Driving the sustainable transition: battery material dynamics and emission assessments of EU electric mobility

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Chapter 4

The demand and recycling potential for lithium, cobalt, and nickel in the European electric-mobility transition

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Abstract

To address the increasing greenhouse gas emissions in the EU transport sector, the EU has announced climate plans to promote zero-emission passenger vehicles, in practice likely to be implemented in the form of electric vehicles (EVs) due to their technology maturity. This study applies a dynamic material flow model to evaluate the future demand for lithium, cobalt, and nickel in the EU transport sector based on these climate plans and to assess the potential for their secondary supply through 2040. Our results suggest that growing demand for EVs will lead to at least a 21-fold increase in annual demand and a 105-fold stock expansion of these metals in 2040, compared to the 2021 EV sales levels. The available secondary supply of these metals will increase from the early 2030s based on the updated EU Battery Directive, reaching at 20% – 30% of the cumulative material demand by 2040. An accelerated adoption of EVs increases the potential and the need for earlier secondary raw material recovery, underscoring the necessity to promptly develop sufficient recycling facilities in the EU. Shifting towards less critical metal-containing EV batteries, reducing the EV battery capacity, and extending the lifetime of the EV batteries will facilitate the reduction of primary demand.

Keywords: European e-mobility transition, material flow analysis (MFA), material demand, EU battery recycling mandate

4.1 Introduction

Compared to internal combustion engine vehicles (ICEVs), electric vehicles (EVs) powered by rechargeable battery packs can effectively reduce greenhouse gas (GHG) emissions by 30% to 80%, presenting a promising solution for decarbonizing the road transportation sector (Cox et al., 2018; Ellingsen et al., 2016; Hawkins et al., 2013; Messagie, 2017; Notter et al., 2010). Lithium-ion batteries (LIBs) are widely used in EVs due to their high energy capacity, which is determined by the cathode composed of lithium oxides and electrochemically active transition metals (e.g., cobalt, Co and nickel, Ni). The variety of cathode chemistries give rise to different battery types, including lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), lithium manganese oxide (LMO), and lithium iron phosphate (LFP) (Cano et al., 2018; Zubi et al., 2018). Although sodium-ion batteries, have emerged as a cost-effective and environmentally friendly alternative to LIBs, they face challenges related to low energy density, limiting their ability to support long-distance driving and large-scale adoption (Kumar Nayak et al., 2017). For this reason, LIBs are expected to dominate the EV battery market over the next few decades (Cano et al., 2018; Hund et al., 2020).

To address the growing GHG emissions from the passenger vehicles, the EU developed climate policies in 2022 to promote the sale of zero-emission passenger vehicles in all the Member States by 2035 (European Commission, 2022a). This promotion leads to an increasing demand for EVs and the critical raw materials present in EV batteries (e.g., Li, Co, Ni). Given that global mineral reserves for these metals are highly concentrated outside the EU (e.g., over 60% of global Co is supplied by Congo (U.S. Geological Survey, 2023a)), the associated supply risks pose a challenge to the stability and security of the EU electric-mobility (e-mobility) transition (Greim et al., 2020; Sun et al., 2021). Strategies that mitigate reliance on the primary resources are essential, such as improve the domestic material sufficiency by promoting recycling activities. The latest EU Battery Directive calls for improving the collection and recycling rates of the critical metals contained in the EV batteries when reaching their end of life (European Commission, 2022).

Previous studies have projected that the Li, Co, and Ni required in the EU transport sector will increase by twenty to forty times from 2019 to 2050 (Abdelbaky et al., 2021; Bobba et al., 2019; Dunn et al., 2021; International Energy Agency, 2023). The availability of secondary Li, Co and Ni has been evaluated using several schemes of circular economy advocated by the EU, showing that recycled materials are expected to cover 10% – 300% of demand by the 2030s (Albertsen et al., 2021; Kastanaki and Giannis, 2023). Nevertheless, most studies do not assess the impacts of forthcoming implementation of the updated EU policies. A comprehensive assessment of material metabolism is needed, as it can provide insights into the size of materials inflows and waste over time, helping to further identify the influence of EU policy on the dynamics of material demand and secondary supply.

