were determined by multiplying ore tonnages with ore grades (e.g. 1 Megaton of Nickel ore with an indicated resource grade of 0.5 % Nickel metal results in 5000 tons of Nickel metal indicated resources). The same method was applied to calculate other certainty levels of reserves and resources, when the correlated grade was given (i.e., reserves, measured & indicated, inferred, and non-compliant resources). Different data sources provided various grade units, e.g., lithium oxide, lithium hydroxide monohydrate, lithium metal, etc. These were manually converted to the pure metal unit in a spreadsheet. Raw data, including ore tonnages, grades, coordinates and qualitative information, was used to calculate CRM resources and reserves for each

Table 1
Main data sources for the resource estimates and locations.

Lithium	Gourcerol et al. (2019), S&P Global Market Intelligence (2023)
Cobalt	Horn et al. (2021)
Nickel	Makkonen et al. (2017), Stanković et al. (2022), S&P Global Market Intelligence (2023)
Copper	S&P Global Market Intelligence (2023)
Graphite	Gautneb et al. (2021), S&P Global Market Intelligence (2023)
REE	Goodenough et al. (2016), S&P Global Market Intelligence (2023), EURARE project (EURARE, 2022)
Location coordinates	S&P Global Market Intelligence (2023), Mindat (2023), other mineralogical databases
Extraction rates	S&P Global Market Intelligence (2023), company websites, press releases, company reports

location. This served as input for creating maps in ArcGIS version 11.1.

Resource totals were then calculated for each country and for Europe, considering different levels of certainty. To identify the most promising extraction projects, we focused on projects with late development stage (i.e., explored deposits and operating mines) and high certainty (i.e., reserves and measured & indicated resources). Definitions of the different development stages can be found in SI Table 4.

To estimate the depletion date of mining projects, we divided reserves and resources by the extraction rate. If an official end date was available in literature, this date was used. We considered official start-up dates of the mines as indicated on the company websites. For mines already operational, the date of the reserve or resource estimation was selected. This information allowed us to calculate yearly CRM extraction of the mining projects from 2023 to 2050, including mines only active in a specific year. The extraction rates were obtained from literature directly or calculated based on past production averages from the last few years, assuming this extraction rate would remain consistent for future extraction.

2.3. Self-sufficiency

We used a supply-demand balance to assess the EU's self-sufficiency in CRM supply for E-mobility. First, we prepared demand trends for each CRM required for E-vehicles for the European market for the years 2023 to 2050, considering a high demand scenario based on data from Carrara et al. (2023). This includes general E-mobility demand, without considering the source of CRMs (e.g. primary or secondary sources). Carrara et al. (2023) base their demand modeling on three pillars: technology deployment (e.g. EV sales), subtechnology market share (e.g. battery types) and the material intensity and efficiency (tons of material per vehicle). The study examines a High and Low Development Scenario (HDS and LDS). The HDS is in line with the EU's energy and climate targets, and therefore we chose to focus on this scenario in the rest of this paper. Since the analysis by Carrara et al. (2023) is executed by the EC's Joint Res. Centre in collaboration with the EC DG Grow, and thus used to inform EU policies, we believe it is the most relevant demand scenario to assess the primary extraction target as set in the CRMA.

As the raw data only contains demand values for 2020, 2030 and 2050, we used linear regression to fill the gaps in the data. Second, we calculated CRM supply, based on current and projected CRM extractions from European primary sources. We then divided annual projected supply by annual demand to determine *operational* self-sufficiency in a particular year. The operational self-sufficiency provides an overview of the extent to which European primary extraction can fulfill EU demand for E-mobility based on current extraction plans.

We also calculated the *potential* self-sufficiency, based on the primary reserves and M&I resources available and without considering whether extraction plans exist for all of these resources. This provides insight into potential self-sufficiency if extraction plans would be accelerated.

We do not account for potential new discoveries of reserves and resources. Furthermore we assume that materials extracted from European sources will be consumed in the EU, for strategic autonomy reasons. Considering supply from European countries and demand from the EU means the self-sufficiency results in this study may be a bit higher than when demand from these other countries would be included as well. These limitations will be described more elaborately in the discussion section of this paper.

