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

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Chapter 6

General Discussion

6.1 Introduction

The decarbonization of the transport sector is essential for achieving the EU's climate objective. Electric vehicles (EVs), characterized by minimal to zero tailpipe emissions, offer a promising alternative to conventional fossil fuel-powered vehicles. The shift to electric mobility therefore presents significant potential to reduce greenhouse gas (GHG) emissions and promote cleaner, more sustainable transportation across the EU under the condition that low-carbon electricity is used. Advances in lithium-ion batteries (LIB) have positioned EVs, including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), as the dominant market choice throughout the 2020s and likely into the near future. Nonetheless, the growing adoption of EVs drives a substantial increase in demand for new materials essential for low-carbon transport technologies. At the same time, the overall effectiveness of EVs in reducing GHG emissions remains uncertain due to the large emissions associated with the battery manufacturing process. Therefore, the EU and its member states have to navigate these opportunities and challenges. While most studies on climate impacts and material requirements of the EV transition have been conducted at the global level or discussed climate and material challenges separately.

Against this background, this thesis has a core objective *to contribute to the understanding of potential strategies that can effectively promote a more sustainable transition to e-mobility in the EU passenger transport sector.*

The thesis began by focusing on developing an effective research model that can reflect regional dynamics in evaluating material flows during the e-mobility transition. The Dutch e-mobility transition was chosen as a case study, given that the Netherlands is one of the pioneering countries in promoting low-carbon passenger transport systems (Chapter 2). The scope was subsequently expanded to the EU passenger transport sector to evaluate GHG emissions (Chapter 3), material demand (Chapter 4), and secondary material availability (Chapters 4 and 5) within the framework of EU climate and resource policies. This chapter provides a general discussion based on the main findings in previous research chapters. It begins by answering the research questions, followed by a reflection on the model and data, suggestions for future research directions, and policy implications.

6.2 Answers to the research questions

This thesis aimed to realize the aforementioned core objective by addressing the three research questions identified in the introduction and discussed in the sub-sections below.

6.2.1 Question 1: What will be the demand for Li, Co and Ni in the EU transport sector driven by the climate policies promoting the EU e-mobility transition?

In 2020, the annual sales of EVs in the EU countries was about 1 million units, accounting for 6% of the overall passenger vehicle market. BEVs have shared a higher market share than PHEVs since 2017. In total, about 2.5 million units of EVs have been sold by the end of 2020. The annual demand for Li, Co and Ni in the EV batteries in 2020 was estimated to be about 8.6 kt, 11.2 kt and 37.2 kt, respectively.

The demand for the key performance materials for the EU e-mobility transition is expected to continuously grow through 2040. Aiming for a fully EV market across the EU countries by 2035, demand for the EVs is projected to increase by about 25 times relative to the 2020 sales level by 2040. The annual material demand will grow at least by 57 times for Li, 50 times for Co, and 87 times for Ni in comparison to the 2020 demand level. Correspondingly, the stock of these materials will expand by at least 220 times in 2040. The demand growth for Li, Co and Ni driven solely by e-mobility transition in the EU is expected to outpace their average annual mineral production observed from 2016 to 2021. Moreover, assuming an ambitious transition with the phase-out of ICEV sales by 2030 across the EU, closely aligning with the pioneer countries such as the Netherlands, the demand for Li, Co and Ni is expected to firther increase by at least an additional 30% annually.

6.2.2 Question 2: What will be the GHG emissions in the EU transport sector with the implementation of announced climate policies of member countries based on the Green Deal launched in 2019?

GHG emissions from the EU passenger transport sector are expected to decline in the late 2020s. However, this reduction will not be sufficient to meet the climate targets outlined in the EU 2019 Green Deal, which aims for a 37.5% reduction in GHG emissions in 2030 compared with the levels in 1990. Promoted by the 2019 EU

Green Deal, the stock of EVs in the EU passenger fleet is expected to grow by 97 times compared to the 2020 levels, accounting for 22% of the total fleet stock by that time. The combination of EV uptake and declined carbon intensity of the EU electricity system will deliver a 52% reduction in annual GHG emissions in 2040 and a cumulative 2.0 gigatons CO_2-eq of emission savings between 2020 and 2040. One of the reasons for not meeting the reduction target is the continued dominance of ICEVs in the EU passenger fleet. Achieving the 37.5% GHG reduction goal will require an increased stock of EVs through an acceleration of both the adoption of EVs and the phase-out of the ICEVs aligned with increased use of renewable energy in the EU electricity system in the 2020s.