The aim of our study is to quantify the demand for Li, Co, and Ni for use in European passenger vehicles during the e-mobility transition (up to 2040) based on the most updated EU climate plans that promote the transition towards low emission mobility. Using a dynamic material flow analysis (MFA), this study evaluates the primary raw material demand and the timeline and availability of secondary material supply in alignment with the most updated EU Battery Directive. We further assess two scenarios regarding the pace of e-mobility transition and impact of EV battery technology on material demand required for the EU e-mobility transition.

4.2 Methods

In this study, the EVs and respective Li, Ni, and Co demand for the transition to e-mobility was quantified for the EU 27 member countries plus the UK, Iceland, and Norway (27 EU + 3 countries) up to 2040 using a dynamic material flow analysis (MFA) model based on a previous study (Tang et al., 2022). The potential of material secondary supply was assessed based on the newly launched EU Battery Directives that promote the collection and recovery efficiency of EV batteries.

4.2.1 Modelling future EV demand

To estimate the changes in inflows and outflows of the EU passenger fleet, a dynamic flow model was applied. The demand for passenger vehicles ("*Inflow*") was calculated based on sum of the change to the stock and the replacement of old passenger vehicles ("*Outflow*") in a year, following equation (4.1) (Eq. (4.1)). The amount of discarded vehicles for each year was determined by the previous inflows to the system combined with the average lifetime distribution ("*f (T)*") of vehicles, as shown in Eq. (4.2) – Eq. (4.3).

$$Sale_{(t)} = Inflow_{(t)} = Stock_{(t)} + Outflow_{(t)} \qquad \text{Eq. (4.1)}$$

$$Stock_{(t)} = \sum_{\tau=t0}^{t} \left(inflow_{(\tau)} \times f(T)\right) \qquad \text{Eq. (4.2)}$$

$$Outflow_{(t)} = Inflow_{(t)} \times (1 - f(T)) \qquad \text{Eq. (4.3)}$$

The historical stock data of total passenger vehicles for each country from 2011 to 2021 was collected from Eurostat (European Commission, 2023) and the European Automobile Manufacturers Association (ACEA) (European Automobile Manufacturers' Association, 2023). For the assessment on demands for passenger vehicles from 2022 onwards, the prospective stock of passenger vehicles was estimated using a constant vehicle-to-population ratio with the future population growth obtained from the Shared Socio-economic Pathways, SSP2, as shown in Figure C1 (A). The lifespan of passenger vehicles was modelled using a Weibull distribution function, with scale and shape parameters estimated based on country-specific data detailed in Table C2 (Held et al., 2021). The average lifespan of ICEVs was assumed to align with historical trajectories across countries, and the average lifespan of both BEVs and EV batteries was assumed to be equal, 12 years, as suggested by many EV automakers (Dominish et al., 2021).

The historical market share of various types of passenger vehicles, including ICEVs, hybrid vehicles (HEVs), plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs), was calculated for each country based on their annual registration data from 2011 to 2021, collected from Eurostat (European Commission, 2023) and ACEA database (European Automobile Manufacturers' Association, 2023). The prospective EV demands were then estimated by assuming a changing market share of EVs in the total market projected in two scenarios. The "strengthened transition" scenario assumed the full implementation of latest climate policies that promote a full EV market across the EU countries by 2035 (European Commission, 2022a) in which the countries with higher ambitions (e.g., Norway, Austria, Ireland, Iceland and the Netherlands) follow their announced targets (Tang et al., 2022). An "ambitious transition" scenario was carried out under the consideration of mitigating the GHG emissions in the transport sector at a faster rate. In this scenario, we assumed a more accelerated transition whereby all the 27 EU + 3 countries promote an ICEV sale phase out by 2030, closely aligning the transition pace in the pioneer countries (e.g., the Netherlands). More details on the promotion targets are described in the Table C1, Figure C1 (B) in the Appendix C (Appx C). Details on vehicle lifespan were described in the section Appx C1.