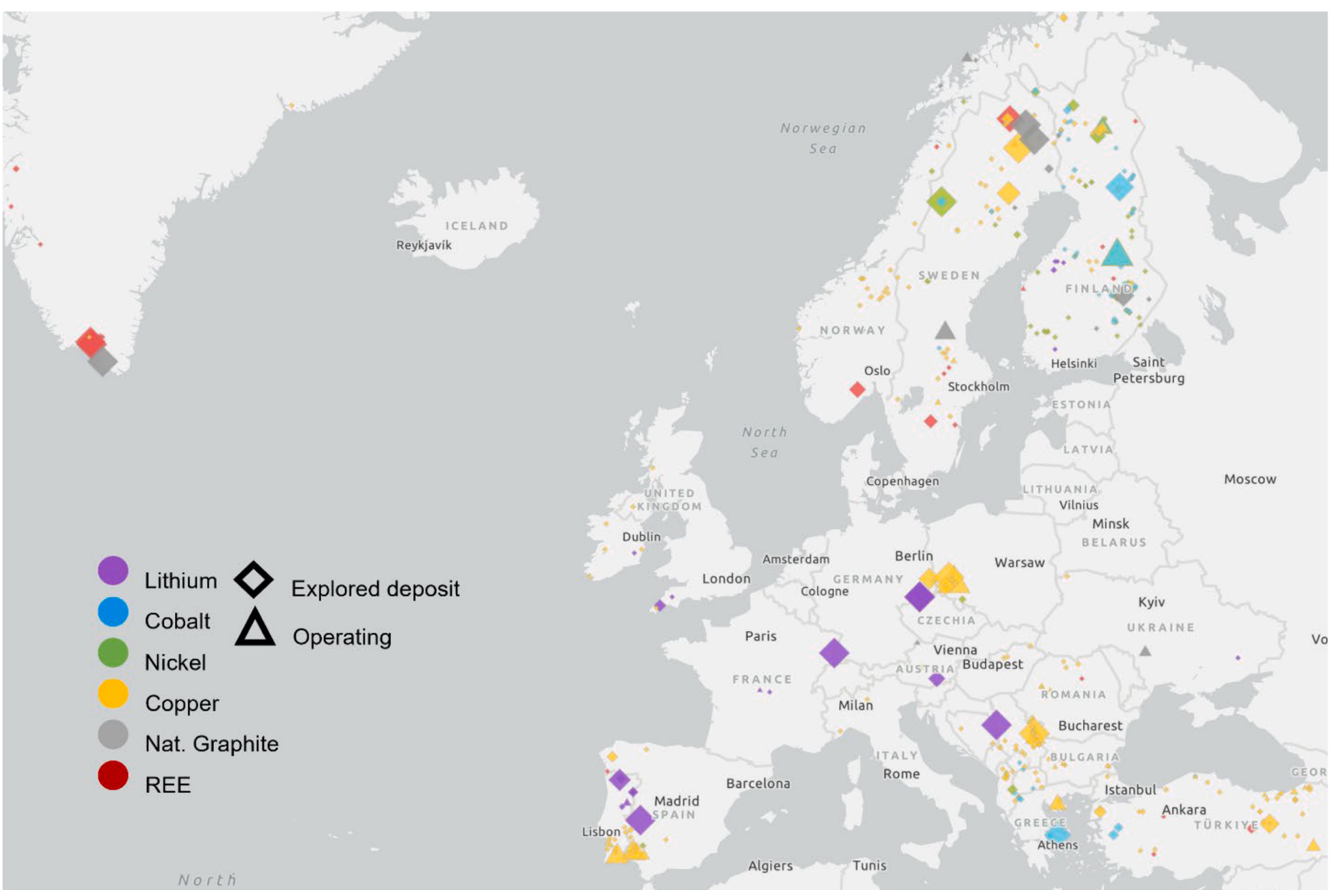

Fig. 1. GIS overview map of explored deposits and operating mines of CRMs in Europe. For better overview the numerous locations of unknown status and unexplored occurrences/prospects were hidden. Data partly based on S&P Global Market Intelligence (2023).

3. Results

3.1. Mapping of the sources

Fig. 1 displays the six CRMs relevant for E-mobility and their available deposits and mines across Europe. An interactive map, providing more insight into the specific projects, can be accessed through the following link: https://arcg.is/1bDD0a. The map shows a considerable presence of cobalt in Finland, Sweden and the Balkans, while lithium has been found in sites in Portugal, Spain and central Europe. Copper is abundant in the Balkan region, Norway and Sweden, but also in other parts of Europe. Finland and Sweden dominate in terms of nickel presence, while known REE deposits are distributed across Europe and occur over the whole European continent but particularly in Greenland. The map also indicates that most occurrences are explored deposits, with a limited number of operating mines.

3.2. Resources and reserves per material

The number of locations with occurrences and the size of reserves and resources differ per material (Table 2). For most materials, only a handful operating mines exist in Europe. Copper is mined most, with 32 operating projects. Table 2 also indicates the size of the reserves and resources for the different resource categories. In the rest of the results section, we will focus on reserves and M&I resources, since inferred or non-compliant resources are associated with high uncertainty. All results are expressed in pure metal unit.

3.3. Planned extraction per material

Fig. 2 illustrates the planned extraction compared with the cumulative demand for E-mobility under a high development scenario for the six assessed materials. We assume all materials are used to cover European E-mobility demand, and do not consider other sectors. For lithium, the demand can be met until 2029 but production is expected to decline from 2040 due to resource exhaustion and a lack of new extraction plans. Cobalt extraction, with a rate of <5 kt per year, is insufficient to meet demand. Even with a forecasted decrease in demand between 2030 and 2050, supply cannot keep up due to limited planned extraction but also lacking resources and reserves. Nickel's extraction rate is insufficient for covering current needs and the future increasing demand. Graphite extraction, now slightly above 100 kt per year, will drop to around 20 kt per year in 2030 due to the depletion of the three mines currently operational. While new mines are planned, the growing demand will still lead to a substantial supply-demand gap. Copper is extracted at a rate of around 800 kt per year, which is more than sufficient to cover demand for E-mobility up to 2050. REEs are currently not extracted in Europe, nor are there any plans for REE extraction in the future, which means European sources will not be able to cover any of European REE demand for E-mobility. However, European REE reserves would be more than sufficient to cover cumulative demand until 2050, as will be discussed in section 3.6.

