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Life cycle assessment of electric vehicle batteries and new technologies

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Abstract

Electrification of vehicles has for decades been explored as a possible solution to the problem of climate change. Today, in 2021, the issue is no longer whether the electrification of vehicle fleets ought to happen but rather how it can be achieved with as little environmental impact as possible.

The objective of this thesis is therefore to facilitate the use of life cycle assessment (LCA) for the evaluation and improvement of the environmental performance of electric vehicle traction batteries. The lack of LCA data on several traction battery chemistries and some associated LCA methodological difficulties have been identified as important research gaps. The broader purpose of this thesis is to contribute to sustainable industrial and societal change that involves new technologies.

This thesis examines three research questions related to LCA in new technology introduction: (1) LCA data issues regarding present and future lithium traction battery chemistries. (2) LCA methodological issues regarding present and future lithium traction battery chemistries. (3) Use of LCA in product and production development to advance the introduction of sustainable consumption and production of any new technology.

The results emphasise e.g. to always include the use phase in LCA traction battery studies and to improve battery energy density but not to the detriment of battery internal efficiency. Furthermore, it points to use two abiotic depletion measures to reflect scarce materials in both the short term and the long term. Additionally, it is recommended to calculate the results for all relevant functional units, because it facilitates comparisons and reflection, to choose environmental impact categories for traction batteries from a ranking list, as well as to use chemical risk assessment from a life cycle perspective to complement and develop within-LCA toxicity impact methods. To some extent, the above results are applicable for most development of new technology. A general recommendation for all technology development striving to include LCA is to use screening LCA, chemical risk assessment and idea generation in early phases to help build engagement, competence and data for a full LCA in later phases.

Keywords: Life cycle assessment; LCA; Electric vehicle; Sustainability; Eco-design.

Sammanfattning

Elektrifiering av fordon har i årtionden undersökts som en möjlig lösning på klimatproblemet. Idag, 2021, är frågan inte längre om elektrifiering av fordonsflottor borde ske utan snarare hur det kan uppnås med så liten miljöpåverkan som möjligt.

Syftet med denna avhandling är därför att underlätta användningen av livscykelanalys (LCA) för utvärdering och förbättring av miljöprestanda för elektriska drivbatterier. Bristen på LCA-data för flera batterikemier samt några därtill hörande LCA-metodologiska svårigheter identifierades som viktiga forskningsgap. Det bredare syftet med denna avhandling är att bidra till hållbar industriell och samhällelig förändring som involverar ny teknik.

Denna avhandling undersöker tre forskningsfrågor relaterade till LCA i introduktion av ny teknik: (1) LCA-data om nuvarande och framtida kemier för litiumbatterier. (2) LCA-metodologiska problem med nuvarande och framtida kemier för litiumbatterier. (3) Hur man använder LCA i produkt- och produktionsutveckling för att främja införandet av hållbar konsumtion och produktion av ny teknik i allmänhet.

Resultaten betonar t.ex. att alltid inkludera användningsfasen i LCA-studier av drivlinebatterier och att förbättra batteriets energitäthet, men inte så att det försämrar batteriets interna effektivitet. Dessutom pekar den på att använda två mått för abiotisk resursutarmning för att spegla knappa material på kort sikt och på lång sikt. Det rekommenderas även att beräkna resultaten för alla relevanta funktionella enheter, eftersom det underlättar jämförelser och reflektion, att välja miljöeffektkategorier för drivlinebatterier från en rankinglista, samt att använda kemisk riskbedömning ur ett livscykelperspektiv för att komplettera och utveckla LCA-metoderna för toxicitet. I viss utsträckning är ovanstående rekommendationer tillämpliga för utvecklingen av all ny teknik. En allmän rekommendation för all teknikutveckling som strävar efter att inkludera LCA är att använda screening LCA, kemisk riskbedömning och idégenerering i tidiga faser för att hjälpa till att bygga engagemang, kompetens och data för en fullständig LCA i senare faser.