4.2.2 Modelling material demands

The Li, Co, and Ni demand in EV batteries was calculated by converting the EV units to the mass of battery materials. We assumed the dynamic change of EV battery technology and capacity over time were the same for all the 27 EU + 3 countries. Six types of EV batteries, mainly differing in cathode chemistry, were included in our study (LMO, LFP, NCA, NMC-111, NMC-622, NMC-811). The assumptions about their dynamic changes were derived from previous study that incorporates the market dynamics of EV battery technology and capacity based on the information of the most popular EV models sold in the European countries up to 2021 (Hund et al., 2020; Kwade et al., 2018; Tang et al., 2022). Although no sales record for EV models using NMC-811 batteries currently exists, we included this technology based on reports indicating that NMC-811 batteries will be a prominent candidate for the EV battery markets in the late 2020s due to their good balance of high energy density and cost-effectiveness (Cano et al., 2018; Hund et al., 2020; Kwade et al., 2018). NMC-622 was assumed as the main cathode technology used in PHEVs and HEVs. The metal composition and intensities of different Li-ion battery types were derived from various studies (Cano et al., 2018; Fishman et al., 2018; Sun et al., 2019) (Table C3).

The average battery capacity in BEVs has grown from 22 kWh to 60 kWh based on the most popular BEV models sold in EU countries up to 2022. We assumed this capacity to grow to around 80 kWh in 2040, mainly depending on the increased driving range to the level of 550 km, as shown in Figure C3 (Delogu et al., 2017; Ellingsen et al., 2016; Notter et al., 2010; Tang et al., 2023). The battery capacity of HEVs and PHEVs was assumed to follow constant average values of 6 kWh and 12 kWh, respectively (Tang et al., 2021).

The metal demand for Li, Co, and Ni in EV batteries was calculated by using the equation below:

$$MD_{(y,t)} = \sum_{i}\sum_{j}\sum_{h} \left(Inflow_{(t,i)} \times P_{(t,j)} \times C_{(c,j,t)} \times D_{(h,j,t)} \times m_{(y,h)}\right) \qquad \text{Eq. (4.4)}$$

where $Inflow_{(t,i)}$ is the annual sale calculated for year t in country i (i = 27 EU + 3 countries); $P_{(t,j)}$ is EV type j in year t (j = PHEV, HEV, BEV); $C_{(c,j,t)}$ is battery capacity c of BEV type j in year t; $D_{(h,j,t)}$ is battery cathode chemistry type h (h = LMO, NCA, LFP, NMC-111, NMC-622, NMC-811) of EV type j in year t and $m_{(y,h)}$ is the metal intensity of a given material y in a lithium-ion battery h.

4.2.3 Potential of secondary supply

To assess the potential of secondary supply during the EU e-mobility transition, we estimated the quantity of materials potentially recovered through the recycling processes based on the recently launched EU Battery Directives (European Commission, 2022b). The collection rate of the discarded EV batteries was assumed to be 100% for all the scenario years (European Commission, 2022b; Melin et al., 2021). The recycling rates for Co, and Ni were assumed to steadily increase from current levels (56% for Co and 44% for Ni) to 95% for each in 2040, in accordance with the EU Battery Directive (European Commission, 2022b). For the recycling rate of Li, it was assumed a growth from 1% to 35% by 2027 and to 70% by 2031, as required by the updated EU Battery Directive (European Commission, 2022b). We further assumed it to increase to 95% by 2040 (thus aligning with the target for Co and Ni), based on optimistic assumptions of the innovative recycling technologies with high efficiencies being applied in EU recycling facilities (e.g., deep eutectic solvents and bioleaching solvents in the in the hydrometallurgical process) (Jin et al., 2022; Latini et al., 2022). More information on the potential advancement of the recycling technologies was described in section Appx C2.2.

4.2.4 Sensitivity Analysis

A sensitivity analysis was conducted for the "strengthened scenario" to evaluate how the material demand and the availability of secondary material are affected by the variations in key assumption, including the vehicle-to-population ratio, parameters of the lifetime distribution, EV battery capacity, and collection and recycling rates of end-of-life EV batteries. A detailed description of the assumed parameter variation is provided in Table C4.

