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

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Chapter 1

Introduction

1.1 Electric vehicles provide a solution to mitigate transport GHG emissions in the EU

The automobile has significantly shaped how people work, commute, and travel, becoming a significant part of modern life. Since the early 20th century, internal combustion engine vehicles (ICEVs) have dominated the passenger car market, a trend supported by steady availability of fossil fuels and continuous improvement in vehicle design and manufacturing processes. The combustion of fossil fuel in the ICEVs stands as a leading contributor to greenhouse gas (GHG) emissions. Over the period from 1900 to 2021, global transport-related GHG emissions have grown at an annual average rate of 1.7%, reaching a level of 5.9 gigatons of CO_2 equivalents (CO_2-eq) in 2021 (International Energy Agency, 2022). To address this issue, car producers have continuously improved fuel efficiency and were mandated the use of three-way catalytic converters for reducing end-of-pipe pollutants (e.g., nitrogen oxides, carbon monoxide). Nonetheless, these measures have insignificant effects in reducing the CO_2 emissions from ICEVs. The modal split for personal transport continues to skew toward private vehicle use, driving rise in traveled distances. The automotive market exhibits a clear preference for heavier vehicles, such as sports utility vehicles, which further amplifies the environmental footprint of the sector.

Efforts to reduce the GHG emissions from passenger vehicles have been shifted towards developing alternative designs and fuels, such as biofuels, hybrid powertrain systems, and electric vehicles (EVs). Biofuels, derived from organic materials, can reduce total GHG emissions by 32% to 80% compared to traditional fossil fuels. Advanced bio-natural gas can efficiently decrease 15% tailpipe GHG emissions compared to standard bio-natural gas (Ternel et al., 2021). Nonetheless, the side effects of biofuel production related to land use (e.g., soil degradation, food insecurity, and biodiversity loss) raise the concern about the feasibility of their large-scale application, as land is an integral part of the climate system (Deprez et al., 2024). A hybrid powertrain system combines a traditional internal combustion engine with an electric motor. The battery in hybrid electric vehicles (HEVs) is recharged through regenerative braking and the gasoline engine, which is not intended for long-distance driving but allows the vehicles to run on electricity at lower speeds and thus improves fuel efficiency. Compared to HEVs, plug-in hybrid vehicles (PHEVs) have a larger battery pack that can be charged by the grid system and support driving in electric mode alone for around 50 to 80 kilometers. These hybrid designs can effectively reduce CO_2 emissions by 20% to 30% in comparison to the ICEVs (Mendoza Beltran et al., 2018). EVs have theoretical zero emissions of pollutants and CO_2 at the tailpipe, as they are propelled by electric motors and fully powered by electric energy. Electricity for EVs can be provided by grid energy stored in battery packs (BEVs) or generated by chemical reactions between hydrogen and oxygen in a fuel cell (FCEVs). Rapid improvement in battery technology and its cost reduction since the 1990s have positioned the BEVs as the most mature low-carbon transportation technology at present. Compared to ICEVs, the GHG emissions from EVs powered by battery packs can be reduced by 20 – 80%, depending on the carbon intensity of the local electricity supply (Cox et al., 2020; Küfeoğlu and Khah Kok Hong, 2020; Milovanoff et al., 2019). The effectiveness of EVs in controlling CO_2 emissions provides a promising solution for reducing GHG emissions in the road transport sector.

Over the period from 2000 to 2020, the annual GHG emissions from EU transport sector have increased by 5.8%, reaching 650 million tons CO_2-equivalent. To mitigate the increased GHG emissions, a combination of policies and incentives has been announced to promote the adoption of low-carbon passenger vehicles, mainly in the form of EVs, in the EU countries. Between 2016 and 2022, the EU recorded the fastest growth in EV sales globally, with a compound annual growth rate of 61%. Although growth has slowed since 2022, the region remains the world's second-largest EV market after China. By 2022, about 55% of Europe's electric vehicle stock consisted of fully battery-powered vehicles (BEVs) (International Energy Agency, 2023). The rollout of the EVs reflects the transition of the EU's passenger transport fleet from fossil fuel-based technologies to electrified mobility that will likely be completed in the next decades (in short: the e-mobility transition).