3.4. Operational and potential self-sufficiency

Fig. 3 illustrates Europe's operational self-sufficiency in supplying the six assessed CRMs for E-mobility, based on current extraction projections and assuming all minerals mined in Europe are used domestically for E-mobility only. Operational self-sufficiency is evaluated by comparing total planned extraction against expected demand in 2030 and 2050, based on projected production from reserves (dark green) and projected production from resources (light green) with reserves offering higher supply certainty.

Fig. 3 shows that, when only considering E-mobility demand and assuming all supply is used for that, Europe could fully meet its copper needs for E-mobility in 2030. It is projected to cover at least 10 % of 2030 demand for lithium (72 %) and nickel (23 %), and could achieve this for graphite (26 %) as well if extraction efforts are accelerated and resources turn into reserves. For cobalt (9 %) and REEs (0 %) this target is not within reach. By 2050, with the current extraction projections, Europe can achieve full self-sufficiency for E-mobility for copper only and reach the 10 % target for lithium. It could cover 10 % of its 2050 demand for E-mobility for nickel and graphite as well, depending on accelerated extraction plans and resources turning into reserves. The analysis shows variable trends in self-sufficiency across minerals and timeframes. For lithium, nickel and graphite self-sufficiency is higher in 2030 than in 2050 due to rising demand and insufficient extraction growth after 2030. For cobalt on the other hand, self-sufficiency is lower in 2030 and slightly improves in 2050 due to planned increases in extraction from resources.

Fig. 4 illustrates the potential self-sufficiency of Europe in terms of supplying the six assessed CRMs required for E-mobility demand. The potential self-sufficiency is the ratio between the total potential extraction, based on reserves and M&I resources, and the expected

Table 2
Resources and reserves per material. Data partly based on S&P Global Market Intelligence (2023).

Resource	Number of locations	Development stage	Total (Mt)	Reserves (Mt)	M&I resources (Mt)	Inferred resources (Mt)	Non-compliant resources (Mt)
Lithium	528	Operating: 2; Explored: 22; Unexplored: 7 Unknown: 497.	17.2	0.9	3.4	4.6	8.3
Cobalt	152	Operating: 2; Explored: 70; Unexplored: 80.	1.6	0.1	0.3	0.3	0.9
Nickel	78	Operating: 2; Explored: 57; Unknown: 19.	23.1	4.2	2.8	2.6	13.5
Copper	266	Operating: 32; Explored: 191; Unknown: 43.	102.6	29.2	31.9	15.8	25.7
Graphite	31	Operating: 5; Explored: 12; Unexplored: 10; Unknown: 4.	24.4	1.2	9.3	11.1	2.8
Rare earth Elements	81	Operating: 2; Explored: 23; Unexplored: 36; Unknown: 20.	45.1	1.7	4.9	36.9	1.6