Reducing embodied carbon emissions is crucial to maximize the environmental benefits of low-carbon transport technologies. GHG emissions associated with the energy-intensive manufacturing of EV batteries can substantially offset the emissions savings by driving the EVs. It simultaneously transfers the environmental burden to actual EV manufacturing countries, most of which lie outside the EU. As a result, clear environmental benefits of adopting EVs will be realized when the manufacturing GHG emissions are completely offset, projected to occur after 2030. The improvement of net environmental benefits of EV adoption needs a focus on the reduction of embodied emissions of EVs, for instance, by accelerating carbon mitigation of the electricity system in parallel with the e-mobility transition, both in the EU countries as well as in EV-producing countries.

6.2.3 Question 3: How will the availability of secondary Li, Co and Ni support the development of a sustainable EU battery sector?

The availability of secondary Li, Co and Ni will gradually grow from the early 2030s. In the 2020s, secondary materials availability is limited, as most EVs remain in their use phase. Assuming full compliance with the recycling targets set out in the 2023 EU Battery Regulation, the availability of secondary Li, Co and Ni is projected to account for 20% to 30% of the cumulative material demand in the 2030s. This indicates that closing the material loops of Li, Co and Ni for the EU e-mobility transition will be difficult to achieve before 2040. The biggest reason is that EV battery demand is expected to grow faster than the generation of end-of-life batteries when the stock of EV continues to expand in the coming decades. In addition, there is a potential technological mismatch between the average end-of-life material composition and new battery material demand due to the decadal EV lifetimes.

Domestic closed-loop battery recycling alone may not be sufficient to support the development of a sustainable battery sector in the EU. In the 2030s, secondary Li, Co and Ni collectable from the expected end-of-life EV batteries can meet the requirements of secondary materials for new EV battery production, particularly as low-Co-content batteries become prevalent in the market. This growth will help boost the EU battery production and thereby mitigate dependency on the BEV imports seen by historical trade trends from 2017 to 2022.

The expected growth in deploying advanced recycling technologies in the EU recycling system will improve overall recycling process efficiency in coming years. Nonetheless, mismatches between the known recycling capacity and end-of-life material availability are found until 2036. Uncertainties about the expansion of recycling capacity and depth of recycling in the 2030s may limit the actual return of recovered Li, Co and Ni that are suitable for new battery production, resulting in shortfalls relative to the secondary-material demand targets required in the updated EU Battery Regulations. This will present potential obstacles to the growth of EV battery manufacturing. Therefore, it is essential to establish a comprehensive EU recycling system before the first large wave of EV batteries reaches their end of life to ensure efficient processing of spent batteries and provide a steady supply of battery-grade recycled materials.

6.2.4 Overall research question: What are the potential strategies that can effectively promote a more sustainable transition to e-mobility in the EU passenger transport sector?

Advancements in EV battery technology can play a significant role in optimizing the use of battery materials. The growth in demand for Li, Co and Ni, as well as waste generation, is highly sensitive to battery capacity and advancements in LIB technologies. Smaller battery capacities contribute to the reduction of demand and waste generation of these materials. Compared to Co, the demand for Li and Ni appears less sensitive to developments in current-generation LIB technologies. Co demand will be mitigated with greater use of low-Co chemistries, such as lithium iron phosphate (LFP) batteries, resulting in a projected demand peak in the mid-2030s. An accelerated shift to low-Co battery technology will narrow the Co loop at an earlier time. These strategies can be considered by automakers and battery manufacturers as effective actions to optimize material demand and reduce reliance on primary resources during the e-mobility transition.

Circular approaches for the EV batteries can promote long-term sustainability in the EU e-mobility transition. Secondary Li, Co and Ni are expected to become increasingly available in the 2030s. Sourcing from efficient recycling processes, secondary materials can alleviate pressure on global production from primary sources and support the growth of the EU battery sector, helping to reduce reliance on the BEV imports as observed in historical trade patterns. Extending the lifespan of both BEVs and EV batteries to 18.1 years, reaching the historical average lifetime of motor vehicles in the EU, can significantly reduce annual material demand and lower the GHG emissions from the EV manufacturing sector. These circular approaches are expected to sustain the environmental benefits from the 2030s, serving as long-term strategies to improve the material efficiency and reduce carbon footprint. Nonetheless, an extended battery lifespan keeps materials longer in the economy, which can also slow the turnover of EV batteries via end-of-life recycling. Despite this, extending battery lifespans remains crucial to reduce overall material demand and waste generation while also allowing time to scale up a comprehensive recycling infrastructure in the EU.