1.2 Challenges in material use and environmental impact of EV adoption

Introducing EVs into the transport sector to reduce GHG emissions can trigger the demand for specific materials, valued for their unique properties essential to achieving decarbonization function. In the early 2000s, nickel metal hydride (NiMH) batteries were commonly used in hybrid electric vehicles, such as the Toyota Prius. Since 2009, lithium-ion batteries (LIBs) have become the dominant technology in battery electric vehicles, including models like the Nissan Leaf. One major reason for this shift is the improved driving performance offered by LIBs, which provide faster charging abilities and longer driving ranges. These improvements are largely achieved through the use of cathode materials with excellent electrochemical properties, such as lithium (Li), cobalt (Co), and nickel (Ni) (Cano et al., 2018; Kwade et al., 2018; Schmuch et al., 2018; International Energy Agency, 2018). Further technology improvements and breakthroughs in battery energy density, affordability, and sustainability may lead to the development of battery chemistries that are possibly composed of different materials than LIBs (e.g., sodium-ion batteries), indicating the demand of material types in future is technology-dependent (Crabtree, 2019; Janek and Zeier, 2016; Vaalma et al., 2018).

Driven by the growing demand for EVs, the annual consumption of Li and Co in rechargeable LIBs increased from less than 20% in 2005 to more than 60% of total production in 2022 (International Energy Agency, 2023; Olivetti et al., 2017a). With the foreseen promotion of EVs aiming to mitigate GHG emissions in the transport sector, the demand for battery materials is expected to increase by at least two orders of magnitude globally and twenty to forty times at the EU level from 2016 to 2050 (Albertsen et al., 2021; Deetman et al., 2018; Dunn et al., 2021; Xu et al., 2020; Zhang et al., 2023).

The expected demand growth has led to a high interest in assessments of the future availability and supply of these materials. Resource availability is of the first importance. Studies of ore types, ore grades, deposit distribution, and mining technologies have quantified the abundance of battery materials and assessed the feasibility of their future exploitation on a global or regional scale (British Geological Survey, 2021; Horn et al., 2021; Sanjuan et al., 2022; Talens Peiró et al., 2013; U.S. Geological Survey, 2023a; Ziemann et al., 2012). Their findings suggest that the known global reserves of Li, Co and Ni are sufficient to meet the future cumulative material demand driven by the EV boom. Nonetheless, such reserves are concentrated in specific regions. Lithium reserves are primarily located in South American countries, cobalt is mainly sourced from the Democratic Republic of Congo, and nickel extraction is led by Southeast Asian countries (da Silva Lima et al., 2022; Sun et al., 2019a). In addition, metal reserves are dynamic, influenced by socioeconomics, environmental policies and technology. Scenario analyses have shown significant variations in the projected primary supply, particularly in relation to changes in the concentration of mineral deposits and estimates with regard to the size of future mining operations (Fu et al., 2020; Greim et al., 2020; Murdock et al., 2021; Seck et al., 2022; Tisserant and Pauliuk, 2016).

Another challenge arises from the supply chain of EV batteries, which is more complex than the comparatively straightforward fossil fuel supply chain for ICEVs. Previous studies examined the potential upstream supply risks of EV batteries, covering various battery types, network linkages of material production (e.g., Co mining and refining), and region-specific supply vulnerabilities (Bridge and Faigen, 2022; Greenwood et al., 2021; Helbig et al., 2018; Olivetti et al., 2017; van den Brink et al., 2020). Their findings suggest that EV batteries with high Co content (e.g., lithium cobalt oxides, LCO) have relatively higher supply risks than other battery types due to the highly concentrated market for Co mining and refining in specific areas (e.g., Congo and China). The supply chain of LIBs in the 2020s has shown limited diversification across multiple supply stages, leaving regions with high import dependence on the EVs and associated primary materials, such as the EU, less resilient to supply disruptions and developments in battery chemistry. However, previous estimates of material demand in the EU transport sector have been mostly derived from an aggregated evaluation at the global level (Albertsen et al., 2021; Deetman et al., 2018a; Dunn et al., 2021; Jones et al., 2020; Zhang et al., 2023). Therefore, it is essential to develop a clearer understanding of material demand that captures the dynamics of the transition to e-mobility at the European level.

