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

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1 General introduction

1.1 Background

Global greenhouse gas (GHG) emissions continued to grow with the annual addition of 59 Gt CO2-Eq in 2019, despite slowed growth in recent years. Combating climate change and meeting the Paris Agreement's long-term temperature goal is only possible with urgent and ambitious actions across all sectors. These actions include a transition to low-carbon electricity production, electrification of transport, a low or nearly zero energy build environment and low-carbon industry processes, amongst others, next to implementing carbon capture and utilization and circular material use.

As the second-largest GHG-emitting sector next to the energy sector, the transportation sector accounts for ~15% of global annual GHG emissions in 2019[1]. Electrification of transportation services has been demonstrated as a technically feasible, cost-efficient, and rapidly scalable option to mitigate GHG emissions in the transportation sector. Vehicle electrification can significantly reduce GHG emissions of passenger cars[2], alongside reducing dependency on oil resources[3]. It can further contribute to the 'smart city' concept if electrification is combined with automated driving[4] and fleet sharing[5].

Passenger cars are the fastest growing segment of the transport sector that makes a shift from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs). The global EV fleet grew from a few thousand vehicles in 2005 to 10.1 million vehicles in 2021[6]. Strong growth can be foreseen in the next decades. The International Energy Agency (IEA) projects 175-244 million EVs on the road globally in 2030, including 130-190 million battery electric vehicles (BEVs) and 45-54 million plug-in hybrid electric vehicles (PHEVs)[6,7], depending on policy support, technology advancements, and other factors.

1.2 Sustainability challenges and opportunities related to the EV transition with a focus on batteries

The EV transition faces technical challenges (*e.g.,* range and durability of EV batteries); economic challenges (*e.g.,* purchase price compared to ICEVs); and consumer awareness challenges (*e.g.,* environmental benefits of EVs). These EV transition challenges relate to and impact each other[8]. Understanding this complexity will help address these EV transition challenges and even create opportunities that maximize the benefits of the EV transition.

The batteries play a key role in understanding the EV transition challenges[8,9]. Here, we focus on the challenges for achieving environmentally sustainable batteries, as well as the opportunities that battery use can bring to sectors other than the EV sector. The following sections introduce the challenges and opportunities of EV batteries from a battery life cycle perspective: battery production, battery use, and battery end-of-life.

Battery production. The future global EV fleet will demand massive amounts of batteries, reaching 1.8-3 terawatt-hour (TWh) of batteries in 2030[6]. This requires the rapid scale-up of battery production capacity and related supply chains, starting from materials extraction and concentration, smelting, leaching, cathode (and other components) production, cell production, to battery pack assembly. Concerns have been raised with regard to various aspects: economically available reserves for battery materials[10]; affordable, secure and sufficient supply of raw materials[11] (especially for lithium, cobalt, nickel); how to minimize carbon emissions related to battery production[12]; and other social and environmental impacts[13].

Battery use. The increasing EV fleet, supported by large-scale battery production, is set to reduce the demand for oil-based fossil fuels that would otherwise be required by ICEVs. EVs also increase net GHG emissions benefit because EVs are 2-4 times more efficient than ICEVs and the electricity supply is decarbonized by the transition to renewables[6]. EVs are expected to lead to a reduction of 3-4.5 million barrels of oil per day that would otherwise have been consumed by light-duty vehicles in 2030[6], depending on EV fleet size. The net reduction of GHG emissions can reach 460-580 million tons (Mt) CO2-Eq in 2030[6], where 280-340 Mt CO2-Eq (generated from EV use due to electricity consumption) are offset by the avoidance of 740-920 Mt CO2-Eq (which would have been emitted from ICEVs).

In addition, EV batteries on the vehicle board can provide energy storage service and economic value for the power system through vehicle-to-grid technology. Vehicle-to-grid charging can be smart to enable dynamic EV charging and load-shifting services to the grid. EVs can also store electricity and deliver it to the grid at peak times when power generation is more expensive[14]. These opportunities rely on standards and market arrangements that allow for dynamic energy pricing and the ability of owners to benefit from the value to the grid (value includes deferred or avoided capital expenditure on additional stationary storage, and power electronic infrastructure, transmission build-out[14]).

Battery end-of-life. Battery useful capacity degrades as being used for EV driving and vehicle-to-grid service (hereafter called battery degradation). Usually, when the remaining battery capacity drops to between 70-80% of the original capacity batteries become unsuitable for use in EVs[15] (hereafter called retired batteries). However, these retired batteries may still have years of useful life in less demanding stationary energy storage applications[16]. These batteries can contribute to grid stability and generate substantial grid-based economic value.