Preface and acknowledgements

The research behind this thesis started in 2004 in Swerea IVF, which in 2019 was incorporated in RISE Swedish Research Institutes. I would like to thank all my colleagues at Swerea IVF and RISE that have in some way or other assisted me in writing the papers and the thesis, in particular Anna-Karin Jönbrink, Peter Bökmark, Mats Lundin, Elis Carlström, Lisa Schwarz Bour, Jutta Hildenbrand, Sasha Shahbazi, Lars Avellán, Jessica Orlenius, Kristin Fransson, Christina Jönsson and Martin Kurdve, the latter two also acting as assisting supervisors in a very helpful way.

Towards my main supervisor Magnus Wiktorsson, I am very grateful for guiding me through the art of writing a doctoral thesis, thoughtful and thorough reading of the manuscript and lots of very good advice. Many thanks also to my colleague Steffen Schellenberger for illustrating the cover page. Finally I would like to thank my family and friends for their support and for being there for me.

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In part, this doctoral thesis can be considered a continuation of my licentiate thesis (Mats Zackrisson 2009). Therefore, some of the material published in this doctoral thesis has already been published in my licentiate thesis, for example, the stepwise EPD paper (A) (see below).

Publications - Appended papers

This thesis is based on the following papers, presented here in chronological order, and referred to in the text by their names in bold below and their alphabetic designation:

Paper A. The stepwise EPD paper. Zackrisson, M., Rocha, C., Christiansen, K., & Jarnehammar, A. (2008). Stepwise environmental product declarations: ten SME case studies. Journal of Cleaner Production, 16(17), 1872-1886.

Contribution in the stepwise EPD paper: the research for this paper was carried out in the EU financed stepwise EPD project. The author coordinated this project that involved 18 partners. The author managed three of the case studies and drafted all the text for the paper, receiving and integrating comments and suggestions from the co-authors.

Paper B. The lithium-ion battery paper. Zackrisson, M., Avellán, L., & Orlenius, J. (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles - Critical issues. Journal of Cleaner Production, 18(15), 1517–1527.

Contribution in the lithium-ion battery paper: the author coordinated and conducted the LCA and drafted all the text for the paper. The co-authors and research colleagues at IVF took part in defining the goal and scope, data collection, modelling, interpretation and commenting on the paper.

Paper C. The lithium-air battery paper. Zackrisson, M., Fransson, K., Hildenbrand, J., Lampic, G., & O´Dwyer, C. (2016). Life cycle assessment of lithium-air battery cells. Journal of Cleaner Production, 135, 299–311.

Contribution in the lithium-air battery paper: the research for the paper was carried out in the EU project STable high-capacity lithium-Air Batteries with Long cycle life for Electric Cars (STABLE). The author coordinated and conducted the LCA and drafted all the text for the paper. The co-authors and research partners took part in defining the goal and scope, data collection, modelling, interpretation and commenting on the paper.

Paper D. The lithium-metal battery paper. Berg, H., Zackrisson, M. (2019). Perspectives on environmental and cost assessment of lithium-metal negative electrodes in electric vehicle traction batteries. Journal of Power Sources, 415 (September 2018), 83–90.

Contribution in the lithium-metal paper: The research behind the paper was carried out as part of the national technology development project TriLi – Longlife lithium electrodes for EV and HEV batteries. The author coordinated and conducted the LCA, drafted all the LCA-related text in the paper and assisted the main author in accommodating comments and suggestions on the paper.

Paper E. The structural battery paper. Zackrisson, M., Jönsson, C., Johannisson, W., Fransson, K., Posner, S., Zenkert, D., Lindbergh, G., (2019). Prospective Life Cycle Assessment of a Structural Battery. Sustainability 11(20), 5679.

Contribution in the structural battery paper: the author coordinated and conducted the LCA, drafted all the LCA-related text in the paper and coordinated the inputs from the co-authors.

Additional relevant publications in reverse chronological order

Hu, Xianfeng, Astrid Robles, Tommy Vikstrom, Pekka Väänänen, Mats Zackrisson, and Guozhu Ye. 2021. “A Novel Process on the Recovery of Zinc and Manganese from Spent Alkaline and Zinc-Carbon Batteries.” Journal of Hazardous Materials 411 (2021) 124928.

Kurdve, M., Zackrisson, M., Johansson, M. I., Ebin, B., & Harlin, U. (2019). Considerations when Modelling EV Battery Circularity Systems. Batteries 2019, 5, 40.

