Lithium-ion batteries and the transition to electric vehicles: environmental challenges and opportunities from a life cycle perspective

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Summary

A rapid and large-scale shift from Internal Combustion Engine Vehicles (ICEVs) to Electric Vehicles (EVs) is one of the most effective pathways to meet climate mitigation goals for the transportation sector. Such a shift can reduce driving emissions of cars significantly, especially when combined with the supply of renewable electricity. At the same time, the use of batteries - dominated by lithium-ion batteries - will increase drastically. To maximize the greenhouse gas (GHG) mitigation potential of EVs, further efforts to lower the lithium-ion battery-related GHG emissions are essential. To guide such efforts, it is essential to have a quantitative understanding of both the sustainability challenges and opportunities that the large-scale use of EV batteries provides.

In this thesis, I built an integrated model that combines dynamic MFA (material flow analysis), prospective LCA (life cycle assessment), and battery technology modeling. We use the integrated model and scenario analysis in chapters 2 to 5 to answer the overall research question: What are the future environmental challenges and opportunities for automotive lithium-ion batteries from a life cycle perspective? By combining dynamic MFA and battery technology modeling, we estimate the global stocks and flows of battery materials until 2050 (Chapter 2). By combining prospective LCA and battery technology modeling, we assess life cycle GHG emissions of future battery production discerning different battery production regions, battery chemistries, and energy mix scenarios (Chapter 3). By combining dynamic MFA, prospective LCA, and battery technology modeling (*i.e.*, combining Chapter 2 and Chapter 3), we explore the total GHG emissions associated with global EV battery production and also discuss the effect of closed-loop material recycling (Chapter 4). Lastly, in addition to the above-mentioned battery environmental challenges, we evaluate the energy storage capacity potentially available from EV batteries by combining the dynamic MFA model and the battery technology modeling. We compare this storage potential to the demand for the grid storage capacity (Chapter 5). The model integration enables us to systematically investigate and analyze the sustainability challenges and opportunities of the large-scale deployments of EV batteries.

Chapter 2 assesses the future material demand for EV batteries, including critical materials (lithium, cobalt, and nickel) that are crucial to the global economy and

associated with environmental and social impacts. Our analysis in Chapter 2 is based on the detailed modeling of the future battery chemistry mix and the material compositions of each chemistry. For modeling battery material compositions, the parameter inputs include EV type (battery electric vehicle/plug-in hybrid electric vehicle), size (small/mid-size/large), and performance (EV range and fuel economy) as well as battery chemistry (positive and negative active material capacity of 8 chemistries) and performance (*e.g.*, specific energy). Results show the dynamic development of battery stock, the demand for 8 battery materials, and the number of end-of-life batteries. We find a strong demand growth for battery materials (a factor of ~20 from 2020 to 2050). The modeling results for three battery chemistry scenarios assert that the material demand strongly depends on the battery chemistry. The demand for nickel and cobalt is lower when deploying more lithium iron phosphate batteries and lithium-sulfur/lithium-air solid-state batteries instead of lithium nickel cobalt aluminum/ lithium nickel cobalt manganese batteries. This, in turn, reflects the importance of modeling future battery chemistry mixes and the material compositions of each chemistry.

Chapter 3 quantifies the GHG emissions of future battery production using a prospective LCA model that simulates the life cycle inventories (LCIs) of future battery production. The data source for the foreground LCIs is based on the EverBatt model (Argonne's closed-loop battery life-cycle model), China battery industry reports (environmental assessment reports for battery production), and others (such as literatures); the background LCIs are based on the integration of ecoinvent 3.6 (world's most consistent and transparent life cycle inventory database), future energy mix scenarios with an ambitious and moderate GHG emission reduction policy based on the REMIND (Regional Model of Investment and Development) Integrated Assessment model, and future technology changes for the supply of key battery metals. The analysis is performed for different combinations of battery production regions, battery chemistry, and energy mix. The results show that the future life cycle GHG emissions of battery production relies heavily on the future energy mix. The scenario that includes a low-carbon energy transition, which aims well below 2 degrees Celsius for global warming, can result in an 50%-75% reduction in the life cycle GHG emissions of EV batteries.

Chapter 4 shows the total GHG emission of global EV battery production. This chapter is based on the dynamic MFA model from Chapter 2, but develops three more specific future battery demand scenarios (low/medium/high) considering EV fleet size and battery capacity per vehicle. Taking into account the life cycle GHG emissions of battery production including differences therein between battery production regions (China/EU/US), Chapter 4 presents the magnitude and range of total GHG emissions related to global EV battery production. The decreasing life cycle GHG emissions of battery production result in a relative decoupling between total GHG emissions of battery production and global battery demand. Despite this relative decoupling, results show that there is no absolute decoupling due to the strong demand increase overall until 2050. Reduction of the production emission requires an even faster penetration of renewable energy production, using battery chemistries (such as lithium iron phosphate batteries) that emit less GHG during production, etc.

Finally, Chapter 5 presents an opportunity of EV battery use: the co-benefit of providing grid storage. This is important, since in future a significant part of electricity production will come from intermittent sources such as wind and solar power. Chapter 5 uses the results of Chapter 2 on future battery stocks and outflows, which are differentiated by battery capacity and chemistry. Further, based on a detailed dataset on the daily driving distance of various EV types/sizes/models, Chapter 5 models the EV driving behavior and battery use states. The battery use states (driving/charging) over time, combined with the battery chemistry and information on ambient temperature, are used to estimate battery degradation over time (*i.e.*, the dynamic battery capacity under various conditions). Results present the total gird storage capacity from EV batteries until 2050, including both vehicle-to-grid and second-use, under assumed market participation rates of vehicle-to-grid and second-use. By comparing this total grid storage capacity with demand scenarios for storage capacity, we find that EV batteries alone could satisfy short-term grid storage demand by as early as 2030.

Combining the results of Chapters 2-5, increasing battery demand and battery production driven by EV fleet penetration will continue to pose challenges to raw materials supply and GHG mitigation in the context of achieving climate goals. Large-scale production of EV batteries would weaken the driving emission reduction benefits resulting from EVs. The results point out the important factors (*e.g.*, battery chemistry, production region, and low-carbon energy transition) and their effects on the magnitude of the challenges. This has fundamental implications for the guidance with respect to relieving these challenges and even turning challenges into opportunities for achieving environmentally sustainable batteries.

A lower emission and even net-zero battery industry can be achieved by the adoption of new battery production processes using low-carbon electricity, in addition to other potential low-carbon energy sources. Reducing life cycle emissions from battery production should require further coordinated actions throughout battery value chains to promote all mitigation options. This includes reducing battery demand (such as stimulating the use of small EVs that can be driven with low-capacity batteries); improved and innovative battery technologies that enhance battery lifetimes, and are less dependent on materials that are critical or require high levels of energy to be produced; increasing material and energy efficiency during battery production; implementing circular economy principles (such as close-loop recycling).