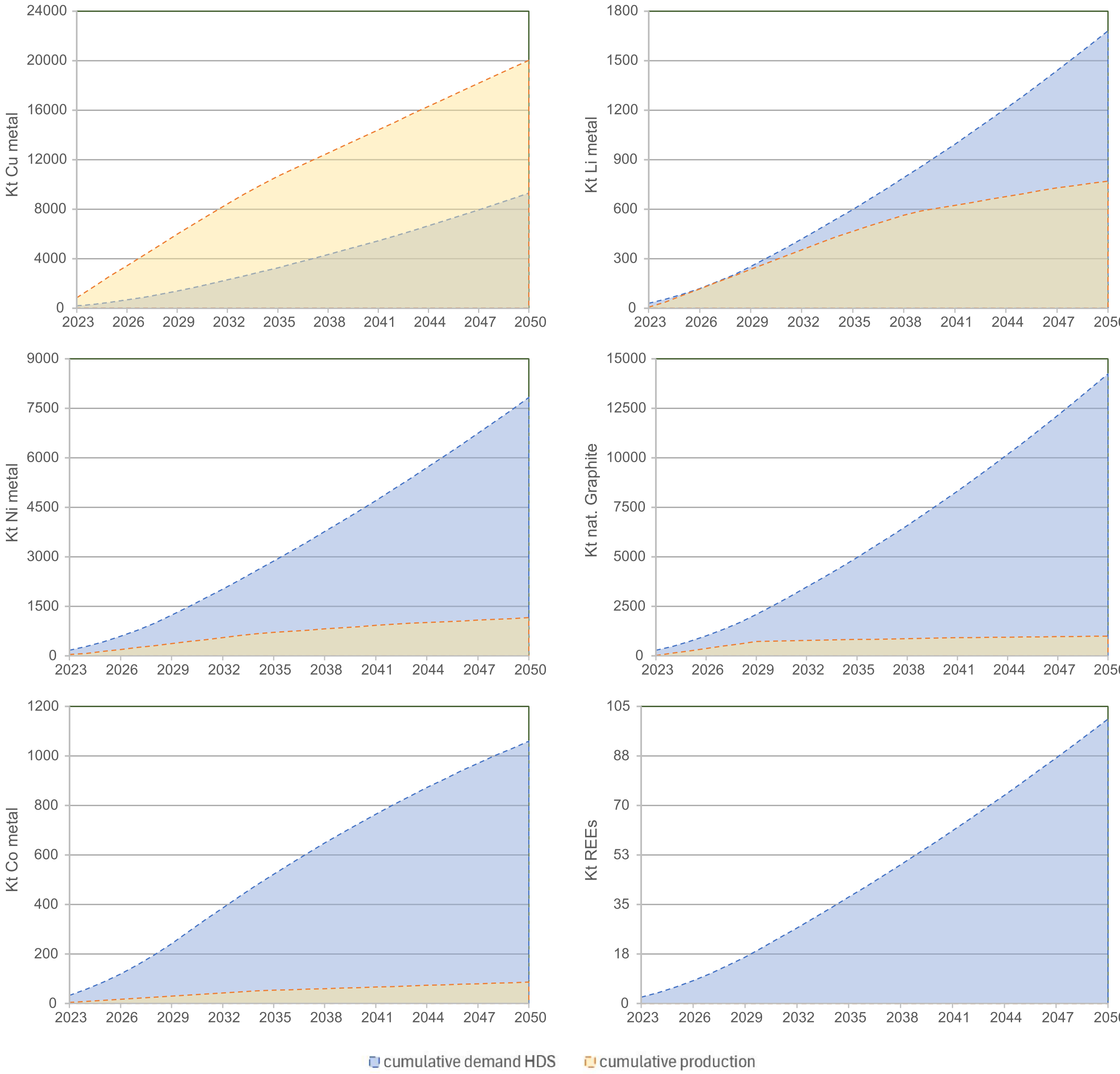

Fig. 2. The cumulative planned extraction of the six assessed minerals up to 2050 in Europe, compared with the cumulative European demand for E-mobility under a high development scenario. The further into the future, the more uncertain the planned extraction.

demand up to 2050 under a high development scenario. These numbers demonstrate Europe's resource potential, when assuming extraction is not a limiting factor at all and when all minerals mined in Europe are used domestically. This shows that Europe could potentially be fully self-sufficient for E-mobility based on reserves in 2030 for lithium, nickel, copper, and REEs. For cobalt and natural graphite, the EU will not be self-sufficient by 2030. However, if M&I resources are turned into reserves, Europe could be fully self-sufficient for E-mobility up to 2050 for lithium, copper and REEs. For cobalt, nickel and graphite, full self-sufficiency is not feasible, but especially for the latter two European sources could contribute considerably to meeting E-mobility demand.

Table 3 demonstrates how much of the reserves per material will have to be extracted per year to achieve the 10 % self-sufficiency target for E-mobility. These tables show that, for most materials, 10 % of the yearly demand in 2030 will only require the extraction of a very small percentage of existing reserves for all minerals, except for cobalt (5.28 %) and natural graphite (9.54 %). In 2050, with considerable demand increases, this increases even further for cobalt (6.96 %) and graphite (34.33 %), and supplying 10 % of the yearly mineral demand will require a relatively large share of existing reserves for lithium as well (8.52 %). Both in 2030 and 2050 a self-sufficiency target of 10 % will only require the extraction of a very small part of total reserves for nickel (0.68–1.19 %), copper (0.13–0.50 %), and REEs (0.02–0.03 %).

4. Discussion

We show that achieving 10 % self-sufficiency as targeted in the CRMA seems feasible for most assessed materials, although acceleration of extraction efforts and turning resources into reserves will be needed. Fully covering the EU demand for E-mobility with European sources will be more challenging, especially when considering current planned extraction rates. Besides increasing the supply from European sources,

