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

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6 General discussion

6.1 Answers to research questions

Table 6.1 summarizes the related research questions identified in the introduction as well as the methods applied and the answers provided in the previous chapters.

Table 6.1: Summary of research questions, and the methods applied to come to answers on the research questions.

Questions	Methods	Results
What is the future material demand for automotive lithium-ion batteries?	<ul style="list-style-type: none"> ✓ Dynamic MFA ✓ EV fleet and battery chemistry scenarios 	<ul style="list-style-type: none"> ✓ Strong demand growth for lithium, cobalt, nickel ✓ Closed-loop recycling only matters after 2030
What are future cradle-to-gate GHG emissions per kWh automotive lithium-ion battery production?	<ul style="list-style-type: none"> ✓ Prospective LCA model including 8 battery chemistries and 3 production regions 	<ul style="list-style-type: none"> ✓ GHG emissions per kWh storage capacity during 2020-2050 ✓ LiOH matters for LFP emissions, NiSO₄ for NCA/NCM emissions
What are the future GHG emissions of global automotive lithium-ion battery production?	<ul style="list-style-type: none"> ✓ Combine dynamic MFA and prospective LCA 	<ul style="list-style-type: none"> ✓ Global EV battery demand will result 149-266 Mt CO₂-Eq of GHG emissions in 2050 ✓ GHG emissions reduce from 50%-75% by 2050 per kWh of battery, which results in a relative decoupling ✓ Battery demand matters more than recycling for GHG emissions reduction
What is the future grid storage capacity available from global automotive lithium-ion batteries?	<ul style="list-style-type: none"> ✓ Vehicle-to-grid and second-use ✓ EV driving behavior and battery degradation 	<ul style="list-style-type: none"> ✓ Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030

6.1.1 RQ1: What is the future material demand for automotive lithium-ion batteries?

Methods

Dynamic MFA. To project battery material flows, we build a battery stock dynamics model⁷ that consists of an EV layer, a battery layer, and a material layer. The EV layer models future EV fleet size (*i.e.*, EV stock) and battery capacity demand. EV stock determines battery stock. The battery stock determines the battery demand and end-of-life (EoL) batteries each year, considering EV and battery lifespan distributions. The battery layer reviews battery chemistry development and models future market shares by chemistry. The material layer uses the BatPac model⁷⁰ to model material compositions of different battery chemistries, with parameter inputs of intended EV type (BEV or PHEV), EV performance (range, fuel economy, motor power⁷⁶), and battery performance (positive and negative electrodes and their active capacity⁷⁰).

EV fleet and battery chemistry scenarios. We use two EV fleet scenarios of IEA: the stated policies (STEP) scenario and the sustainable development (SD) scenario⁶³. The IEA scenarios only project EV fleet size until 2030, split by BEVs and PHEVs. We further project the EV fleet size in the period from 2030-2050 based on literature reviews of EV fleet penetration and global vehicle stock⁷² during this period. We assume that the future share of BEV in the global EV fleet in 2030-2050 increases at the same rate as that in the US⁷³.

NCM, NCA, and LFP are three common lithium-ion battery chemistries used for EVs, and they are expected to dominate the EV market in the next decade. However, NCM/NCA/LFP chemistries differ in technical lifespan, specific energy (Wh stored energy capacity/kg battery weight), stability, and other performance factors²⁹. NCM and NCA batteries (NCX, with X denoting manganese and aluminum) possess higher specific energy and power performance than LFP. LFP has advantages of materials cost, cycle life, and thermal stability over NCX. Researchers also develop lithium-based solid-state chemistries, such as Li-Air and Li-Sulphur batteries that have a potentially very high specific energy and that are very safe to use. But given the current development stage, only after 2030 Li-Air and Li-Sulphur batteries⁷ can be expected to be practically applied in EVs at a large scale. Based on reviews of battery technology development roadmaps, we therefore develop an NCX scenario where NCM and NCA

batteries will dominate the EV market until 2050, an LFP scenario where LFP batteries will dominate the EV market by 60% after 2030, and a Li-S/Air scenario where Li-Air and Li-Sulphur batteries will dominate the EV market by 30% each (totally 60%) during 2040-2050.