The decarbonization of the energy system is vital for reducing the overall carbon footprint and improving the environmental benefits of adopting EVs. The production and operation of EVs are energy-intensive processes, and their overall lifecycle emissions are strongly influenced by the carbon intensity of the electricity used. The development of a decarbonized energy system, including the expansion of renewable energy sources, is crucial to ensure that the expansion of the EV fleet contributes to a meaningful reduction of GHG emissions.

Coordinated and coherent policies across multiple sectors are essential to support the overall sustainability of the e-mobility transition. Ambitious policy targets can be an effective driver to reduce transport-related emissions and promote the sustainable material use in EV batteries. While our findings showed several implementation challenges, such as potential over-ambition and the underlying tensions of the circularity targets across different sectors. Therefore, an effective systematic framework is highly recommended for timely monitoring and assessment, one that accounts for a wide range of interrelated factors from multiple dimensions. In addition, scenario analysis can serve as a useful tool to provide quantitative insights for the decision-making processes. But it also needs to be interpreted with caution, as the results often represent collective potential and contain inherent uncertainties. This underscores the necessity for policymakers to clearly understand the underlying assumptions and details of the scenarios when using scenarios to inform future strategies.

6.3 Reflection on model and data

This thesis applied a dynamic material flow analysis model combined with scenario analysis next to GHG emissions accounting to quantitatively assess the dynamics of material flows and emission performance during the EU e-mobility transition. By exploring the EU passenger fleet from a vehicle metabolism perspective, we can understand how future material flows are influenced by the system's past state and other contributing factors, providing valuable information for resource management. This thesis takes advantage of accessing detailed regional data to capture the characteristics of the EU passenger transport sector and improve the accuracy of related parameter assumptions. This can support the development of clear and traceable scenarios, enabling the exploration of potential pathways for material use and GHG emissions reductions. This bottom-up approach, however, relies on intensive data collection and harmonization from diverse sources, including official statistics, scientific literature, technical reports, and others, which vary in terms of data validity and quality. Therefore, discussing the limitations and uncertainties is essential for better understanding the underlying data and results of our model.

Stock data

The in-use stock of passenger vehicles is a key factor in the dynamic MFA model, as it directly influences materials flows associated with the adoption of EVs. Historical data on mobility levels and fleet sizes of conventional vehicles are well documented by national statistics offices. Data on emerging low-carbon technologies are often aggregated or classified inconsistently across different databases, making it challenging to compile and describe changes in the composition of the passenger fleet during the e-mobility transition. The lack of consistent data can introduce uncertainty in assessing material demand and waste generation, particularly given the varying pace of e-mobility transition planned by each EU country as presented in Chapter 3.

Assumptions on changes in prospective stock of the EU passenger fleet determine material flows in the scenario years. Our study implemented vehicle ownership (a vehicle-to-population ratio) for each member state and the population trends derived from the SSP2 scenario, which represented a "middle-of-the-road" pathway (Riahi et al., 2017). The socioeconomic assumptions in the SSP2 scenario were based on the historical data up to 2016. Vehicle ownership was assumed to remain constant, reflecting the relatively stable mobility levels observed in past trends. The simplicity in the stock estimation may overlook the impacts of economic activities, which can alter the

EU mobility patterns, such as the disruptive changes caused by the covid-19 pandemic (Richter, 2022). Future improvement of stock estimation can incorporate indicators of economic prospects to provide a responsive representation of e-mobility transition to economic disruptions.

Lifetime and material composition of EV battery

The lifetime of conventional vehicles in our model was derived from a previous study that explicitly modelled passenger fleet turnover dynamics in each EU country, accounting for the real-world survival rates of ICEVs (Held et al., 2021). In contrast, the lifespan of EVs and EV batteries was mainly assumed based on their technical lifetimes recommended by automakers. We explored different scenarios for the lifetime of EVs and EV batteries in Chapters 2 to 5, revealing that the results are highly sensitive to lifetime distributions. Therefore, better estimates on lifetime distribution of EVs and EV batteries, based on more empirical data, are needed in future studies to have a more accurate understanding of the realistic lifespan of EVs and EV batteries.