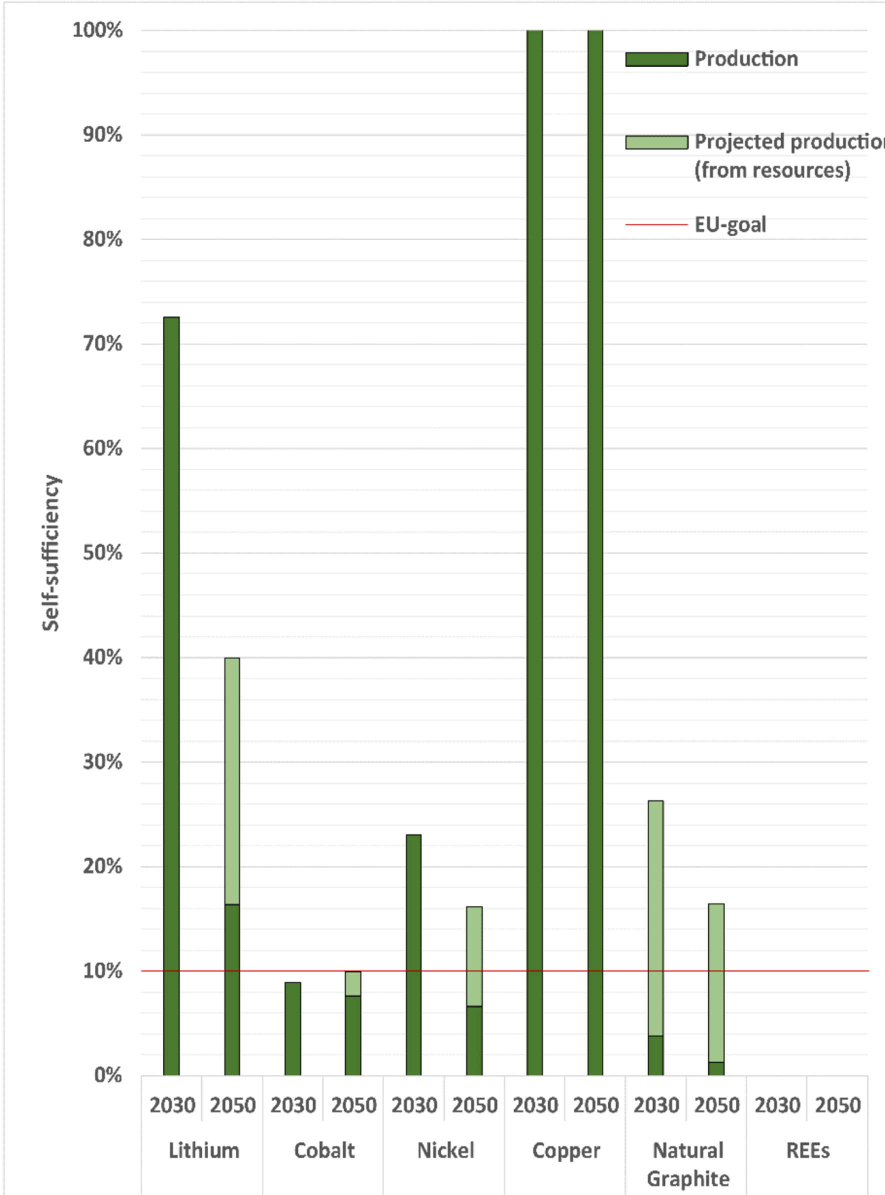

Fig. 3. Expected operational self-sufficiency (i.e. the European planned extraction for that particular year divided by EU demand for E-mobility for that year) under a high development scenario (HDS). For copper, the projected self-sufficiency is 287 % in 2030 and 130 % in 2050.

self-sufficiency can also be improved by decreasing demand. In this section we discuss several strategies to influence both European supply and demand, and their impact on self-sufficiency. Finally, we go into the limitations of this research, and suggest future research priorities.

4.1. Supply side

The example of REEs demonstrate that often reserves or resources are sufficient, but plans for extraction are inadequate. There are several reasons for this, such as the lack of a positive investment climate for new mining projects, higher energy prices and labor costs in Europe compared to the rest of the world, and the presence of stricter environmental and social regulations. Also, frequently the size and quality of reserves and resources is lower (Gregoir and Van Acker, 2022). Mining projects often face resistance from local communities, such as in Greenland where local people voted against REE extraction in 2021 due to fear for negative environmental impacts on the area (Henriques and Böhm, 2022). The CRMA aims to ease and accelerate the process of starting new mining projects in the EU, which could increase self-sufficiency in the coming decades.

This study only considers M&I resources as known in 2023 as potentially extractable, excluding inferred or non-compliant resources and potential new discoveries. The potential for self-sufficiency is likely to be larger than presented here, due to possible new discoveries of reserves and resources. Exploration technologies have advanced significantly over the past decades, but exploration has mainly concentrated on regions outside of the EU (Stilltoe and Thompson, 2005). On the other hand, not all deposits might be extractable. Projects should be assessed based on different factors, e.g. through the United Nations Framework Classification for Resources which can be used to assess projects in terms of environmental-socio-economic viability, technical feasibility and degree of confidence (United Nations, 2020).

Despite our society's pressing need for CRMs, environmental concerns and human safety should be priority in new mining projects. The environmental impact from mining varies by mineral (Farjana et al., 2019; Nuss and Eckelman, 2014), time and location (Northey et al.,