4.3 Results

4.3.1 EV demand and Battery technology innovation

The steady growth of EV (BEV and PHEV) sales within the 27 EU + 3 countries have positioned the EU as the second-largest EV sales market in the world. As shown in Figure 4.1, the EV sales within the 27 EU + 3 countries reached 2.1 million in 2021, accounting for 33% of the annual global EV sales and 17.8% of the annual new sales of passenger vehicles within the EU. By 2021, about 4.5 million units of EVs in total have been sold within EU Member States, with BEVs comprising 56% of the total sales (European Automobile Manufacturers' Association, 2023). Under the strengthened transition scenario, the annual demand for BEVs is expected to reach 25.8 million units in 2040, circa 22 times larger than the 2021 BEV sales (Figure 4.1 (B)). By then, EVs will account for 72.7% of the total passenger fleet. Under the ambitious transition scenario, the annual demand for BEVs will increase up to 28.5 million units in 2040, or a cumulative demand (2022 – 2040) that is 1.2 times larger than those for strengthened policies, with 59.9% increase occurring in the 2020s. The faster transition to fully EV-dominated markets results in an 7.8% increase in the stock share of EVs, reaching 80.5% by 2040.

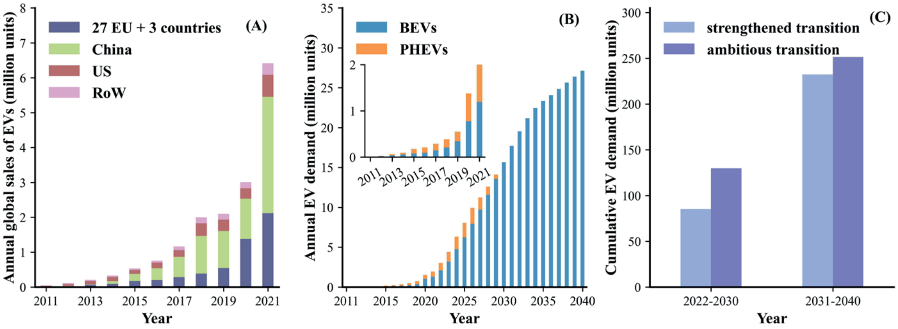

Figure 4.1 (A) Historical global sales of EVs (PHEVs and BEVs) by 2021 (million units). (B) Annual demand for BEVs and PHEVs (million units) under the promotion of strengthened policies through 2040 for the 27 EU + 3 countries. Stacked bars in the inserted figure represent historical sales of PHEVs and BEVs by 2021. (C) Cumulative demand for BEVs and PHEVs under the promotion of strengthened policies and the assumption of a more ambitious transition from 2022 to 2040.

4.3.2 Metal demands and potential from secondary supply

As expected, the projected EV growth results in an increasing demand for Li, Co and Ni in EV batteries (Figure 4.2). The annual demand for Li and Ni will continuously increase until 2040, reaching to about 274 kilotons and 1667 kilotons respectively by 2040. For Co, its annual demand will increase to 325.8 kilotons until 2035 and then start to fall off. In total, the demand for Li, Co and Ni from 2022 to 2040 will be about 3.3, 3.9 and 16 million tons based on the strengthened policies of the e-mobility transition (Figure 4.3). A greater EV demand following an ambitious transition will lead to at least 30% growth in the annual demand and the in-use stock of Li, Co and Ni will grow to 2.6, 3.1, and 13 million tons by 2040, respectively (Figure C5). From 2028, the annual demand for Li, Co, and Ni for EU EVs alone will start to exceed their global historical annual production average (2016 – 2021) (Figure 4.2). Assuming that the global production of these metals would follow their most recent historical trend up to 2040, their share of use in the EV batteries for the EU e-mobility transition would increase from less than 1% in 2020 to 82% in 2040 for Li, 134% in 2035 for Co, and 143% in 2040 for Ni.

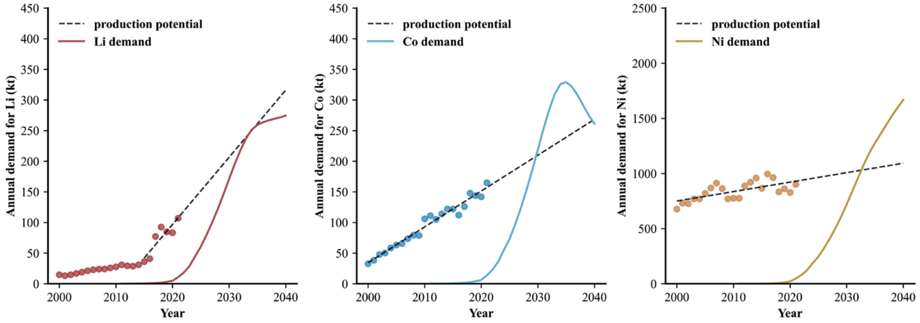

Figure 4.2 Annual demand for Li, Co and Ni (kilotons) for the 27 EU + 3 countries under the EV promotion following the strengthened policies through 2040, compared to the global annual mine production of Li, Co and class-I Ni. Note that the dots represent the historical annual mine production from 2000 to 2021 collected from the USGS database (U.S. Geological Survey, 2023a, 2023b, 2023c), and the dash lines represent annual mine production trends through 2040, assuming that it would follow the historical trend.