Results

Strong demand growth for lithium, cobalt, nickel. The SD scenario results in a 1.7-2 times higher annual material demand than the STEP scenario since the EV fleet in that scenario is almost twice as big. The annual material demand for lithium does not differ a lot between the three chemistry scenarios, but for nickel and cobalt the chemistry scenario influences demand a lot. The annual demand for nickel and cobalt is lower in LFP scenario and Li-S/Air scenario since lower market shares of NCX batteries, which contain nickel and cobalt, in these two scenarios. Depending on EV fleet and battery chemistry scenarios, demand is estimated to increase by factors of 18-20 for lithium, 17-19 for cobalt, 28-31 for nickel, and 15-20 for most other materials during 2020-2050. The cumulative material demand during 2020-2050 is in the range of 7.3-18.3 Mt for lithium, 3.5-16.8 Mt for cobalt, and 18.1-88.9 Mt for nickel.

Closed-loop recycling only matters after 2030. EVs are a fast-growing market and EVBs hence inevitably need primary material input. Given the average battery lifetimes of ~15 years, in the coming decades the amount of EoL batteries materials are hence just a fraction of primary material demand for batteries. So closed-loop recycling can, at best (*i.e.*, without delay of recycling), reduce 20%-23% of the cumulative material demand for lithium during 2020-2050, 26%-44% for cobalt, and 22%-38% for nickel. A crucial condition for realizing this closed-loop recycling potential is that recycling technologies are developed that can economically recover battery-grade. Second-use of batteries will obviously delay recycling.

6.1.2 RQ2: What are future cradle-to-gate GHG emissions per kWh automotive lithium-ion battery production?

Methods

Prospective LCA model including 8 battery chemistries and 3 production regions. To project cradle-to-gate GHG emissions per kWh automotive lithium-ion battery production, we build a prospective LCA model that simulates battery production by

five life cycle stages: “mining”, “raw materials production”, “upgrading battery materials”, “component production”, and “cell production”. We present 24 combinations of LCIs for battery production: 8 battery chemistries, which result in different material compositions and production processes, and 3 production regions (China, US, and EU), which affect where raw materials and energy are supplied. We compile a battery production Life Cycle Inventory (LCI) based on the EverBatt model⁴⁸, China battery industry reports¹⁶⁵, and literature assumptions⁴⁰ where applicable. The prospective LCA model also incorporates a prospective LCI background database that is derived from the ecoinvent 3.6 database¹⁵⁸, but takes into account changes in the production of key battery metals (nickel¹⁶⁰, cobalt¹⁶¹, copper¹⁶⁰, and others), next to changes in energy/electricity mixes by region based on outputs of the Remind Integrated Assessment Model¹⁸⁰, for the period between 2020 and 2050.

Results

GHG emissions per kWh storage capacity during 2020-2050. GHG emissions per kWh automotive lithium-ion battery production vary significantly between the 3 production regions (China, US, and EU). The GHG emissions per kWh battery cell produced in EU are 16%-18% lower than in the US, and 38%-41% lower than in China in 2020. This is mainly due to the substantial difference in the share of renewable energy and resulting emission intensities for electricity used for battery cell production across the regions: 0.36 kg CO₂-Eq per kWh electricity in EU (low), 0.48 kg CO₂-Eq per kWh electricity in US (middle), and 0.74 kg CO₂-Eq per kWh electricity in China (high) in 2020.

The battery chemistry also affects GHG emissions since different materials and production processes are used. A clear example is that LFP production does not require nickel and cobalt - their production is energy intensive and generates significant emissions - while NCX cell production requires these metals. Due to this and other differences in production processes between LFP and NCX, LFP cell production generates 20%-28% lower GHG emissions per kWh storage capacity than NCX cell production in 2020.