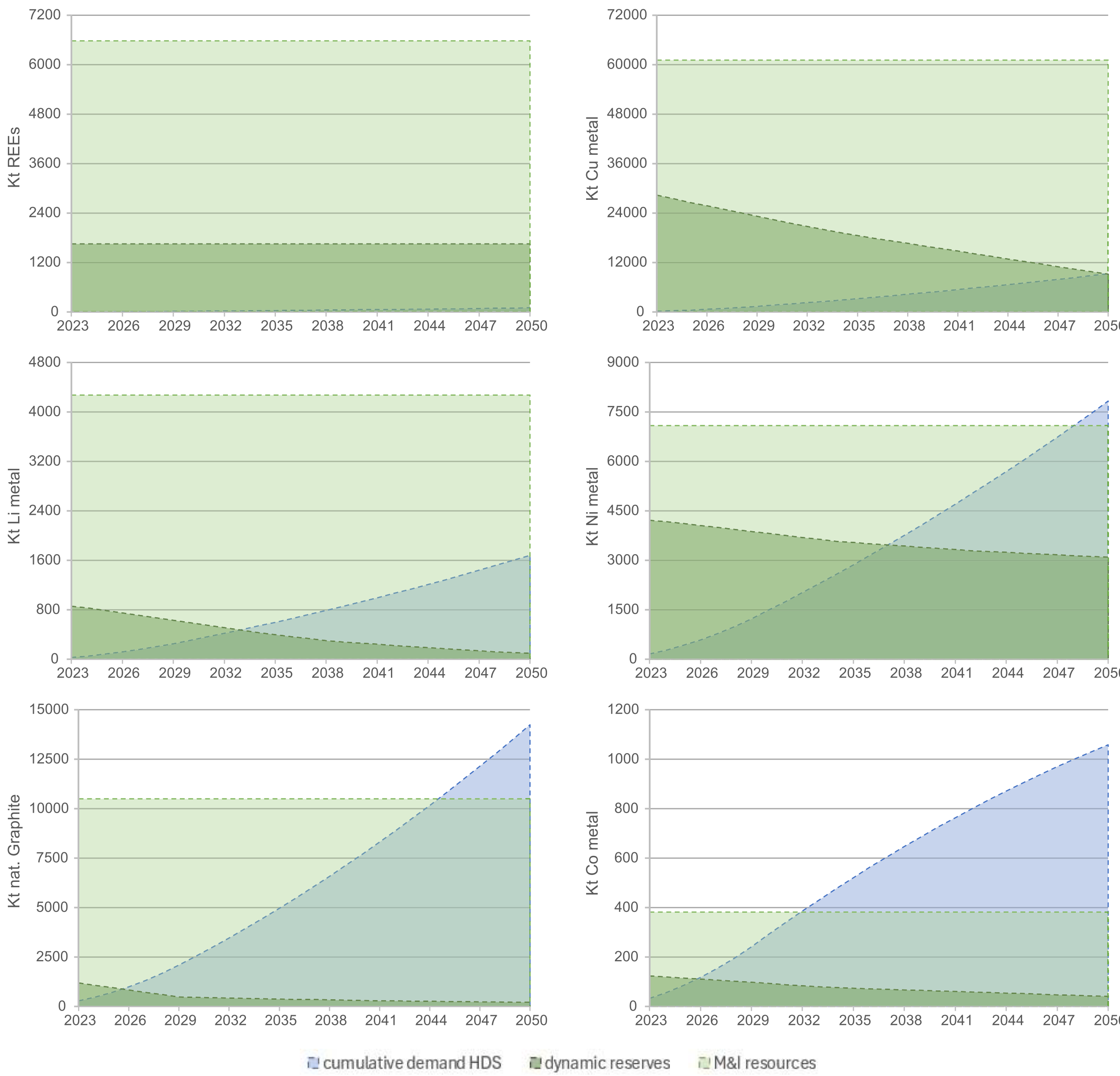

Fig. 4. Overview of resources and reserves for the six assessed materials, combined with the cumulative demand for E-mobility under a high development scenario, without demand for other sectors taken into account. The reserves decline since planned extraction is taken into account.

Table 3
Percentage of the reserves we need to extract to achieve 10 % self-sufficiency, or full self-sufficiency for each material in 2030 and 2050 (assuming no new reserves are discovered).

Material	*Year*	Reserves needed to cover 10 % of E-mobility demand
Lithium	*2030*	0.92 %
	2050	8.52 %
Cobalt	*2030*	5.28 %
	2050	6.96 %
Nickel	*2030*	0.68 %
	2050	1.19 %
Copper	*2030*	0.13 %
	2050	0.50 %
Natural Graphite	*2030*	9.54 %
	2050	34.33 %
REE	*2030*	0.02 %
	2050	0.03 %

2014), but is often significant. Mining can have drastic impacts on local communities, including high risks for workers (Stewart, 2020) and pollution-related health impacts (Li et al., 2014). The environmental and human health impacts, combined with inadequate community representation, participation and compensation often lead to local resistance against mining projects (Conde, 2017).

Mining in Europe, however, could reduce many of the negative impacts of mining occurring in places around the world. Due to relatively strict environmental standards and regulations, control over whether mining happens in an ethical and responsible way increases (Mudd, 2021; Bice, 2016; Jarvie-Eggart, 2015). Starting projects detrimental to local communities and the environment is more difficult in Europe compared to many other parts of the world, due to its relatively strong civil society and democratic governments. Examples of mining projects subject to resistance of local communities, such as potential new lithium mines in Portugal (Dunlap and Riquito, 2023) and Serbia (Stefanovic et al., 2023), show projects being delayed or even cancelled due to strong civil objection and protest. Even though challenges still remain, there is ample knowledge on increasing sustainability in mining in Europe, e.g. through electrification of transport within and around mines or biodiversity conservation programs, as implemented in mines in Europe already (Endl et al., 2021; Paneri et al., 2021; Walton, 2023).