Shahbazi, S., Kurdve, M., Zackrisson, M., Jönsson, C., & Kristinsdottir, A. R. (2019). Comparison of Four Environmental Assessment Tools in Swedish Manufacturing: A Case Study. Sustainability 2019, 11, 2173.

Zackrisson, M., & Hildenbrand, J. (2018). Including grid storage to increase the use of renewables – the case of an island in the North Sea. CARE Innovation. Vienna.

Zackrisson, M., Kurdve, M., Shahbazi, S., Wiktorsson, M., Winroth, M., Almström, P., Myrelid, A. (2017). Sustainability performance indicators at shop floor level in large manufacturing companies. Procedia CIRP, 61, 457–462. The 24th CIRP Conference on Life Cycle Engineering.

Kurdve, M., Zackrisson, M., Wiktorsson, M., & Harlin, U. (2014). Lean and green integration into production system models – experiences from Swedish industry. *Journal of Cleaner Production*, *85*, 180–190.

Zackrisson, M., & Boss, A. (2013). Recycling production cable waste - Environmental and economic implications. In Book of proceedings: Wastes, Solutions, Treatments and Opportunities. 2nd International Conference, Braga, Portugal, 11-13 September 2013, 601-606.

Zackrisson, M. (2009). Product orientation of environmental work: barriers & incentives. Licentiate Thesis. Department of Machine Design, Royal Institute of Technology, Stockholm.

Zackrisson, M. (2005). Environmental aspects when manufacturing products mainly out of metals and/or polymers. Journal of Cleaner Production, 13(1), 43–49.

List of acronyms and abbreviations

BEV	Battery electric vehicle
BMS	Battery management system
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
CML	Institute of Environmental Sciences (CML), which is an institute of the Faculty of Science of Leiden University in the Netherlands
CRA	Chemical risk assessment
EPD	Environmental product declaration
ERV	Energy reduction value
EV	Electric vehicle
HEV	Hybrid electric vehicle
ICV	Internal combustion vehicle
ILCD	International reference life cycle data system
ISO	International organization for standardization
kg	Kilogram
kWh	Kilowatt-hour, 1 kWh = 3.6 MJ
LCIA	Life cycle impact assessment
LCA	Life cycle assessment
LFP	Lithium-iron-phosphate ($LiFePO_4$) battery cell
$LiFePO_4$	Lithium-iron-phosphate (LFP) battery cell
LIB	Lithium-ion battery
LMB	Lithium-metal batteries
MJ	Megajoule
MSDS	Material safety data sheets
MWh	Megawatt-hour
NCA	Lithium-nickel-cobalt-aluminium-oxide battery cell
NEDC	New European driving cycle
NMC	Lithium-nickel-manganese-cobalt-oxide battery cell
NMP	N-methyl-2-pyrrolidone
PCR	Product category rules
PEFCR	Product environmental footprint category rules
PHEV	Plug-in hybrid electric vehicle
PO_4	Phosphorus
PVDF	Polyvinylidenfluoride

RQ	Research question
SCP	Sustainable consumption and production
SME	Small and medium-sized enterprise
TEGDME	Tetraethylene glycol dimethyl ether
TRL	Technology readiness level
WLTC	Worldwide harmonized light-duty vehicles test procedure

How to read this thesis

For those mostly interested in electric vehicles and their environmental impact, it is recommended that they read Chapters 1, 5 and 6 first, and of course, battery-related papers B to E. Chapter 2 describes some key concepts in the LCA methodology, while Chapters 3 and 4 address how this research was carried out.

Content

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Part II Appended papers

Paper A. The stepwise EPD paper

Paper B. The lithium-ion battery paper

Paper C. The lithium-air battery paper

Paper D. The lithium-metal battery paper

Paper E. The structural battery paper

1 Introduction

The main research of this thesis began in 2009. At that time, the electrification of vehicles was still in its infancy and was not clearly seen as a partial solution to the problem of climate change. Today, in 2021, the issue is no longer whether the electrification of vehicle fleets will happen but rather how it can be achieved with as little environmental impact as possible.