Depending on production regions and battery chemistry, GHG emissions per kWh of automotive lithium-ion battery production are in the range of 41-89 kg CO₂-Eq in 2020. Compared to 2020, GHG emissions could more than halve to 10-45 kg CO₂-Eq in 2050,

mainly due to the development and use of low-carbon electricity for cell production.

LiOH matters for LFP emissions, NiSO₄ for NCA/NCM emissions. The production of the cathode is the biggest contributor (33%-70%) to the cradle-to-gate cell GHG emissions between 2020-2050, followed by anode production and cell production, the latter using energy (such as electricity) to assemble battery components to a cell. Cathode production requires the supply of different battery materials.

Cathode production requires the supply of different battery materials, especially metal-based chemicals and compounds. These metal-based materials may contribute significantly to the battery cell's GHG emissions. The contribution analysis of different battery materials to GHG emissions will differ between cathodes of LFP and NCA/NCM since their differences in the production process and the required materials (LiOH, Fe₂(SO₄)₃, H₃PO₄, etc., are necessary materials for the production of LFP cathode, while NiSO₄, CoSO₄, LiOH/Li₂CO₃, etc., for NCA and NCM cathodes).

The production and use of LiOH and electricity together account for 82%-86% in 2020 and 64%-82% in 2050 of GHG emissions for LFP cathodes, depending on the production regions. From the perspective of the whole battery cell, LiOH and electricity together contribute to 27%-29% in 2020 and 28%-35% in 2050 of the GHG emissions of LFP cells.

For NCX cells a different picture arises. There, the production of NiSO₄ and Li₂CO₃ is the most important contributor to GHG emissions. CoSO₄ and other cathode materials are less important. Using NCM622 as an example, NiSO₄ and Li₂CO₃ contribute to 18%-30% and 6%-11% of GHG emissions of NCM622 cathode in 2020 respectively. These numbers change to 25%-46% and 8%-21% in 2050, depending on the production region and energy scenarios. In other words, NiSO₄ and Li₂CO₃ account for 16%-31% and 5%-14% of the life cycle GHG emissions of NCM622 cell production in 2050.

6.1.3 RQ3: What are the future GHG emissions of global automotive lithium-ion battery production?

Methods

Combine dynamic MFA and prospective LCA. We build a model to estimate the GHG emissions of global automotive lithium-ion battery cell production during 2020-2050. The model framework combines the dynamic MFA model discussed under RQ1⁷, which

projects global demand for EV battery cells, and the prospective LCA model discussed under RQ2¹⁷⁸, which projects cradle-to-gate GHG emissions per kWh battery production. As main scenarios discern a low, medium, and high demand for batteries. The low demand scenario follows the STEP scenario but combined with an average battery capacity of 33 kWh per BEV and 14 kWh per PHEV; the medium demand scenario follows the STEP scenario in section 2.1.1 combined with an average battery capacity of 66 kWh per BEV and 14 kWh per PHEV; The high demand scenario assumes the same battery capacity per vehicle as the medium demand scenario, but follows the SD scenario in section 2.1.1 that is about double EV fleet size than the STEP scenario. We incorporate further in these battery demand scenarios with 2 battery chemistry scenarios (in section 2.1.1) and two energy mix scenarios (in section 2.1.2). In addition to scenario analysis, we conduct sensitivity analysis of battery production region and closed-loop recycling with regard to total GHG emissions for global battery production.

Results

Global EV battery demand will result in 149-266 Mt CO₂-Eq of GHG emissions in 2050. We find the life cycle GHG emissions of the global EVB cell production will increase to 26-155 Mt CO₂-Eq in 2030 and 58-468 Mt CO₂-Eq in 2050, depending on EV demand growth, battery chemistry, and energy mix scenarios. In the medium battery demand scenario, the global GHG emission of EVB cells production will range 44-99 Mt CO₂-Eq in 2030, 54-173 Mt CO₂-Eq in 2040, and 99-287 Mt CO₂-Eq in 2050 (the range depends on battery chemistry and energy mix scenarios). The high battery demand scenario leads to 1.5-1.7 times higher annual GHG emissions than in the medium demand scenario, while the low demand scenario results in 58%-59% of the annual GHG emissions of the medium demand scenario. Between the high and low demand scenario there is a factor of 2.6-2.9 difference in GHG emissions of global EVB cell production in 2050.