The distinctive demand trends among Li, Co, and Ni mainly results from the shift to low-Co content in cathode chemistry for the EV batteries (Figure C2). LMO and NMC-111 batteries dominated BEV models before 2016, and they are being gradually replaced by the NCA and NMC-622 batteries. No sales data of LFP batteries were found before 2020, but zero Co-content batteries are showing promise in the BEV market (e.g., Tesla has equipped the LFP batteries on Model 3 since 2020 (Energy Storage News, 2020)) and is projected to reach a BEV market share of about 15% in 2025. The NMC-811 battery is projected as the most promising substitution of NCA and NMC-622 batteries from 2020 due to its potential performance improvements and reduction of Co content (Hao et al., 2017; International Energy Agency, 2018; Kraytsberg et al., 2012; Mahmoudzadeh Andwari et al., 2017; Pelegov and Pontes, 2018; Schmuch et al., 2018; Valero et al., 2018; Watari et al., 2019).

Secondary Li, Co and Ni can become available as EV batteries reach their end of life. Under the mandated recycling regulations on the EV batteries within the EU countries (as shown in Figure C4), annual recovered Li, Co and Ni will increase from less than 7.4 kilotons in the mid-2020s to 133.2, 169.7 and 575.7 kilotons in 2040, accounting for around 51.6%, 69.1% and 36.7% of their annual demand driven by the strengthened policies, respectively (Figure C6). As shown in Figure 4.3, 0.6, 0.7 and 2.5 million tons of Li, Co and Ni will be cumulatively recovered in the 2030s, amounting to 20% – 30% of their cumulative metal. The faster adoption of EVs increases by 40% of the available amount that could be used as secondary supply sources, keeping the remaining annual demand from the primary source lower than them in the strengthened scenario from 2036 to 2040.

The relative changes in the cumulative demand for primary sources from 2022 to 2040 can be assessed under different combinations of mitigation options for scenarios (Figure 4.4). Compared to the baseline, represented by the cumulative demand without a secondary supply in the strengthened transition, both scenarios demonstrate that the maximum reduction (32% for the strengthened transition and 24% for the ambitious transition) can be achieved through the promoting batteries with lower capacity and increasing the supply from secondary sources that follows the EU acts. This suggests that the mitigation strategies for ensuring more efficient material use could even be independent of battery lifetime extensions.

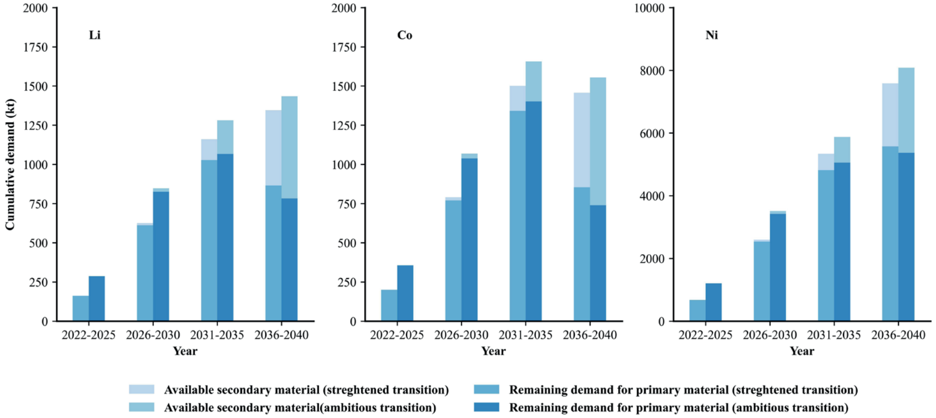

Figure 4.3 Cumulative demand for Li, Co and Ni for the 27 EU + 3 countries including potential availability of secondary supply from recycling process during the EV promotion following the strengthened policies and the assumption on an ambitious transition from 2022 to 2040.