The concept of sustainable development, developed by the Brundtland Commission (World Commission on Environment and Development 1987), urges us not to endanger the needs of future generations while satisfying our own needs. Electric vehicles (EVs) offer tremendous advantages over internal combustion vehicles (ICVs) in that they do not have any tailpipe combustion emissions. In addition, with carbon-lean electricity generation, EVs have much less of an impact on the climate than do ICVs during their whole life cycle (Muratori et al. 2021)(Helmers and Weiss 2017)(Hoekstra 2019)(Temporelli et al. 2020)(Hill et al. 2019)(Niklas Hill, Samantha Morgan-Price 2020), as can be seen in Figure 1.

There are other solutions to the climate impact of transportation like biofuels, hydrogen and fuel cells. The focus on traction batteries in this thesis does not imply any ranking of such solutions; they are likely all needed to solve the problem of climate change, both separately and in combination.

1.1 Electromobility

Electromobility can be defined as a road transport system based on vehicles that are powered by electricity (Grauers et al. 2017). To set the research questions in context, distinct aspects of electromobility and traction battery technology are briefly presented in the following.

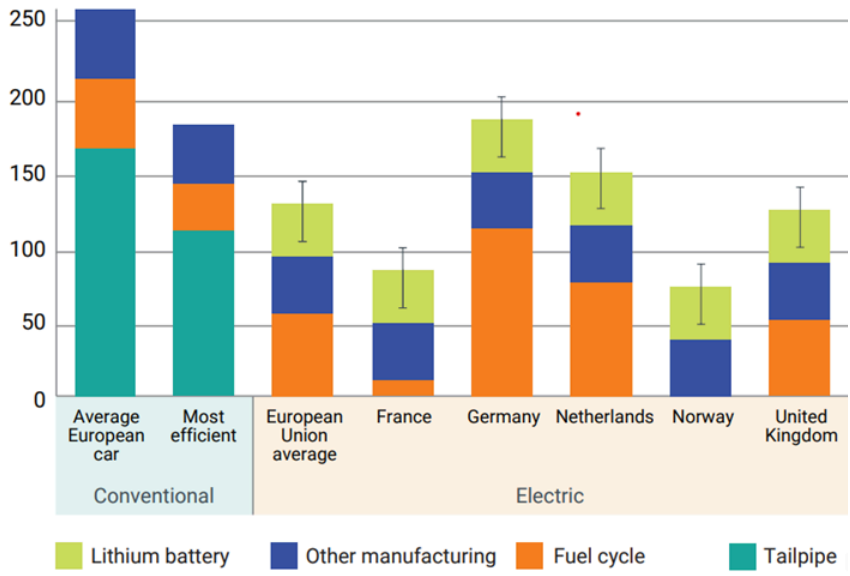

Figure 1: Vehicle CO_2 emissions in grams per kilometre for conventional combustion vehicles compared to electric vehicles over a 150,000-km life cycle (adapted from UNEP (2020)).

1.1.1 Legislative and policy drivers for electromobility

Legislation drives the development of electromobility to a large extent. European Commission Regulation 443/2009 imposes large financial penalties on vehicle producers that do not comply with the European passenger car fleet average emission standards of 95 g of CO_2-eq/km by 2021 (European Commission 2009). In 2021, regulation 2019/631 (European Commission 2019) will take over and gradually tighten these limits. It also mandates the Commission to evaluate the possibility of developing a methodology for the assessment and reporting of full vehicle life-cycle CO_2 emissions by 2023. While not stipulating electromobility or electrification, vehicle producers in the European market have, at the moment, no other technology to apply to comply with these regulations without bringing about the risk of being financially forced out of the market. For traction batteries, a carbon footprint declaration is suggested to become mandatory from 1 July 2024 under the new EU Sustainable Batteries Regulation (European Commission 2020b). Other large markets, like California, together with nine other states in the US and China, also have forceful legislative drivers towards electrification (Shikha Rokadiya 2020) (Grauers et al. 2017).