Mining, processing and using the mined materials within Europe has additional benefits. It reduces transport and shipping needs for required materials, which reduces emissions associated with transport and lowers the risk for supply chain disruptions. These disruptions are often caused by political instability in a country controlling a majority of supply, but have also been triggered by global events like the COVID-pandemic (Habib et al., 2021) or incidents like the blocking of the Suez Canal (Kinch et al., 2021). Addressing these issues would however require an increase in European processing capacity as well. Also, social impacts are often lower in material supply chains in Europe compared to other places, due to e.g. favorable working conditions and more secured worker rights (Koese et al., 2023). Finally, it is questionable whether it can be morally justified to outsource resource extraction and the negative impacts associated with it to other and often poorer countries. European society profits while people and ecosystems elsewhere suffer (Carley and Konisky, 2020). At the same time, we cannot ignore that mining can provide substantial economic benefits to communities (Eggert, 2001).

When projects in Europe finally materialize, they are likely to have less detrimental impacts on local communities and the environment than projects happening elsewhere in the world. Especially compared to Africa, Asia and South America, where most of the materials used in Europe are currently sourced from (Grohol and Veeh, 2023). Still, also in Europe mining poses considerable risks, e.g. for indigenous communities (Conde, 2017), and mining is an inherently destructive activity. Also, the economic costs of mining are often higher in Europe compared to the rest of the world (Gregoir and Van Acker, 2022). More sustainable material supply and improved strategic autonomy come at a cost, since with the current economics materials extracted in Europe will most likely be more expensive. A trade-off emerges between cheap materials on the one hand and strategic autonomy on the other. Public and political debate is required to address the consequences of our society's insatiable need for raw materials and the tradeoffs that might arise accordingly. The most sustainable solution is invariably reducing material demand, as discussed in the next section.

4.2. Demand side

Increasing European self-sufficiency – and strategic autonomy – can also be increased by reducing CRM demand. The less materials the EU needs, the more feasible it is to source these domestically and the less impacts are generated in third countries. Technology developments, such as a shift from current lithium-ion to emerging EV battery types can significantly reduce future material requirements. New, organic cathode materials are increasingly competitive (Chen et al., 2023). Lithium-iron-phosphate (LFP) batteries do not contain any nickel, cobalt or manganese and sodium-ion batteries do not require lithium, and also significantly less cobalt or nickel (IEA, 2023; Vaalma et al., 2018). The latter are currently being developed within EU borders, with the Swedish Northvolt claiming a major breakthrough in 2023 (Milne, 2023).

There is a risk of opening mines for materials we will not need once a developed mine is operational, which can take up to 10–15 years. Interest in sodium-ion batteries only reemerged in the early 2010s (Hwang et al., 2017) and these batteries are already used in commercial electric vehicles today (IEA, 2023). This indicates that technology development can progress rapidly. A trade-off emerges between being able to address supply risks, and being able to flexibly respond to technology developments. Further research, including demand forecasts with different technology development scenarios, is required to appropriately address future European self-sufficiency.

We should not rely on technology development alone. New battery types will not lead to reduced copper or REE requirements, while especially for the latter demand is expected to grow, supply risks exist and no European extraction is projected. Even though REE demand growth could be limited through the use of REE-free propulsion motors, the demand surge will still be substantial (Riba et al., 2016; Pavel et al., 2017). For copper, demand would be considerably higher than projected in this paper if material requirements for EV charging infrastructure would be taken into account as well. Raghavan et al. (2023) finds that charging infrastructure could be responsible for up to 30 % of the total E-mobility copper demand. Finally, rebound effects are always a risk, where a more efficient technology leads to a higher demand, offsetting the efficiency benefits (Sorrell, 2007).

Reducing material demand can also be achieved by extending product lifetimes or changing social practices. Prolonging the usage duration of cars reduces the need for new vehicles, materials remain in-use longer, and thus the primary demand is alleviated and peak demand delayed (Liang et al., 2023). Using smaller cars limits material requirements as well. Promoting sustainable transport methods like cycling or public transport can decrease the reliance on private vehicles, thus reducing demand for CRMs. Reusing vehicles and their components should be stimulated. End-of-life EV batteries could potentially be used for grid energy storage, complementing renewable energy generation (Xu et al., 2023).

When demand reduction and reuse are not possible, effective recycling should take place to recover valuable materials, e.g. from lithium-ion batteries (Ziemann et al., 2018) or REE permanent magnets (Van Nielen et al., 2023). Recycling is expected to contribute considerably to CRM supply from around 2040 onward (Liang et al., 2023; Gregoir and Van Acker, 2022). Wang et al. (2024) show that 30–40 % of demand for REEs could be met by reuse and recycling in 2050. Gregoir & Van Acker (2022) state that, for CRMs in general, secondary supply can cover 45–65 % of demand in 2050. Implementing these strategies will be challenging, since sometimes the technology for recycling is lacking. An example is the recycling of REE permanent magnets, which is emerging but not implemented on a large scale yet (Koese et al., 2024). The singular focus on recycling often seen when policy makers discuss circular economy should be substituted by the simultaneous implementation of multiple circular economy strategies.

Technology developments can affect mineral prices, which in turn influence potential self-sufficiency in Europe. Mineral prices determine whether resources become reserves, since mining will only be economically viable if prices justify the cost. With an increasing demand – as is projected for these minerals – prices are likely to rise as well. Resources will then turn into reserves, and exploration efforts for new resources will be expanded. This results in a paradox regarding self-sufficiency: higher demand initially reduces self-sufficiency but potentially increases it in the long term. Price developments and their effects on material supply should be incorporated into further research, e.g. through the use of System Dynamics modelling (Guzzo et al., 2021; Bradley et al., 2021).