In addition to the battery demand scenarios, the battery chemistry and energy mix scenarios also affect the GHG emissions of global EVB cell production. Since LFP battery production generates lower GHG emissions than production of NCX batteries, the GHG emissions in the LFP scenario are 12%-15% lower than in the NCX scenario (range depends on battery demand scenarios). Changes in the GHG intensity of energy have a higher influence on GHG emissions as changes in the battery chemistry. In a GHG emission scenario that aims to keep temperature rise well below 2 °C, GHG

emissions from battery production are 48%-65% lower than in a GHG emission scenario that will end up with 3.5 °C temperature rise.

GHG emissions reduce from 50%-75% by 2050 per kWh of battery, which results in a relative decoupling. Despite an 8%-12% annual growth rate of the global demand for battery cells during 2020-2050, life cycle emissions of battery production only increase annually by 2%-10% in the same period. There is hence relative decoupling, which can be defined as the relative change of annual growth rates of life cycle emissions of battery production, and battery demand. The relative decoupling rate can range from 19% to 70%, depending on battery demand, battery chemistry, and energy mix scenarios.

Battery demand matters more than recycling for GHG emissions reduction. Battery demand - determined by the EV fleet size and battery capacity per vehicle - provides a promising opportunity to reduce battery GHG emissions. This is reflected by the GHG emissions comparison among three battery demand scenarios. The comparison indicates that drastic reductions are possible if mainly small EVs are used with 33kWh storage capacity, as opposed to the 66 kWh we used on average. If additionally, self-driving cars breakthrough, which are more intensively used, a further reduction could be realized of required battery stock and related life cycle GHG emissions of their production.

Materials recycling only has a minor but increasing role to reduce life cycle GHG emissions of battery production. The relative maximum impact reduction potential by recycling for GHG emissions (see methods in Chapter 4) is increasing from 0.25%- 0.76% in the period from 2021-2030 to 2%-5.4% in 2031-2040, and to 3.8%-10.7% in 2040-2050. This is mainly because the volume of materials entering the EoL stage in a specific year is, given the vast expansion of the EV fleet, just a fraction of the required new use (5%-30%). This situation can be only partly solved once the EV battery market has reached a steady state, *i.e.*, when recycled EoL materials can almost completely meet material demand. Under a hypothetical future steady state, the relative maximum impact reduction potential can improve from 8%-22% in 2021-2030 to 10%-30% in 2031-2040, and to 13%-35% in 2040-2050. Note that this potential is not taking into account the GHG emissions from collection and recycling processes. It is hence essential that efficient, low-carbon techniques for battery recycling are developed.

6.1.4 RQ4: What is the future grid storage capacity available from the global use of automotive lithium-ion batteries?

Methods

Vehicle-to-grid and second-use. We develop an integrated model¹⁵⁵ to assess the future available (both technical and actual) grid storage capacity from EV batteries. In the following, we describe both vehicle-to-grid capacity (*i.e.*, batteries in use in EVs) and second-use capacity (*i.e.*, EV batteries that reached their end of life but can be used in less critical storage applications).

We define the technical vehicle-to-grid capacity as the availability of EV battery stock capacity for vehicle-to-grid application, considering the capacity reserved for EV driving, the capacity of PHEVs that will not participate in vehicle-to-grid, and capacity loss due to battery degradation. We further define the actual vehicle-to-grid capacity, under different consumer participation rates, as the actual availability of technical vehicle-to-grid capacity for the grid.