It has been identified as very negative from a climate perspective, that the current 2021 market logic (which dictates that customers are willing to pay extra for power (Kristiansson 2020)) favours the building of powerful but heavy battery electric vehicles (BEVs) or heavy parallel plug-in hybrid electric vehicles (PHEVs), which will not avoid as much climate impact (Ambrose et al. 2020) as will smaller, lighter BEVs or BEVs with range extenders. The latter, also referred to as serial PHEVs, has been identified as the current best choice in terms of low climate impact (Stark et al. 2018) but is no longer available on the market.

1.1.2 The range and cost dilemma

Range anxiety and the high cost of traction batteries drive battery technology development, resulting in many different battery chemistries, presently with a focus on cobalt chemistries because of their high energy density. Decreasing the weight of a car's body decreases its electricity consumption; thus, this is an additional strategy to alleviate the range and cost dilemma. The plethora of chemistries is making it more difficult to keep pace with the development of suitable recycling technologies (Kurdve et al. 2019) (Skeete et al. 2020). The development of credible life cycle assessment (LCA) and inventory data for all new chemistries is also a daunting task. This lack of LCA data for several traction battery chemistries is the main research gap taken on by this thesis.

1.1.3 Sustainable mobility

As mentioned above, electromobility will hardly accomplish sustainable mobility on its own. To accomplish sustainable mobility, low-mobility societies and collective transport 2.0 are also needed (Holden et al. 2020). Another way to view the two narratives of electromobility and low-mobility societies is as three major innovations that have disruptive potential: electrification, shared mobility and automation (Sprei 2018). Sprei pointed to the additional disruptive element of an electric vehicle (EV) in that it can connect to the grid and thus facilitate more decentralized power generation from renewable sources, like wind and sun (Mierlo et al. 2021).

It is ultimately people who decide when and where to travel, to take the bus or ride a bicycle, to buy a car or not and who select politicians who subsequently design policies (Holden et al. 2020). This is one good reason to increase the engagement of people in, for example, LCA studies of vehicle traction batteries. In conclusion, there is a need for further examination of how to engage people or citizens in the evaluation of how electromobility leads to sustainable mobility.

1.1.4 Traction battery technology

Lithium-ion cell production takes place in increasingly larger facilities; e.g., Tesla Gigafactory 1 in the USA has a planned Li-ion battery cell annual production capacity of 35 GWh, and Northvolt Ett, under construction in Skellefteå, Sweden, intends to reach a yearly production capacity of 32 GWh (Kurland 2020). A schematic layout of cell production is shown in Figure 2.

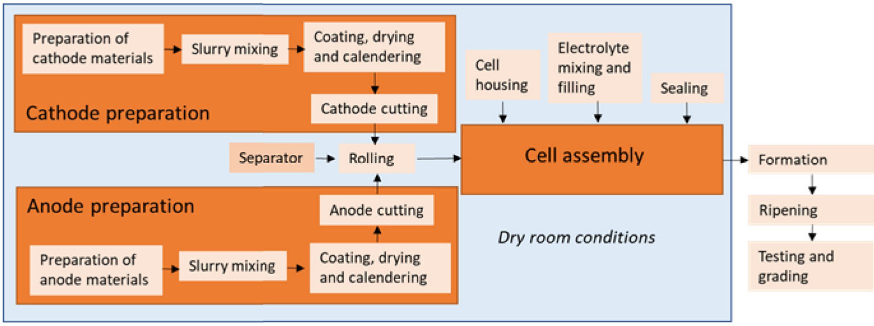

Figure 2: Production of LIB cells (adapted from Northvolt (2017)).

A large part of the production process must take place in dry room conditions. Along with the drying of the cathode and anode pastes, the maintaining of dry room conditions leads to relatively high energy use for cell manufacturing (Dai et al. 2019). The crucial formation of the solid electrolyte interphase at the negative electrode, by cycling the cells, is another major driver of electricity use, even if some of this energy can be reused (Kurland 2020).

A vehicle traction battery system consists of several hundred or even thousands of cells (Helena Berg 2015) contained, protected and connected in a box that includes thermal and battery management mechanisms (see Figure 3). Typically, only 50% of a traction battery system, by weight, consists of battery cells, and the rest is made up of housing, cooling, connections and electronics. Electronics make up approximately 5% of the weight of the system. Housing, cooling and connections are largely integrated and, together, make up the remaining 45% (Ellingsen et al. 2013). From an LCA perspective, it is important to remember that half the weight of a traction battery system is not battery cells but rather aluminium, steel, copper, different plastics and different electronic circuitries. Thus, any energy density at the cell level is approximately halved at the battery system level. The efficiency at the pack level ultimately determines the crucial vehicle range.