The intensity of Li, Co and Ni, which refers to the material content required per unit of energy output, in various types of EV batteries is available in existing literature. However, the data on average metal intensity in regional market demand is not always available. This challenge also extends to the data on battery capacity. In Chapters 3 to 5, we evaluated the dynamics of battery technology share and battery capacity by using the EV sales data from the EU market. The data, collected from multiple open data sources, covered approximately 80% to 90% of the overall market. However, more granular, transparent open access to data, such as the Netherlands Vehicle Authority (RDW) database used in Chapter 2, could help improve the analyses. In addition, detailed battery information will be closely linked to the concept of digital battery passports, which, once implemented, could serve as a valuable data source for identifying and tracking material use and battery value chain in future studies (Berger et al., 2022).

GHG emissions assessment

The assessment of GHG emissions in our analysis was conducted by combining the results from the MFA model with emission factors sourced from previous lifecycle assessment (LCA) studies. Given that both the manufacturing and operation of EVs are energy-intensive, with electricity being the most important contributing factor to the GHG emissions, our model focused on how changes in energy sources influence

GHG emissions over the scenario years. The evaluation of the GHG emissions performance in Chapter 3 depends most critically on the background electricity system, which can be represented by different carbon mitigation pathways (Mendoza Beltran et al., 2020). Due to the absence of a bottom-up LCA modeling process, the GHG emission factors of the EV and EV battery production represented an aggregated value. Our analyses therefore did not reflect the potential emission reductions from technological improvements in battery manufacturing or more sustainable sourcing of raw materials, as highlighted by other studies (Istrate et al., 2024; Xu et al., 2022). Our evaluation for GHG emissions of the passenger fleet was assumed to be constant based on the historical travel pattern in the EU. This may overlook possible decarbonization pathways arising from changes in driving behaviors or transport demand (Amatuni et al., 2020; Chen et al., 2022; Ellingsen et al., 2016). Moreover, the evaluation of the GHG emissions performance in Chapter 3 depends most critically on the background electricity system, which can be represented by different carbon mitigation pathways (Mendoza Beltran et al., 2020).

Scenario development

The results in scenarios offer a forward-looking assessment of the demand ranges and trends of battery materials and possible GHG emissions in the EU passenger transport sector driven by the deployment of low-carbon transport technologies. Overall, the results were broadly in line with stated environment policies. However, the realization of these policy goals is subject to considerable time lags and implementation challenges. For instance, the current uptake of EVs has remained below the trajectory of announced EV adoption across the EU countries (Chapter 4), and the ability of the EU recycling system remained highly uncertain with respect to the effective deployment of planned recycling initiatives as listed in Chapter 5. These potential gaps indicate that the scenario outcomes need to be interpreted as an upper-bound pathway aligned with policy ambitions. The actual growth of material demand and the availability of secondary resources are likely to follow a more conservative and delayed pattern than the scenarios suggested. Moreover, the dynamics of regional material intensities and battery capacity were based on the most up-to-date literature and EV market data in the EU. The ongoing development of EV technologies introduces uncertainties, which are expected to increase over the projected timeline considered in the scenarios. Breakthroughs in battery chemistries beyond current LIB technologies could substantially reshape material demand landscapes and change the potential of material circularity in the battery value chains. One way to improve the precision of analysis is to perform systemic sensitivity analysis of the input parameters (Chapters 2 to 5) or identify the variation range caused by a set of input parameters through Monte Carlo analysis (Chapter 3). In addition, validating the most influential factors through alternative assumptions, or synthesizing knowledge from industry sources, if available, can contribute to improving the understanding of the scenario developments (Langkau et al., 2023).

6.4 Research outlook

This research can be further extended in several directions to achieve broader insights. A key area is to incorporate a wider range of technological factors that can capture implications of emerging low-carbon transport technologies, such as EV battery swapping schemes, innovative EV battery technologies, and the development of fuel cell electric vehicles (International Energy Agency, 2024; Navinkumar and Bharatiraja, 2025; Simas et al., 2025). The dynamics of material flows are also shaped by factors beyond the technology aspects. Examples include rebound effects associated with secondary material markets, reduced demand driven by a preference for low-carbon transport modes, and circularity constraints imposed by immature business models (Amatuni et al., 2020; Chen et al., 2022; Rizos and Urban, 2024; Seebauer, 2018; Schulz-Mönninghoff et al., 2023). Another important direction for future research is to explore the interactions between material cycles and factors in economic, social and behavioral aspects to gain insights from a multidimensional perspective, potentially by integrating the MFA model with other approaches, such as agent-based models, partial equilibrium models, and multi-level perspective models (Koide et al., 2023; Nong et al., 2023; Nurdiawati and Kumar Agrawal, 2022; Rai and Henry, 2016; Sovacool et al., 2025).