We assume that batteries will retire from EVs when vehicles reach their EoL. Typically, the retired batteries should have over 70% of their original capacity to meet the technical and economic feasibility of the second use. We define the technical second-use capacity as the capacity of the retired batteries that can be repurposed for a second use, considering the capacity loss during their use in EVs. We further investigate the actual second-use capacity under different market participation rates (*i.e.*, not all retired batteries maybe end up as second-use).

Results

EV driving behavior and battery degradation. A battery degradation model - based on the latest battery degradation test data differed by battery chemistries (LFP and NCM) - is developed to estimate battery capacity loss over time under different conditions of EV use, battery chemistry, and temperature. The model builds upon the battery degradation method of Smith, et al. from NREL⁶¹ and considers both calendar life and cycle life aging. The calendar life aging consists of all aging processes that result in a degradation of a battery cell independent of charge and discharge cycles, which is modeled based on factors of battery temperature and state-of-charge; the cycle life aging refers to a degradation of a battery cell due to charging and discharging

cycles, which is modeled based on factors of battery temperature, depth-of-discharge, and current rate. The calendar life aging is an important factor than the cycle life aging for the lithium-ion batteries applied in EVs where the driving periods are substantially shorter than the idle parking periods.

We build an EV use model including behavioral factors such as the EV driving cycle and charging behavior (charging power, time, and frequency), based on daily driving distance datasets for small/mid-size/large BEVs and PHEVs provided by Spritmonitor.de¹⁹⁹. In this model, EV battery SoC (state-of-charge) is simulated second-by-second under three EV states: driving; parking and charging; and parking without charging. For battery SoC during driving, we use the FASTSim model²⁰², developed by NREL, to simulate battery SoC second-by-second with inputs information on the EV driving cycle (vehicle speed over time), EV configurations (such as drag coefficients), and battery performance parameters (specific energy and battery capacity). For battery SoC during parking and charging, we assume a constant charging power with a 90% charging efficiency²⁰³ such that the battery SoC increases linearly until a full charge state. If an EV is parked without charging, the SoC of the battery is slowly decreasing due to losses caused by battery self-discharging. We assume a typical discharge rate of 5% per month for lithium-ion batteries²⁰⁴.

Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030. The expanding use of wind and PV for electricity generation will lead to a need for short- and long-term storage of electricity. Here, we focus on short-term electricity storage since this accounts for the majority of the required power storage capacity in kW¹⁹². We have used the Planned Energy Scenario and the Transforming Energy Scenario developed by the International Renewable Energy Agency² as well as the conservative and optimistic scenarios¹⁹⁴ developed by the Storage Lab. These scenarios all give the level of penetration of renewable wind and PV technologies. These levels of penetration estimate a short-term storage capacity requirement of respectively 3.4, 9, 8.8-19.2 TWh by 2050 globally. The future demand for short-term grid storage refers to the 4-hour storage capacity defined as a typical 1-time equivalent full charging/discharge cycle per day, amounting to 4 hours of cumulative maximum discharge power per day.

EV and second-use batteries are in principle an option to provide this storage capacity. We define total technical storage capacity as the cumulative available EV battery

capacity in use and in second use at a specific time, taking into account battery degradation and the capacity needed to meet the demand for driving. Under all EV fleet and battery chemistry scenarios, the total technical capacity will grow dramatically, by a factor of 13-16 between 2030 and 2050. Putting this total technical capacity into perspective against the future demand for short-term grid storage, we find that our estimated capacity growth is expected to increase as fast or even faster than short-term grid storage capacity demand in several projections^{56,194}. Technical vehicle-to-grid capacity or second-use capacity are each, on their own, sufficient to meet the short-term grid storage capacity demand of 3.4-19.2 TWh by 2050. This is also true on a regional basis where technical EV capacity meets regional grid storage capacity demand. Modest market participation rates (12%-43%) are needed to provide most if not all short-term grid storage demand globally.

6.1.5 Answers to overall research question

Overall RQ: What are the future environmental challenges and opportunities for automotive lithium-ion batteries from a life cycle perspective?