Figure 3: Lithium-ion traction battery pack (The News Wheel 2014).

1.2 Environmental and social aspects of traction batteries

The life cycle impacts of electric vehicles in general and their batteries in particular have been contested. Two aspects or impacts related to the sustainability of battery production have come into focus: energy use for producing the battery and the associated carbon footprint and the use of scarce metals sometimes mined under very adverse working conditions from a social perspective (low wages) and regarding occupational hazards. The toxicity related to the chemicals and materials used has not attracted as much attention but will nevertheless be scrutinized in this thesis.

1.2.1 Energy use for battery production and its carbon footprint

The energy requirements for cell manufacturing and battery assembly can vary largely, mainly depending on 1) which share of the assembly steps require dry room/clean room conditions and 2) assembly plant throughput. Part of the variance may be due to misinterpretations. Another complicating factor is that the openly available energy data have been retrieved/calculated/estimated in a number of different ways, united only by their indirectness. Very few studies can claim direct readings of electricity meters or energy invoices. In conclusion, there is a need for the further examination of energy use for producing lithium-ion traction batteries.

1.2.2 Use of scarce metals considering working conditions

Given the success of lithium chemistry as traction battery cell chemistry, the lithium supply has been intensively investigated. Most studies have pointed to the challenges of increasing capacity to produce lithium carbonate, while the reserves of lithium should be sufficient (Kushnir and Sandén 2012)(Olivetti et al. 2017)(Ambrose and Kendall 2020). According to Vikström et al. (2013), the demand for lithium is likely to exceed production capacity by 2021. Cobalt is judged as being an even more problematic resource than lithium in the context of lithium batteries (IEA 2018)(Helbig et al. 2018).

One response to these supply constraints is to develop recycling technology (Larouche et al. 2020) and circular business models (Mossali et al. 2020) for traction batteries. Several studies (Kurdve et al. 2019)(Skeete et al. 2020) have pointed to the importance of building agile reuse, remanufacturing, and recycling (3R) systems for traction batteries that can respond to growing volume, changing chemistries, various secondary uses, and legislative requirements.

The national supply of carbon-lean electricity is a comparative advantage for the metallurgy and battery cell production industries in Sweden. The Swedish high voltage average electricity mix has a climate impact of 42 grams of CO_2-eq/kWh. The high-voltage Western European or global average electricity mix has a climate impact that is ten times higher than that of Sweden (Wernet et al. 2016).

Another solution to this supply constraint is the use of alternative cell chemistries. Here, LCA can help with the environmental evaluation of novel chemistries and materials. However, it is then important that LCA can correctly measure the abiotic depletion potential of different materials. In conclusion, there is a need to ensure that resource constraints are correctly measured in LCA.

1.2.3 Chemical risks

It is questionable whether characterization factors for LCA toxicity impact cover the materials present in many battery chemistries in an adequate way. For example, among the recommended characterization factors in the USEtox scientific consensus model for the characterization of the human and ecotoxicological impacts of chemicals (Rosenbaum et al. 2011), there are no characterization factors for metals. In conclusion, there is a need both to improve the characterization factors for LCA toxicity impact and to study the risk of emissions of toxic substances and reaction products throughout the life cycle of traction batteries.

1.3 Sustainable products, production and consumption

In this thesis, the term sustainable consumption and production (SCP) is used to emphasize that industries hold the key to SCP, as they develop and produce products and thereby influence both upstream and downstream environmental factors, not only what happens inside their own factory gates but also what happens throughout the whole life cycle, including downstream suppliers, product development, and the use and recycling of the product. Shahbazi et al. (2019) acknowledged the importance of LCA as one of several important tools for industry in their sustainability work. The role of LCA in new technology introduction, to identify environmental hotspots and focus improvement work on what is most important, is a common theme in this thesis and in all the appended papers.