The study scope can be broadened to examine a broader range of spatial, temporal, and organizational scales. The model developed in this study for assessing battery material cycles at the regional level can be modified for application beyond the EU. This is particularly relevant for regions in the Global South. These regions are both key suppliers and demand drivers of the raw materials essential for EV battery technologies (Santos da Silva et al., 2021). Gaining a deeper understanding of local material cycles in these areas helps identify resource strategies suitable for unique regional contexts and needs. Such efforts are crucial for promoting sustainability within the global EV battery supply chains, especially in light of the continued growing primary material demand. Given the founded lack of recycling capacities in the EU, spatial parameters can be linked to the current model for providing spatially explicit insights into the optimal scales and locations for future establishment of battery circular facilities (Tsui et al., 2024). Additionally, the MFA model can also be tailored with greater depth to the company level to investigate new business models related to the battery circularity (Helander and Ljunggren, 2023).

The time horizon of this model needs to extend beyond 2040 to thoroughly assess the timeline of batteries in a circular economy. The expected longer EV battery lifetimes promoted by possible circular approaches require a longer time horizon to fully assess the best strategies for battery material circularity. Extending the timeframe will also help identify when the stock of EVs reaches plateaus, marking the turning point at which closing the material loops becomes feasible for the EU passenger transport sector. In addition, the challenges posed by limited data availability in the MFA model can be addressed through applying novel computational models in future research, which can mitigate the absence of detailed statistical data and enhance the accuracy of model assumptions and results (Amatuni et al., 2023; Mason et al., 2025).

Circular approaches of end-of-life EV batteries play a critical role in promoting material sustainability during e-mobility transition. Alongside immediate recycling, other approaches, such as remanufacturing, reusing, and repurposing have been suggested to improve the utilization efficiency of battery materials (Chirumalla et al., 2023; Iqbal et al., 2023; Rufino Júnior et al., 2023; Zhu et al., 2021). Potential inconsistences in resource policies may arise from the implementation of different battery circularity strategies (Chapter 5). The interactions and trade-offs among these approaches, therefore, remain important areas for future research, which could further integrate the influence of environmental, economic, and social dimensions to provide a holistic view for designing coherent and mutually reinforcing resource policies that effectively advance the circular battery economy in the EU. In addition, as secondary materials become increasingly integrated into the battery value chain and investment in circular practices continues to grow (Gracia et al., 2024), evolving market dynamics are expected to progressively influence the proportion of secondary materials in total material inputs. Future research can therefore focus investigating how evolving market dynamics shape the circularity potential of critical EV battery materials over time.

6.5 Policy implications

Drawing on the findings and insights from the analysis of material cycles and GHG emissions in the EU e-mobility transition, this section proposes several recommendations for future policymaking.

It is crucial to promote the design of emerging low-carbon transport technologies that integrate sustainability principles and minimize environmental impacts through all life stages. The opportunities to integrate environmental guidance and sustainability principles are more feasible for the technologies in early development stages than in later stages (Arvidsson et al., 2017). Given the large embodied environmental impacts of current EV batteries, it is crucial to promote the adoption of environmentally responsible approaches to material sourcing and battery production processes in the design of emerging low-carbon transport technologies to minimize environmental trade-offs. Beyond the recycling infrastructure hurdles previously discussed, operational complexity arises from diverse designs of EV batteries across different EV models. This variation makes disassembly and sorting processes labor-intensive and costly, thereby reducing recovery efficiency of materials (Davis and Demopoulos, 2023; Latini et al., 2022). Future policies can focus on standardizing low-carbon technology designs that incorporate features promoting recycling-friendly solutions and second-life applications (Zhu et al., 2021). Moreover, current mandates on the use of secondary materials in new EV batteries primarily target Li, Co and Ni. This scope could be further expanded given that advancements in recycling technologies enable more comprehensive material recovery in the future.

The establishment of a more comprehensive and efficient end-of-life battery processing system needs to be implemented as soon as possible. Circular approaches to EV batteries can effectively address the growing demand for Li, Co and Ni and promote a sustainable battery value chain during the EU e-mobility transition. Recycling also presents the ultimate solution when batteries reach the end of their entire usable life. The deployment of second-life batteries and secondary materials underscores the need for effective collection systems that preserve performance and quality of recovered materials. Much like geological mining, the establishment of the end-of-life processing system requires time (Ma et al., 2025; Rizos and Urban, 2024). Therefore, early actions and investments in the development of a technologically advanced, comprehensive processing system are critical to efficiently manage end-of-life EV batteries through multiple circular pathways and support long-term sustainability in the battery sector.