Methods

We build an integrated model that links dynamic MFA, prospective LCA, and state-of-art battery technology modeling. The model was adjusted to answer various specific RQs. First, we use this model to estimate the future battery material demand (challenge 1). It links the dynamic MFA method and the battery chemistry model (including battery chemistry mix and material compositions). Second, we use this model to assess the GHG emissions per kWh of battery production (challenge 2). It links the prospective LCA method and the battery chemistry model. Third, we use this model to quantify the GHG emissions of global battery production (challenge 3). It links the dynamic MFA approach, the prospective LCA method, and battery chemistry modeling. Last, we use this model to explore available grid storage capacity from global EV battery use (opportunity 1). It links the dynamic MFA method and battery degradation modeling (*i.e.*, battery capacity over time).

Results

According to our model, EV battery production poses several challenges to the environment. There are however ways to limit these challenges. First, increasing EV

battery deployments will lead to strong demand growth for raw materials - especially lithium, cobalt, and nickel, which are defined as critical materials by the European Commission. We can reduce battery material demand by developing batteries that use low amounts of (critical) material (such as batteries based on chemistries using low amounts of cobalt), closed-loop material recycling, and stimulating the use of small cars using small batteries. Self-driving cars that are driven much more intensively than private cars could lower materials demand even further. Further, transparent, secure, and sustainable supply chains of battery raw materials should be promoted. Second, battery production will generate a significant amount of GHG emissions. The future GHG emission per kWh battery storage capacity varies a lot by production region (China/EU/US) and battery chemistry, and most importantly the energy mix (the share of low-carbon renewable energy). Therefore, the use of low-carbon renewable energy, especially for energy-intensive processes, during battery production should be promoted. Third, the GHG emissions related to global battery production will increase due to battery demand growth. This increase in GHG emissions can be reduced if we use smaller cars with smaller batteries that have a lower GHG emission intensity. And as already discussed under material demand, the use of self-driving cars could reduce battery requirements and related GHG emissions from production even further.

Although the production of EV batteries will pose challenges to the environment, they obviously will lead to a massive reduction in driving emissions in the first place (an issue not further researched in this thesis). The use of EV batteries can further generate co-benefits in terms of providing energy storage capacity for the power system. This co-benefit, including both vehicle-to-grid capacity and second-use capacity, could satisfy short-term grid storage demand by as early as 2030. The co-benefit/opportunity of EV batteries to the power system should be promoted by supporting policy, innovative business, and consumer participation.

6.2 Limitations and recommendations for future research

Projecting EV fleet size. We compiled two EV fleet scenarios for the period between 2020 and 2050. Such scenarios were done in 2020, however, are by definition uncertain. They should be updated regularly, maybe even on a yearly basis, to incorporate the implications of the fast development of EV technology, supply equipment (such as charging infrastructure), and policy incentives. For instance, the IEA publishes a global

EV outlook report and updates EV fleet scenarios each year, with projections until 2030 only. The IEA's projection of EV fleet size in 2022⁶ is slightly higher than that in previous years 2020⁴⁷ and 2021²³⁹. Also, instead of two EV fleet scenarios in 2020 and 2021, IEA in 2022 presents three EV fleet scenarios that are associated with different climate and EV policy goals: a stated policy scenario; an announced policy scenario; and a net-zero emissions by 2050 scenario⁶. Among the three scenarios, the net-zero emissions by 2050 scenario projects the highest EV fleet size that follows a net-zero emissions trajectory for energy system⁶, which should be included in future research.

Moreover, we do not consider self-driving vehicles⁴ and vehicle sharing⁵ in our EV fleet scenarios. This is rarely considered in current studies, due to uncertainties with regard to commercialization timelines and consumer acceptance of these potential developments. Yet, such developments have potentially dramatic impacts on EV fleet sizes and battery demand. Future research is hence recommended to include the impacts of self-driving and sharing vehicles, since these technologies could lead to lower EV fleet size and battery demand while at the same time reducing challenges with regard to material requirements and life cycle GHG emissions of battery production.