1.3.1 Life cycle assessment and its role

Life cycle assessment (LCA) is a system analysis tool that models the relationships among the social system, the natural system and the technical system (Baumann and Tillman 2004). The LCA procedure is standardized in ISO 14044 (ISO 2006c).

LCA is, to an extent, already considered the best quantitative environmental assessment tool. Numerous policy papers and political initiatives have advocated and even prescribed the use of life cycle assessment, such as the Integrated Product Policy (European Commission

2003), the Directive for Energy-Using Products (EC 2005) and the proposed Action Plan on Sustainable Consumption and Production and Sustainable Industrial Policy (European Commission 2008a). As described in Chapter 1.1.1, by 2023, it may become legally mandatory to report vehicle life cycle CO_2 emissions in addition to tailpipe CO_2 emissions.

LCA also plays a role in evaluating and justifying the current electrification. Numerous LCAs have compared the life cycle emissions of internal combustion vehicles (ICVs) with those of electric vehicles (EVs), for example (Notter et al. 2010)(Yu et al. 2018)(Helmers and Weiss 2017)(Hoekstra 2019)(Temporelli et al. 2020). From a climate perspective, a common learning is that EVs need relatively carbon-lean electricity to have less of a climate impact compared to ICVs.

LCA has also put focus on the energy intensiveness of battery cell production; see Chapter 1.2.1. The second use of traction batteries in stationary applications is a way to prolong the useful life and distribute the environmental production footprint on more delivered kilowatt hours or other services provided by the battery pack (Yang et al. 2020; Zackrisson and Hildenbrand 2018). Here, LCA is needed to evaluate whether the extra inputs needed for refurbishment cancel out the potential improvement of increased utilization.

1.3.2 LCA of traction batteries

There are several guidelines for LCA involving traction batteries, including the following:

1. Guidelines for the LCA of electric vehicles by Andrea Del Duce et al. (2013)
2. LCA guidelines for electric vehicles by Loon et al. (2018)
3. PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications (Recharge 2018)
4. Preparatory Study on Ecodesign and Energy labelling of Batteries (Lam et al. 2019)
5. Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA - Interim Report (Hill et al. 2020)

The recommendations for and use of the functional unit, the reference unit to be used, differ across guidelines (Tolomeo et al. 2020)(Dolganova et al. 2020). A natural dividing line is whether the guidelines concern vehicles, like numbers 1, 2 and 5 above, or batteries for vehicles and other applications, such as numbers 3 and 4 above. While guidelines 1, 2 and 5 agree that vehicle or passenger kilometres is a suitable reference flow, numbers 3 and 4 recommend reporting the environmental burdens per kWh of the total energy delivered over the service life. Since many studies have reported environmental burdens per nominal battery capacity, i.e., per kWh battery capacity, there is an obvious risk of misunderstanding and one possible cause for the results in the research field to appear divergent and inconsistent. Thus, the issue of suitable functional units for traction battery studies needs further examination.

1.4 Objective and research questions

The objective of this thesis and the research behind it is to facilitate the use of life cycle assessment (LCA) for evaluating and improving the environmental performance of electric vehicle traction batteries. The lack of LCA data for several traction battery chemistries and some associated LCA methodological difficulties are identified as the main research gaps; thus, this thesis and the papers behind it aim to make available inventory data for present and future battery chemistries, highlighting the critical parameters and methodological issues.

The broader purpose of this thesis is to contribute to industrial and societal change. Considering the entire life cycle while developing and industrializing products is a prerequisite for sustainable development. The electrification of vehicles is, from that perspective, used as an example, where sustainable production rises in importance and to show how the use of LCA can contribute to sustainable change. To clarify how LCA can be used to improve the design and production of traction batteries, research questions (RQ) 1 and 2 focus on the data and methodology for LCA of traction batteries:

1. What are the significant data issues related to the LCA of present and future lithium traction battery chemistries? Significant data issues refer to both which data are significant for the total life cycle results, i.e., the hotspots, and which specific data are missing or show large variability.

2. What are the significant methodological issues related to the LCA of present and future lithium traction battery chemistries? Methodological issues refer to the process or way of carrying out LCA. There is an overlap between RQ1 and RQ2 in that the lack of data (RQ1) disqualifies certain methods (RQ2) and makes other methods (RQ2) more suitable.

