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

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Electric vehicles (EVs) provide a promising solution for reducing the greenhouse gas (GHG) emissions in the passenger transport sector. Advances in lithium-ion batteries (LIB) have positioned EVs, partially or fully powered by batteries, as the dominant market choice in the current and forthcoming decades. To address the growing GHG emissions in the EU passenger transport sector, the EU has announced a set of climate policies and initiatives, including the European Green Deal and the 'Fit for 55' package, to promote the adoption of EVs in the EU passenger fleet. Challenges related to the supply of key materials in EV batteries, along with their energy-intensive production process, introduce uncertainties regarding the sustainability of the transition from fossil-based internal combustion engines to EVs in the EU. This highlights the need for an improved understanding of the material cycles as well as the GHG emissions during the e-mobility transition.

The aim of this thesis is to quantify strategies to effectively promote a more sustainable transition to electrified mobility (e-mobility) in the EU. To achieve this aim, it combines material flow analysis with future vehicle use scenarios to assess the demand for lithium (Li), cobalt (Co) and nickel (Ni) during the EU e-mobility transition through 2040. The market share dynamics of passenger vehicle types and the EV battery composition are assessed together with the potential decarbonization of the grid system to evaluate GHG emissions from the e-mobility sector. Chapter 2 focuses on developing an effective research model that can reflect regional dynamics in evaluating the material demand during the e-mobility transition. The Dutch e-mobility transition was selected as a case study, given that the Netherlands is one of the leading countries in promoting low-carbon passenger transport systems. Chapters 3 to 5 expand the spatial scope to more European countries. These chapters further evaluate the end-of-life fate of Li, Co and Ni, and the potential for circular material use. The availability of secondary materials is assessed in the context of the updated EU Battery Directive as well as the prospective development of the EU recycling system. In addition, the GHG emissions savings that follow the national e-mobility ambitions of 30 European countries up until 2030 are compared with the EU 2030 climate target outlined in the 2019 Green Deal.

Findings from Chapters 2 and 4 demonstrate that the demand for Li, Co and Ni is expected to continuously grow through 2040. Aiming for a full EV market by 2035 in the EU countries, the demand for the EVs is projected to increase twenty fold relative to the 2020 sales level by 2040. Correspondingly, the annual material demand will increase at least by 50 times, and the stock of these materials will expand at least 220 times from 2020 to 2040. This growth in demand is expected to outpace the average annual mineral production level observed from 2016 to 2021. A more accelerated transition across the EU countries, which is closely aligned with the speed of transition in pioneer countries such as the Netherlands, will lead to the demand for Li, Co and Ni increasing by at least an additional 30% annually. Smaller battery capacities and longer lifetimes help reduce material demand, while larger capacities and shorter lifespans will increase material requirements. The demand for Li and Ni is relatively insensitive to developments in current-generation LIB technologies. Co demand, however, can be largely mitigated with increased use of low-Co chemistries in LIB batteries.

Chapter 3 indicates that the stock of EVs in the EU passenger fleet is projected to grow 97-fold from 2020 levels by 2040, driven by the e-mobility transition set out in the 2019 Green Deal. This uptake of EVs, combined with declining carbon intensities of the EU electricity system, is expected to deliver a 52% reduction in annual greenhouse gas (GHG) emissions by 2040 and to achieve cumulative emission savings of 2.0 gigatons of CO_2 equivalent between 2020 and 2040. However, this level of reduction will not be sufficient to meet the EU's 2019 Green Deal climate targets, which aim for a 37.5% reduction in GHG emissions in 2030 compared with the 1990 levels. These results showcase that different e-mobility ambitions among EU member states still lead to a dominance of internal combustion engine vehicles (ICEVs) in the EU passenger fleet, and they will still account for 78% of the total passenger fleet in 2040. To achieve Green Deal reduction targets, there is a need for 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 during the 2020s.

In addition, the emission savings achieved by driving EVs can be substantially offset by the GHG emissions associated with the energy-intensive manufacturing of EV batteries. These emissions further transfer the environmental burden to EV manufacturing countries, most of which currently lie outside the EU. As a result, clear environmental benefits of adopting EVs will only be realized when the manufacturing GHG emissions are completely offset, which is projected to occur after 2030. Further improvements of the net environmental benefits of EV adoption need to tackle reductions of embodied EV emissions, for instance, by accelerating carbon mitigation of the electricity system in parallel with the e-mobility transition, both in the EU countries and in EV-producing countries. Lifetime extensions for both EVs and EV batteries can significantly lower the annual GHG emissions from the EV manufacturing sector.

Chapters 4 and 5 show that secondary Li, Co, and Ni do not become available until after the 2020s, as most EVs remain in the use phase. Meeting the demand targets outlined in the 2023 EU Battery Regulation for secondary materials for new EV battery production is not feasible through closed-loop recycling during this period due to increasing material demand through the 2030s. Closing the material loops of Li, Co, and Ni for the EU e-mobility transition will be difficult to achieve before 2040. Under full compliance with the recycling targets set out in the EU Battery Regulation, the recoverable Li, Co, and Ni from end-of-life batteries are projected to meet 20% to 30% of the cumulative material demand in the 2030s. Their availability can ease pressure on global primary material production and will be sufficient to meet the EU Battery Regulation guidelines, particularly as low-cobalt content batteries become dominant in the market. The growth of EU battery production can help to reduce the EU's reliance on battery electric vehicle (BEV) imports, as reflected in trade patterns from 2017 to 2022.

Nonetheless, uncertainties about the expansion of recycling capacity and recycling processing levels in the 2030s may limit the timely return of recovered materials that are suitable for new battery production, posing potential obstacles for the continued growth of EV battery manufacturing. Therefore, scaling recycling capacity at all processing levels in line with the expected increase of the number of spent batteries and ensuring high collection rates is essential to prevent material loss and ensure timely valorization of secondary materials.

Reducing material demand through extending battery lifetimes will also affect the availability of secondary materials. Longer battery lifetimes slow the turnover of EV batteries and delay the return of end-of-life EV batteries to recycling facilities. Therefore, reducing overall material demand and waste generation is an important step to allow for a comprehensive scaling up of recycling infrastructure in the EU.

Advancing EV battery technologies, implementing circular practices, and decarbonizing energy systems are pivotal for a sustainable e-mobility transition in the EU. Our findings suggest that prioritizing battery innovations such as optimized battery capacities and low-Co chemistries can reduce reliance on critical primary resources. Circular approaches are expected to sustain long-term environmental benefits, emphasizing the need for establishing an effective collection system and a comprehensive recycling system. These material-efficiency gains are contingent upon a parallel reduction of the carbon intensity of the electricity system, without which the environmental benefits of large-scale EV adoption cannot be fully realized. In addition, challenges regarding over-ambitious climate targets or the underlying tensions of the circularity targets across sectors underscore the necessity of coherent and well-coordinated climate policy frameworks that enable environmental targets to effectively drive the long-term sustainability of the EU e-mobility transition.

To have a more comprehensive picture of material dynamics, future assessments can extend beyond the current EV technologies by including emerging low-carbon transport options, incorporating multidimensional insights into resource use in light of economic and social changes. Furthermore, integrating prospective life-cycle modeling into current assessment framework can provide more emission mitigation options, helping to define optimal decarbonization pathways for the EU fleet. Moving from static to dynamic circularity indicators is necessary to capture the evaluation of sustainability over time in future studies.