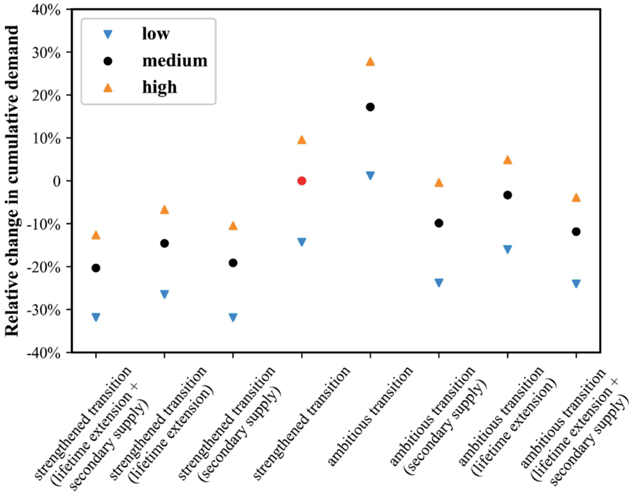

Figure 4.4 Relative changes in cumulative primary material demand from 2022 to 2040 with different combinations of mitigation options. Note that the baseline is set as the cumulative material demand in the strengthened scenario from 2022 to 2040 under the assumption of medium EV battery capacity, represented by the red dot. "Low, medium and high" refers to assumptions about EV battery capacities.

The sensitivity analysis of our model parameters indicates that the results are largely insensitive to the potential growth of the vehicle ownership in the EU countries. A variation of ±7.5 % in annual growth rate of the vehicle ownership results in a change of ±2 % in annual material demand and secondary material availability. The ±7.5% variance follows the observed limited changes in the vehicle stock over time. An overall fluctuation around ±27% in the shape parameter of the Weibull distribution can lead to changes in material demand for each country ranging between -0.3% and 6.2%, resulting in an overall 1.4% and 5.1% increase in cumulative material demand and cumulative availability of secondary materials from 2021 to 2040. In comparison to shape parameter, the variation of scale parameter in the Weibull distribution shows more significant impact to our results. The extension of lifespans for both EV batteries and BEV to 18.1 years will gradually reduce the annual demand for metals from the 2030s, leading to the reduction of annual demand and availability of secondary materials by around 30% and 65% in 2040 (shown in Figure C7). The annual metal demands vary from -22.0% to 14.0% if a low or high battery capacity is assumed (Figure C8). Any reduction in the collection rate will lead to loss of recovered materials, as the collection rates directly relate to amount of EOL materials reaching to the recycling facilities (Figure C9). An early achievement of 95% recycling rates of metals in 2030 contributes to 2.3% improvement in the cumulative recycled content (Figure C10), suggesting that the improved recycling rates mandated by the updated EU recycling directive are feasible for managing the initial wave of EV batteries reaching the end of their life. These results indicate that the material demand and secondary availability are significantly influenced by the variations of EV battery capacity, lifespan and collection rate of EOL batteies.

4.4 Discussion

4.4.1 Main findings of the study

Based on the strengthened policies, we find that the annual Li, Co, and Ni demands in EV batteries are expected to increase at least 21 times in 2040 compared to the 2021 level. These annual demands will further increase at least by 29.5% in the 2020s if EVs fully dominate passenger vehicle sales market in 2030. Correspondingly, the stocks of Li, Co and Ni will grow by two orders-of-magnitude by 2040.

Although the projected cumulative demand for Li, Co, and Ni may be adequately met by the known global reserves for these metals, our results show that the fast-growing demand for these metals may pose challenges for the exploitation of primary resources. More specifically, the rapid annual growth in Li, Co, and Ni from the EU transport sector will exceed their historical growth in production rates since the mid-2030s.

The EU e-mobility transition will require a global expansion in material production, especially in terms of battery-grade level. Within the EU in particular, Li production has primarily focused on ceramics and glass manufacturing (Gourcerol et al., 2019). Opening new sites and establishing new refinery facilities presents opportunities to expand domestic EU production of battery-grade Li and decrease the dependence on imports. Investments in upgrading mining and refinery technology will also play a significant role in ensuring a more responsible and sustainable growth of mineral production and in reducing environmental impacts within the EU countries (Ali et al., 2017; Sovacool et al., 2020). Other schemes like establishing firm trade partnerships at the entrepreneurial and national levels and increasing domestic stockpiles will also be essential in ensuring long-term resource availability (Bridge and Faigen, 2022; Sun et al., 2021).