Batteries with extremely poor state-of-health (SoH) are not useful anymore for any applications (hereafter called EoL batteries). Recycling can be applied to EoL batteries to recover valuable battery materials and used them for new battery production (*i.e.*, closed-loop recycling). In theory, closed-loop recycling can reduce the materials-related environmental impacts of EV batteries. The reduction efficiency depends on the input battery chemistry and recycling technology applied. Various recycling technologies are developed and optimized to increase the recycling rates of materials as well as lower the cost of input chemicals and energy[17].

The above points lead to questions with regard to insights that have to be developed on battery demand and associated battery material flows, battery production and related environmental impacts, the grid storage potential of EV battery use, *etc.* In the next section, we discuss analytical methods that can give insights into these aspects, followed by sections that specify research gaps, research questions, and the structure of this thesis.

1.3 Analytical methods to assess challenges and opportunities

Various modeling tools and approaches exist that can help to analyze and understand the challenges and questions discussed in the former section. The research methods include mainly the dynamic material flow analysis and the prospective life cycle assessment. Executing the dynamic material flow analysis and the prospective life cycle assessment methods requires detailed insights into the battery chemistry, chemistry mix, amongst others, battery lifetime, and compositions of batteries, which can be provided via battery technology modeling. Below we describe each method applied in this thesis.

Dynamic material flow analysis. Dynamic material flow analysis (MFA) is a method used to quantify past, current, and future stock and flows of materials used in our society[18,19]. The inflow or in-use stock data of a product, a product lifetime distribution, and product material compositions are essential information for the calculation of dynamic MFA, and they can be extrapolated based on relevant social-economic variables (GDP, population, *etc.*) or summarized based on the social questionnaire. Inflow- or stock-driven dynamic MFA has been used widely to assess the flows of various materials, such as metals[16], plastics[20], rare earth elements[21], *etc*. The applications of dynamic MFA have increased the knowledge basement of materials flows, including both the quantity and quality of materials[16]. The flows of critical battery materials, mainly metals, can be assessed by dynamic MFA[22], combined with scenario analysis of EV fleet and battery chemistry.

Prospective life cycle assessment. Life cycle assessment (LCA) is a tool to assess the current environmental impacts of a product along the life cycle, *i.e.*, from raw materials extraction, via production and use, to end-of-life treatment/recycling[23]. To determine the environmental impacts of emerging technologies, prospective LCA approaches have been proposed by researchers[24]. A key aspect for prospective LCA is how to model the future performance[23] of the foreground technology system (*e.g.*, how to extrapolate a life cycle inventory from pilot to commercial scale[25]) as well as the background system (*e.g.*, taking into account the energy transition[26]). A common way to implement prospective LCA is to combine dynamic emerging foreground technology scenarios[27] (such as battery chemistry change), long-term background scenarios from integrated assessment models[28] (IAMs, such as the energy mix scenarios from REMIND model), and other important changes that are not considered well in IAMs. Prospective LCA methodology can provide a future dynamic perspective in environmental impact assessment, although it faces comparability, data, and uncertainty challenges that should be solved in future research[24]. When performing a prospective LCA for batteries, the changes in battery technology next to other changes in the foreground and background technology systems should be fully considered.

Battery technology modeling. Based on EV type, size, range, and other factors, various lithium-ion battery chemistries have been developed, including lithium iron phosphate battery (LFP), lithium nickel cobalt manganese battery (NCM), and lithium nickel cobalt aluminum battery (NCA). LFP, NCA, and NCM differ in cost, special energy (Wh/kg), and cycle life, as well as in material compositions and production processes. LFP features lower cost and longer cycle life than NCM and NCA, while NCM and NCA show higher special energy than LFP[29]. In the next decade, LFP, NCA, and NCM are expected to dominate the EV market[7]. In the long term, solid-state lithium-based batteries, such as lithium-air and lithium-sulfur batteries[7], or sodium-ion batteries could breakthrough and gain a foothold in the EV market.

Modeling the technical characteristics of different chemistries and the future battery chemistry mix is significant for assessing the challenges and opportunities of battery sustainability. The battery models can provide information on battery material compositions, which can be used as inputs to the dynamic material flow analysis and prospective life cycle assessment to assess the battery sustainability challenges. Also, the battery models can give battery capacity degradation, which is an important input to assessing the battery capacity available for grid storage that represents one key battery sustainability opportunity.