On top of the challenges in resource availability and supply security, the environmental impacts associated with EV adoption should not be overlooked. Mining and production processes of raw materials used in the LIBs, such as lithium carbonate and cobalt sulfate, require high amounts of energy and fresh water, which are the most significant contributors to the overall embodied water use and emissions of GHGs and air pollutants (e.g., sulfur dioxide and nitrogen oxides, etc.) of the battery pack in the EVs (J. Dunn et al., 2015; Kelly et al., 2021; Rahimpour Golroudbary et al., 2022). GHG emissions from the battery manufacturing process vary widely due to differences in battery cell materials and the energy requirements, ranging from 40 to 200 kg CO_2-equivalent per kilowatt-hour of battery capacity. At their end of life, the recycling of batteries for material recovery through pyrometallurgical methods is particularly energy-intensive. As a result, the overall cradle-to-grave GHG emissions of EVs are estimated to be 30% to 60% higher than those of ICEVs (Dewulf et al., 2010; J. B. Dunn et al., 2015; Ellingsen et al., 2014; Hawkins et al., 2013a; Kim et al., 2016; Majeau-Bettez et al., 2011; Dominic A Notter et al., 2010).

The reduction of GHG emissions when driving EVs heavily depends on the carbon intensity of the local electricity system used for EV charging, vehicle driving performance, and vehicle lifetime. In regions where only high-carbon electricity is available, EVs tend to have a larger climate burden than comparably configured ICEVs, particularly if the EVs have large battery packs and short lifespans (Cox et al., 2020, 2018; Ellingsen et al., 2016). This is evident in the countries that highly depend on thermal power generation, such as in China (Wu et al., 2019) and in the U.S. (Milovanoff et al., 2019), where driving EVs show limited reduction of CO_2 emissions compared to ICEVs. In the European context, EVs powered by the electricity mix at 2010 level were estimated to offset their relative disadvantage with regard to embodied CO_2 emissions from production as early as after two years of operation or driving approximately 24000 km (Hawkins et al., 2013). While previous research underscores the importance of a low-carbon electricity sector in maximizing the climate benefits of EV adoption, most assessments have relied on static modelling approaches. Therefore, it is essential to evaluate GHG emissions from EU passenger transport while integrating the expected decarbonization of the electricity system. This can provide a more accurate understanding of future emissions trajectories and further support policymaking on effective GHG mitigation strategies.

1.3 Circularity approaches to promote sustainable material use

The challenges in resource availability with the adoption of EVs illustrate the importance of formulating resource strategies that advance the transition towards e-mobility in a sustainable way. A circular economy (CE) approach offers a potential solution, by switching from the traditional linear mode of "take, make, consume, and dispose" to a circular mode. In this mode, end-of-life products are not viewed as waste but as potential resources that can be processed and reconnected to the manufacturing system. Strategies within the CE framework are based on the so-called 'R principles,' which include refusing and rethinking, reducing, repurposing, repairing, refurbishing, and recovering. The core ideas behind these strategies are to preserve material value, improve utilization efficiency, and minimize the materials lost in the economic cycle for as long as possible (Ellen MacArthur Foundation, 2013).

Circular strategies of end-of-life EV batteries have primarily focused on repurposing, reusing and recycling. Retired EV batteries, which retain 70% to 80% of their original capacity, are well-suited for reuse or repurposing in other applications with less-demanding requirements, such as low-speed electric bicycles or motor cars and stationary energy storage systems (Canals Casals et al., 2019; Catton et al., 2019; Rallo et al., 2020; Zhu et al., 2021). However, technical and economic challenges currently limit the large-scale deployment of these second-life applications (Zhu et al., 2021). Recycling, on the other hand, focus on extracting valuable materials from the spent battery cells. Driven by policies and regulations, sophisticated recycling technologies have been developed, including pyrometallurgical recovery, physical material separation, hydrometallurgical recovery, and direct recycling (Davis and Demopoulos, 2023; Dewulf et al., 2010; Rosenberg et al., 2023; Tao et al., 2022; Yao et al., 2018). Recovering battery materials reduces the need for primary mining and associated impacts, including depletion of primary mineral reserves and environmental degradation. The use of secondary materials can also reduce supply risks (Santillán-Saldivar et al., 2021).

The EU has updated battery regulations to promote sustainability in the EU battery sector, including mandates for minimum shares of secondary materials in new battery production (European Commission, 2023b). Against this background, it is hence crucial to quantify the demand for primary EV batteries, EV battery stocks and the flow of end-of-life EV batteries over time. This helps to identify the amount of EV batteries that is becoming available for repurposing or material reuse, and to what extent secondary raw materials can cover the need for primary ones.