Battery chemistry. Three battery chemistry scenarios are developed on a global level, and used also on a regional level. However, battery chemistry scenarios will differ in regions, depending on regional battery policies and development roadmaps. For instance, China prefers LFP batteries over NCA and NCM batteries, while the US and EU prefer NCA and NCM batteries over LFP batteries²⁴⁰. Future research can develop regional-specific battery chemistry scenarios, which will increase the accuracy of projecting regional battery materials demand and environmental impacts.

Further, battery technologies develop fast, and including the impacts of uncertain, but potentially breakthrough battery technologies in our results is challenging. Although we include a Li-S/Air scenario, we do not include any other chemistries beyond lithium-based chemistries, such as aluminum, and sodium-based batteries⁶⁴. Such novel chemistries can also be potentially used for EVs. For example, CATL started the production of first-generation sodium-ion batteries for EVs²⁴¹, which do not require lithium, cobalt, and nickel during battery production. Broader scenario analyses of such possible future changes in battery chemistries are recommended.

Battery production. When simulating battery cell production in the prospective LCA model, future development of material efficiency is not incorporated in the model²⁴². Higher material efficiency will result in lower material use and thus lower GHG emissions. This can be achieved in many ways, such as designing batteries requiring lower amounts of materials, reusing battery components and materials during production, *etc*²⁴³. Future research should include the future development of material efficiency and investigate its potential to reduce GHG emissions of battery cells.

Our analysis showed that the decarbonization of the energy system has a crucial impact on the life cycle GHG emission of battery production. Various energy scenarios exist from different Integrated assessment models, which can result in different life cycle environmental impacts for future energy production. Selecting and adjusting such energy scenarios to match battery production technology developments is hence crucial in further research. Future research should include close-to-reality and specific energy transition scenarios for different battery production stages/processes.

Battery use. We use state-of-art data to model battery degradation for LFP and NCM. However, if drastic innovations in battery technology take place (such as Na-ion, Li-Air, and Li-Sulphur²²⁸, as discussed before), this may have a significant impact on battery lifespans and degradation rates. Further, while we derived driving behaviour from empirical data, future changes in driving habits are uncertain and dependent on various factors such as EV-related infrastructure. Vehicle chargers increase in power output over time and 50 kW charging is already common across some countries²²⁹. Frequent fast charging could lead to faster degradation, especially in hot/cold climates²³⁰. This challenge may be addressed by future technology improvements to battery materials²³¹, electrode architectures, and optimized synergy of the cell/module/pack system design¹⁶⁹.

Our research found that technically EV batteries alone could satisfy by 2030 short-term storage demand in electricity grids relying on input of PV and wind. Optimizing vehicle-to-grid capacity or second-use capacity of EV batteries may enhance the penetration level and use efficiency of renewable energy^{244,245}. This may, in turn, result in lower GHG emissions for battery production. An interesting subject for future research could be building a model which can simulate interactions between EV battery use, renewable energy production and storage, and battery production.

Battery end-of-life. The battery lifespan strongly affects the demand for new batteries and the end of life scenarios (second-use or recycling). It is uncertain due to consumer behavior, battery state-of-health²⁴⁶, etc. Actual battery lifespan data should be collected alongside the EV fleet expansion, and included in future research to increase the reliability of results.

Since recycling can reduce material demand and GHG emissions for EV batteries, we do include the impacts of recycling in the analysis. However, the energy and materials input to recover materials from EoL batteries during recycling are neglected due to the lack of reliable data. Recycling may generate more GHG emissions than the emissions mitigated by recovered materials (such as pyrometallurgical recycling of LFP batteries⁴⁹), depending on battery chemistry and recycling technologies. It is necessary to collect reliable LCI data on battery recycling and use the data along with a consistent methodology for quantifying environmental costs and benefits of battery recycling.