Understanding the factors that influence EV battery and material demand growth is critical to ease the pressure on mining production. Our results show a trend of declining Co demand in the 2030s, driven by a shift to low-Co content EV batteries (Figure 4.2), emphasizing the high sensitivity of the metal demand to EV battery technology development. The reduction of EV battery capacity leads to 22% decrease in the annual material demand in 2040 (Figure C8) and an extension in lifetimes of EV and EV battery decrease 15% of cumulative material demand in 2030s. Therefore, exploring novel EV battery technologies and improving EV battery performance are key strategies to reduce the heavy dependence on primary resources in the short-term. For instance, improvement in battery specific energy to facilitate longer driving ranges and extended battery lifetime without need to raise their capacity in battery pack (Degen et al., 2023; Li et al., 2020). Novel EV battery design could take advantage of sodium-ion batteries, whose cathode materials consist of abundant and widely distributed sodium and transition metals (e.g., Fe, Ni, Mn). The design of hybrid EV batteries could lessen the dependence on the key materials in LIBs while maintaining battery performance (Rudola et al., 2023; Usiskin et al., 2021).

From a long-term perspective, the increasing number of EV batteries reaching their end of life implies the growth of a potential secondary resource supply. Implementing the EU recycling mandate (European Commission, 2022b) and an improvement in recycling rates via a closed-loop recycling processes (Tian et al., 2022), our results show that the annual supply from potential secondary metals will steadily grow from the early 2030s, amounting to 20-30% cumulative demand for these key metals over this period of time.

Compared to the reduction of battery capacity and lifetime extension, the recovery of secondary materials represents a more effective approach to alleviate the cumulative demand from primary sources in the ambitious transition (shown in Figure 4.4). Nonetheless, it relies on well-organized management of the spent batteries and an efficient recycling system. The recycling capacity within the EU for 2021 remained at the level of 40 kilotons battery packs per year, which is not sufficient for the expected amount of end-of-life EV batteries in the coming decades (Windisch-Kern et al., 2022). Pyrometallurgical processing dominates the current EU recycling technology. This method has the advantage of simplifying the pre-treatment process for spent EV batteries, while the quality of recovered materials is more suitable for non-functional applications (open loops), and Li will mostly end up in the slag. Additional treatments are required to process these recovered materials into forms suitable for use in new battery production (Harper et al., 2019; Sommerville et al., 2021). Moreover, pyrometallurgy processes incur in high energy consumption and significant emissions of greenhouse gases and organic pollutants providing limited environmental advantages when compared with primary production process (Ciez and Whitacre, 2019; Rajaeifar et al., 2021). Therefore, the EU must also transitions toward energy-efficient and environmentally friendly recycling technologies, such as the hydrometallurgy process. The establishment of efficient pre-treatment infrastructure are necessary to facilitate the collection and sorting of various EV batteries. Further, the EU must stimulate the processing of valuable materials present in “black mass” for further recovery, which needs to be promptly addressed (Olsson et al., 2018; Ribeiro da Silva et al., 2023). For instance, advanced leaching operation using novel deep eutectic solvents have been reported to leach Li over the other metals from the black mass with improved leaching efficiency of more than 70% (Tran et al., 2019; Zhu et al., 2022). Additionally, improving the collection of EOL EV batteries is essential to ensure a sufficient and consistent supply of EOL batteries reaching to the recycling facilities.

Our results reveal that closing the metal loops within the EU mobility sector is not feasible before 2040 due to the need to grow material stocks, which aligns with previous findings (Haas et al., 2015; van Oorschot et al., 2022). Reducing the EU's material demand from primary sources can be achieved by various combination of different mitigation measures. This involves the trade-offs, for example, between lifetime extension and availability of secondary material supply. The extension of lifetimes can directly reduce the material reliance from primary sources and allow for more time to developing recycling facilities, and ultimately facilitate the reduction of environmental impacts. More availability of secondary resources provides opportunity for the EU to secure critical materials and improve its competitiveness in global supply chain.