1.4 Research aim and methods

1.4.1 Research aim

The decarbonization of the transport sector is essential for achieving the EU's climate objectives. At the same time, a substantial growth in demand for new materials essential for low-carbon transport technologies is inevitable. The EU and its member states have to navigate these opportunities and challenges, while, as indicated most studies on climate impacts and material requirements of the EV transition have been done at the global level, or discussed the climate and material challenges separately. Against this background, this thesis has as its 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*.

To fulfill this core objective, the study investigates the following research questions:

- *Question 1: What will be the demand for Li, Co and Ni in the EU transport sector driven by the announced climate policies on promoting the EU e-mobility transition? (Chapter 2 and 4)*

- *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? (Chapter 3)*

- *Question 3: How will the availability of secondary Li, Co and Ni support the development of a sustainable EU battery sector? (Chapter 4 and 5)*

1.4.2 Research methods

A clear understanding of material demand is the crucial first step for formulating resource strategies. Material flow analysis (MFA) is the go-to scientific method that enables the quantitative evaluation of the material inflows, stocks, and outflows for defined systems, based on the mass balance principle. This method has been applied for quantitatively tracing the historical use of specific materials and discovering their stock or loss, such as the investigation of global material cycles for more than 60 metals (Chen and Graedel, 2012). In this thesis, a dynamic MFA model is applied by using the change in in-use stock in the time series and lifetime distribution of products. Lifetime distribution plays an important role in determining the material metabolism, which allows insights into the timeline and quantity of material stock and throughput of the defined system over longer periods of time than static snapshots. A software package developed in the Python programming language was employed for building up the MFA model (Pauliuk and Heeren, 2020).

Scenario analysis is combined with the dynamic MFA analysis to explore prospective material use and emission performance for the EU e-mobility transition. Instead of being predictive, scenarios take an exploratory approach to present the future development directions that could unfold (Reid, 2005). With the application of scenario analysis, external model drivers, potential factors, and assumptions supported by available empirical data can be integrated into the MFA model to gain better insight into the uncertainty related to exogenous parameters and further provide effective support for forward-looking climate policies and resource strategies. In addition, accounting procedure has been linked to the model for assessing greenhouse gas (GHG) emissions during the EU e-mobility transition and exploring the recycling ability of infrastructure being developed in the EU. The GHG emissions related to vehicle production and driving were assessed by combining the dynamic MFA model with the GHG emission factors per unit of activity obtained from previous LCA studies. More details of data, assumptions applied in the model, and descriptions of scenarios are elaborated in the following research chapters.

1.5 Thesis outline

This thesis starts with a case study on the e-mobility transition in the Netherlands in Chapter 2, representing one of the global pioneer countries that promoted a cleaner passenger transport system. It estimates how the demand for Li, Co and Ni will be influenced by the ambitious goal of achieving a carbon-neutral passenger transport sector. It also assesses the impact of EV battery lifespans, EV battery cathode chemistry, and EV battery capacity on the material flows, providing potential strategies for more sustainable resource usage in the short term.

Chapters 3 through 5 expand the spatial coverage to 30 European countries, including the 27 EU member states plus the UK, Iceland, and Norway, each of which has announced national plans to decarbonize passenger transport through EV adoption. Chapter 3 quantifies EV demand and the GHG emissions associated with driving and producing passenger vehicles through 2040, drawing on the individual national e-mobility ambitions of all 30 countries. It then benchmarks these emissions against the EU 2030 climate target established under the Green Deal (European Commission, 2019a), evaluating both the stated pace of the e-mobility transition and its potential environmental trade-offs.

Chapter 4 builds upon the modeling as presented in Chapter 3. It estimates the material demand for Li, Co and Ni in the EU passenger transport sector up to 2040, in alignment with the strengthened EU climate action plans updated in 2022 (European Commission, 2023a). The recycling potential for materials are examined based on the most updated EU Battery Regulations (European Commission, 2023b). Together, these analyses offer quantitative insights to inform strategic planning for sustainable resource use throughout the EU e-mobility transition.

Chapter 5 extends the evaluation of secondary material availability with consideration of the potential development of the EU recycling system. It further assesses the feasibility of meeting the demand for secondary materials required in new EV battery production in the EU through 2036. This chapter provides information on domestic recycling potential, allowing battery producers, recycling industry and policymakers to make more strategic investments and informed policy decisions toward the sustainable use of EV batteries.

Chapter 6 synthesizes the findings from each research chapter and answers the research questions. It further discusses the limitations of the study, followed by potential directions for future research and implications in a broader context.