6.3 Policy implications of this research

Battery materials. Given the expected strong demand growth for battery materials, the global production capacity for critical materials - lithium, cobalt, and nickel - needs to expand drastically. For lithium, demand from global light-duty EVs alone can exceed the 2019 global lithium production, now mainly used in applications such as portable batteries, ceramics, and catalysts in the next decade. This potential lithium supply bottleneck is reflected by the recent lithium price spike of 438% in 2020²⁴⁷, due to COVID lockdowns and supply chain issues²⁴⁸. It is hence crucial to start lithium mining and refinement projects well ahead of the demand increase given the fact that such projects have years of lead time; considering alternative methods of extracting and refining lithium (such as lithium from seawater) that can expand and speed up the supply²⁴⁷. Similar problems can be expected for cobalt. Cobalt demand for EV batteries alone in the next decade will be as high as the global cobalt production in 2020. Using batteries with low cobalt content (such as NCM batteries in which cobalt content is gradually reduced) or even batteries not containing cobalt (Li-Sulphur and Li-Air batteries) can relieve the potential cobalt supply shortage⁷. For nickel, demand from global EV battery production only, could surpass the 2019 global nickel production used in all applications between two and three decades. The situation for nickel is hence somewhat less critical as for lithium and cobalt in the long term. Increasing the

mining and refining capacity of Class 1 nickel, which is required for batteries, can avoid a nickel supply shortage for EV batteries²⁴⁹. Note the criticalities and supply chain vulnerabilities of different battery materials can change dramatically in a short term due to material trade restrictions, social and political disruptions (such as the recent war between Russia and Ukraine²⁵⁰), and the concentration of material production in a few countries and regions. Building new production sources and developing material reserves for battery materials, such as deep-sea mining²⁵¹ and the recent mining project in Greenland²⁵², can improve the security of the materials supply chain.

In sum, a vast ramp-up of extraction and production of battery materials is required to maintain an adequate supply. However, such a development poses environmental challenges, along with social and governance complexities¹³. Since GHG emissions of battery materials vary significantly under different conditions including production technologies, battery chemistries, and the pace of the low-carbon energy transition, we should stimulate conditions that lead to lower GHG emissions related to battery production. Our results in Chapters 3 and 4 provide a basic understanding of how GHG emissions related to battery production could be minimized.

Low-carbon energy transition. We must highlight the importance of low-carbon energy transition in reducing GHG emissions of battery cell production (over 50% reduction of battery GHG emissions). Increasing the share of low-carbon energy (such as wind and solar) in the energy system and, at the same time, the use of low-carbon energy during battery production should be a priority measure to reduce GHG emissions from battery production. One practical measure is to install a solar power generation facility along with a battery production factory¹⁷⁰ - such that low-carbon electricity is generated and directly used for battery production without long-distance electricity transmission.

Given the fact that the low-carbon energy transition is mainly driven by solar and wind power installments, we should speed up the installations of solar and wind that generate low-carbon electricity. However, electricity production by solar and wind fluctuates due to weather variability (if no/weak/strong wind and sunshine), and they require solutions to ensure a match of supply and demand on the electricity grid, such as stationary battery energy storage. For large-scale deployment of stationary battery energy storage, cutting down battery costs is necessary but challenging²⁵³. The opportunity that EV batteries alone could satisfy short-term grid storage demand by

as early as 2030 should not be missed and used as a cost-effective storage solution (*i.e.*, vehicle-to-grid and second use) for an energy system based on solar and wind. To realize vehicle-to-grid, policy incentives should support the development of an EV charging infrastructure that is capable of using as well vehicle-to-grid services, business models to encourage the participation of EV consumers, and the inclusion of EV battery energy storage in future electricity market design are all necessary supports. The energy storage opportunity can also be provided by the second use of retired EV batteries. Policies should focus on the establishment of a collection system for retired batteries, the technology for rapid battery health checks and remanufacturing, and business that can maximize the value of second-use batteries in the grid storage applications.