4.3. Limitations

For this research, we only considered a high development scenario for determining future material demand. If lower development or stated policies scenarios are followed, (potential) European self-sufficiency might be higher since these scenarios consider a lower material demand. However, considering the rapid technology expansion needed to limit global warming to 1.5 °C, the high development scenario is most relevant in assessing future material demand. Moreover, the demand modelling in this study was based on the foresight study by Carrara et al. (2023) only. Future research should explore potential differences in the self-sufficiency results based on different demand scenarios.

We only accounted for material demand of the E-mobility sector. The E-mobility sector is most important in driving critical material demand (IEA, 2021), and is highly visible in daily life and thus generates the most public debate. However, to provide a more comprehensive picture of European self-sufficiency for critical raw materials, future research should take into account other sectors as well. European self-sufficiency will be lower than projected in the current research if other sectors are considered as well. Particularly copper is crucial for wide swaths of the economy (Elshkaki et al., 2016; Ciacci et al., 2020).

In our research we considered supply from Europe (i.e. the EU, Greenland, Norway, UK, Ukraine) but demand from the EU. Non-EU demand could slightly affect self-sufficiency results. Greenland's demand is negligible with only 50.000 inhabitants, and Norway also has a minimal impact with 2.5 million EVs in 2035 (Rietmann et al., 2020). Ukraine's demand is relatively small as well, with 6.9 million vehicles on the road currently (Ministry of Restoration, n.d.). UK demand is larger, with a total of 38 million vehicles expected in 2035, of which around 24 million EVs (Rietmann et al., 2020). Including these countries would slightly lower self-sufficiency, since demand increases while supply remains the same. Due to the relatively small demand compared to the other EU countries we expect the effect not to be substantial.

For supply, we assume a good relationship between the EU and these third countries, so the EU has access to the resources from these partner countries. However, good trade agreements with these countries are crucial, especially with Greenland and Norway because of their REE reserves. We did not take into account potential supply risks from inside Europe. In practice, also within Europe supply risks may occur, as the example of the war in Ukraine exemplifies. This may influence self-sufficiency rates negatively, and should be addressed in further research.

Finally, there are other elements required for E-mobility beyond the six elements investigated here, such as manganese or tin. Manganese is also used in many traditional EV batteries with nickel manganese cobalt (NMC) cathode (IEA, 2023), and is considered critical in the EU. Tin is not included in the EU's CRM list (European Commission, 2023). However, Bradley et al. (2024) argue that tin's critically is assessed based on incorrect data, and should be considered critical as well.

5. Conclusion

In this paper we show that, under a HDS, the 10 % self-sufficiency target as proposed in the Critical Raw Materials Act (European Commission, 2023) is feasible for all considered EV materials except cobalt and REEs in 2030, with graphite only meeting the target if resources are also developed. For lithium, the 10 % target is attainable in 2030 but for 2050 additional resources need to be developed. Of the six materials investigated in this work, only the E-mobility demand for copper can be fully covered by European sources currently projected to be taken into production. Self-sufficiency rates might improve rapidly if developments of new projects are accelerated. This is assuming production from European sources but EU demand for the E-mobility sector only, and ignoring potential future supply risks from within Europe. This is also without considering secondary CRM supply.

If extraction plans are expanded and primary production is increased, Europe could be fully self-sufficient based on reserves in 2030 for lithium, nickel, copper, and REEs. For cobalt and natural graphite this is highly unlikely to happen by 2030. With some additional effort, if M&I resources are developed into reserves, Europe could be fully self-sufficient for E-mobility up to 2050 for lithium, copper and REEs. For cobalt, nickel and graphite, full self-sufficiency is requires finding hereto unknown deposits, but European sources could nevertheless contribute considerably to meeting E-mobility demand.

European self-sufficiency can be increased in two ways: through reducing demand and through increasing domestic supply. Regarding the first point; material demand should be limited as much as possible, e.g. through innovation, supporting public transport and shared mobility, and reuse of e.g. EV batteries for balancing the electricity grid. When reduction or reuse is not possible, recycling should be the circular economy measure of last resort.

Regarding the second point; there are considerable reserves or resources in Europe, but plans for extraction are lacking. If the process of starting new mines is accelerated, self-sufficiency might improve quickly. Balancing a quick and secure supply with responsible mining is crucial. Simultaneously supply from secondary sources can contribute considerably to covering CRM demand, especially after 2040. With effective circular economy practices, also the reserves currently in stock in the urban mine can be used. By integrating these approaches the EU can achieve higher levels of self-sufficiency in E-mobility materials and improve its strategic autonomy and sustainability.

CRediT authorship contribution statement

Maarten Koese: Writing – original draft, Visualization, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Michael Parzer:** Writing – review & editing, Visualization, Formal analysis, Data curation, Conceptualization. **Benjamin Sprecher:** Writing – review & editing, Supervision, Conceptualization. **René Kleijn:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.108009.

Data availability

Data will be made available on request.

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