1.4 Research gaps

Although dynamic MFA and prospective LCA methods have been applied to analyse the future impact of EV batteries, these two methods have rarely been combined with battery technology modeling. As indicated above, only such a combination of models can give insight into future material requirements and emissions related to battery production for the global EV market. With this combination of models, we aim to overcome four key research gaps that are only partially researched in the existing literature. Please see the four research gaps in detail in the following sections.

Ⅰ. Future battery material demand. Future demand for raw materials for EV batteries is essential for assessing potential supply risks as well as social and environmental impacts, which in turn is essential strategic information for both industry and policy makers. Studies have quantified the future demand for EV battery materials for specific regions such as Europe[30], the United States[31,32], and China[22], or for specific individual battery materials[33-35]. Weil et al.[36] assess the global material demand for EV batteries and find that shortages for key materials, including lithium and cobalt, can be expected. However, their model does not investigate the influence of battery chemistry developments (*e.g.,* improved NCM chemistries or novel Lithium-Sulphur (Li-S) and Lithium-Air batteries (Li-Air)) as well as alternative fleet and different recycling scenarios. There is hence a major need for considering different EV fleet and battery chemistry scenarios and quantifying the global demand for different battery materials.

Ⅱ. Future cradle-to-gate GHG emissions of battery production per kWh battery capacity. Although EVs have environmental advantages over ICEVs[37-39], the impacts of battery production are still rather uncertain[40-42]. Studies find diverging life cycle impacts of battery production[43-45]. This is due to the use of different data and assumptions of battery performance and compositions[46], geographical scope[47], battery production life cycle inventory (LCI) data[48,49], and environmental impact assessment methodologies[50]. All these factors can lead to questionable conclusions on the magnitude of environmental impacts of battery production. Moreover, changes in environmental impacts of battery production in the next decades are often not taken into account, due to the challenges in estimating futurized background LCI data and modeling future battery production processes. There is hence a need for summarizing the up-to-date battery production LCI data (for different battery chemistries) and building a prospective LCA model that incorporates both the battery production LCI data and futurized background LCI data systematically. The prospective LCA model can then be used to estimate the future life cycle environmental impacts of different battery chemistries.

Ⅲ. Future life cycle GHG emissions of global battery production. Environmental impacts of global battery production[51,52] are normally quantified using battery life cycle assessments and used volumes of batteries[40-42]. We discussed the future life cycle GHG emissions of battery production under II. But the total GHG emissions related to battery production depend on the EV fleet size and battery capacity per vehicle, which will differ between the main EV markets (*e.g.,* US, EU, Asia). Further, the distribution of battery production over regions may change due to regional battery production capacity, resource constraints, and other factors. Therefore, there is a need for developing future (regional) battery demand scenarios incorporating the development of EV fleet size and battery capacity per vehicle, and further quantifying the future GHG emissions of global EV battery production considering the future split of battery production over production regions.

IV. Future global battery capacity available for grid storage. The utilization of EV batteries for grid storage could improve the flexibility of electricity supply, while reducing the capital costs and material-related emissions associated with additional storage and power-electronic infrastructure. However, the total grid storage capacity of EV batteries depends on business models, consumer behaviour (in driving and charging), battery degradation, and more factors[53,54]. Investigating the future grid storage capacity of EV batteries is essential to understand the role EV batteries could play in the renewable energy transition. Previous global-level studies, including those on vehicle-to-grid capacity[55-57] and retired battery capacity[57,58], while informative, rarely consider factors such as: non-linear, empirically-based battery degradation (they often neglect the impact of battery chemistry[59-61]); geographical and/or temporal temperature variance (which impacts battery degradation); and, driving intensity by vehicle type in different countries/regions (which constrains the battery capacity available during the day). These factors determine the technical grid storage capacity. Additionally, consumer participation in the vehicle-to-grid market and in the second-use market impacts the actual grid storage capacity[54], which is significant but rarely quantified. There is hence a need for quantifying the total grid storage capacity of EV batteries including both vehicle-to-grid capacity and second-use capacity, which considers factors of the battery capacity degradation and market participation rates.

1.5 Aims and Research questions

With the aim of closing the above-mentioned research gaps, this thesis integrates the method of dynamic MFA, prospective LCA, and battery technology modeling to an integrated model. The model is used to assess the environmental impacts and co-benefits of EV batteries, and to address the overall research question (RQ): **What are the future environmental challenges and opportunities for automotive lithium-ion batteries from a life cycle perspective?**

To deal with the overall RQ, in relation to the research challenges discussed in section 1.4 we formulate four key sub-RQs (see Fig. 1.1):

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

RQ2: What are future cradle-to-gate GHG emissions per kWh automotive

lithium-ion battery production?