Climate policies and regulations are considered to be the most effective drivers to promote the adoption of low-carbon transport technology and the shift to circular economy (Rizos and Urban, 2024; Sovacool et al., 2025). Nonetheless, historical data of EV market share has shown significant adoption variations across the EU Member States. In 2021 EV adoption averages ranged from 0.8% of the Eastern Europe to over 21% in pioneering countries such as Sweden (21%), the Netherlands (27%), and Norway (65%). The fast uptake of EVs in those leading countries has shown a positive correlation with direct national incentives for EV purchases, a well-established charging network, and a population prioritizing environmental protection (Geels et al., 2023; Haidar and Aguilar Rojas, 2022; Peng et al., 2024; Singh et al., 2023; Zhang et al., 2021). Case study of e-mobility transition in Germany has also highlight the resistance of automative industry as the one of the real-world challenges in accelerating the EV adoption (Rogge and Goedeking, 2024). These indicate that implementing policies aimed at EV promotion may be hindered by several barriers, including challenges in the EV use stage (e.g., limited access to charging points, high costs of EV ownership, low levels of income, and insufficient environmental awareness) as well as the incumbency from the industrial supply. Furthermore, obstacles related to economic and technological feasibility may limit the yield of secondary materials to reduce the reliance on primary sources. For instance, market interplay between primary and secondary materials (e.g., price competition) can introduce uncertainty regarding the profitability of recovered materials. This leads to hesitance among recyclers to invest in upgrading EU recycling facilities, and in turn, affects the balance between material supply and demand (Mayyas et al., 2019). Besides the limitations of recycling technology, the challenges of achieving ambitious recycling targets may arise from the complex design and limited transparency of EV battery packs, which leads to the difficulties in effective separation and collection of the valuable components without loss (Rizos and Urban, 2024). These potential barriers underscore the need to develop policies that integrate multiple dimensions of the battery supply chain to enable progress of the mobility transition.

4.4.2 Limitations and further research

Estimates of prospective stock change in the MFA model were restricted to the historical tendencies of vehicle ownership in each country. Future studies can explicitly incorporate endogenous market factors that take into account economic, business, technology, and social changes and the response of EV ownership. Our study also mainly focused on the most feasible and promising low-carbon solutions to the transport sector (EVs using Li-ion batteries). Additional possible decarbonized technologies (e.g., fuel cell electric vehicles, alternative zero emission fuels), emerging EV battery technologies (e.g., sodium-ion battery, organic rechargeable batteries, solid state lithium battery), and vehicles for commercial use and public transport can be included in subsequent studies for a more complete understanding of the material demand across the entire transport sector. Furthermore, more detailed assessments on the potential development of EU recycling facilities, including in-depth data on recycling capacities and technologies and lifecycle assessments, could be further integrated with the model to enhance the understanding of material availability and environmental impacts of secondary raw material supply in the EU Member States. Future studies may further investigate the effects on material dynamics associated with geopolitical risks, technology breakthroughs and economic dynamics, which can be simulated with empirical data and linked to the MFA model.

4.5 Conclusion

In this study, we estimated how the demand for Li, Co and Ni in the EV batteries will be influenced by the implementation of the latest climate actions aimed at promoting the EU e-mobility transition and the recycling of end-of-life EV batteries. Analyzing the metabolism of these metals in the EU transport sector using data at country level can help monitor the patterns of material demand and identify potential opportunities to increase domestic sufficiency in material supply through recycling activities.

Our findings show that the rapid annual growth in Li, Co and Ni demand will outpace their historical growth in production rates, pointing to an imbalance between the estimated global supply and material demand required from the EU transport sector by the mid-2030s. The implementation of new EU Battery Directive facilitates the increase secondary supply in the early 2030s, amounting to 20 – 30% of cumulative material demand by 2040. Establishing more recycling facilities as well as advanced collection and sorting system is necessary to manage the discarded EV batteries in the EU. Shifting towards less critical metal-contained EV battery technologies, reducing the EV battery capacity and extending the lifetime of the EV batteries will greatly facilitate the reduction on the primary demand for these key materials. Various combinations of mitigation measures to attenuate material demand could involve trade-offs, suggesting the need for continuous monitoring, timely assessment, and for the development of flexible strategies of resource utilization to achieve long-term sustainability of material use during the EU e-mobility transition.