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

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

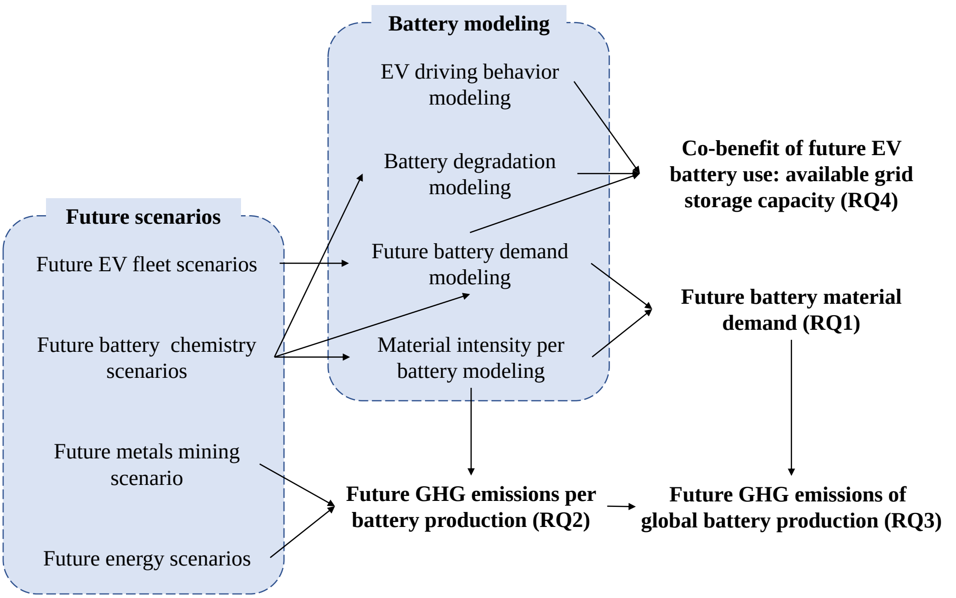

Fig. 1.1: Overview of research methods and models for four research questions, including future scenarios and battery modeling.

1.6 Thesis outline

In relation to the research questions above, this thesis consists of 6 chapters. Chapter 1 presents a general introduction to this thesis. Chapters 2 to 5 answer and discuss the RQs 1 to 4, respectively. Chapter 6 gives a general discussion of this research. In short, the next chapters discuss (see also Fig. 1.1):

Chapter 2 uses a dynamic MFA model that goes beyond previous analyses: including future EV fleet scenarios, future battery chemistry scenarios, and modelling material intensity per battery chemistry type. First, the future EV fleet scenarios cover information on EV technical parameters (range, fuel economy, and motor power) and

EV sales market share of small/mid-size/large BEVs/PHEVs. Second, the future battery chemistry scenarios include information on technical parameters of batteries (capacity in kWh and specific energy in Wh/kg) as well as future battery chemistry mixes. Last but not least, in the dynamic MFA model we incorporate battery material compositions that are modelled based on the technical parameters of both EV and battery. This chapter illuminates the future challenges related to strong demand growth of critical battery materials, such as sustainable supply of raw materials, social and environmental impact of materials production, *etc*. The methods and results of this chapter contribute to the analyses in following chapters 3-5.

Chapter 3 builds a prospective LCA model for battery production. The prospective LCA model incorporates future energy scenarios that indicate (regional) energy mixes and energy-related GHG emissions, in addition to the future metals mining scenarios, *i.e.*, technology changes for the supply of key battery metals. This chapter determines the (future) life cycle battery production GHG emission per kWh battery capacity for different battery chemistries, and gives a contribution analysis by battery components and materials.

Chapter 4 combines the dynamic MFA model in Chapter 2 and the prospective LCA model in Chapter 3 to assess the range of GHG emissions associated with global EV battery production under different scenarios. Sensitivity analysis with regard to key factors (such as closed-loop recycling) is further conducted.

Chapter 5 combines the dynamic MFA model in Chapter 2 (assess future battery stock and EoL batteries), the EV driving behavior model (model EV driving distance and charging behavior), and the battery degradation model (estimate battery capacity over time). This chapter evaluates the future available grid storage capacity - including both vehicle-to-grid capacity and second-use capacity - from EV battery use. Further, this chapter compares "the total available grid storage capacity from EV batteries" with "the demand for short-term storage capacity in an electricity system mainly using renewables".

Chapter 6 answers the RQs, discuss limitations of this work, give recommendations for future research, and provide policy implications of this research.