Research questions 1 and 2, combined, explore how to perform an LCA of electric vehicle traction batteries. To contribute to a sustainable introduction of new technology in general, the external validity of the lessons learned (about how to perform an LCA of electric vehicle traction batteries) will be scrutinized and discussed to answer research question:

3. How can LCA be used in product and production development to advance the introduction of the sustainable consumption and production of any new technology?

1.5 Limitations

Each paper in this thesis is connected to a specific project with specific limitations in terms of scope and budget, which are described in Chapter 4. These same limitations apply to the exploration of the research questions. As mentioned above, the research gap identified is the lack of LCA data for several traction battery chemistries and some methodological difficulties associated with the LCA of traction batteries. The appended papers fill some of these gaps for the following chemistry types: lithium iron phosphate ($LiFePO_4$ or LFP), with water as the solvent, lithium air, lithium with a metal anode and structural LFP chemistry. To a certain extent, lithium nickel manganese cobalt (NMC) oxide and lithium nickel cobalt aluminium (NCA) oxide chemistries are also included because they have been used as benchmarks for lithium with metal anodes. All other traction battery cell chemistries are not included. A bill of materials is only given for one cell type (pouch, prismatic or cylindrical). Calculations are generally carried out with two different electricity mixes: Western European and Swedish, representing today’s global average and the future global average. The recycling phase is not included at all in the first studies due to a complete lack of data and is only roughly approximated in the later studies.

2 Background and theoretical foundation

Concepts like sustainable consumption and production, the circular economy and environmental management systems, like ISO 14001, require the use of LCA to assess and prioritize the proposed solutions to avoid problem shifting. Life cycle assessment (LCA) is used in all the papers in this thesis and is thus its main theoretical foundation. LCA applied to technology in the early stages of development, prospective LCA, calls on special techniques for data gathering and uncertainty assessment.

2.1 Sustainable products, production and consumption and circular economy

The 2015 version of the ISO 14001 standard for environmental management (ISO/TC207/SC1 2015) acknowledges, contrary to previous versions, the need for industrial companies to account for the whole life cycle of the products they produce. According to the United Nations Environmental Programme, UNEP (2010), sustainable consumption and production (SCP) concerns doing more and better with less as well as decoupling economic growth from environmental degradation, increasing resource efficiency and promoting sustainable lifestyles. Sustainable consumption and production refers to "*the use of services and related products, which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product so as not to jeopardize the needs of future generations*" (UNEP 2010). The long-awaited (Mats Zackrisson 2009) inclusion of the life cycle perspective in the environmental management standard, ISO 14001, much used by industries, aligns industries' practical environmental work with the higher-level sustainability concept. In this thesis, the term sustainable consumption and production (SCP) is used to emphasize the life cycle perspective; i.e., we are concerned not only with what is inside the factory gates but also with the whole life cycle, including upstream suppliers, product development, and the use and recycling of the product. Moving the problem outside factory gates and/or to another country is not a solution. The whole life cycle of the product must be considered, and for the evaluation of environmental aspects, LCA is needed.

The circular economy is another popular concept often defined as an "*economy that is restorative and regenerative by intention and design*" (Ellen MacArthur Foundation 2013). Geissdoerfer et al. (2017) investigated the relation between the circular economy (CE) and sustainability and the main similarities and differences between these two concepts to provide conceptual clarity. Geissdoerfer et al. (2017) defined: "*the circular economy as a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling*", and "*sustainability as the balanced integration of economic performance, social inclusiveness, and environmental resilience to the benefit of current and future generations.*" Even though industry is not present in these definitions, it has an undisputed central and leading role in the quest for both a circular economy and sustainability. A recent study by Greim et al. (2020) concluded that the achievement of a balanced lithium supply and demand throughout this century depends on the presence of well-established recycling systems for lithium and transportation services with lower lithium intensity. Similar to sustainable consumption and production, industries can use LCA to evaluate which circular economy solution, such as repair, reuse, or remanufacturing, is optimal in each specific case. This aligns with the objective of this thesis to further the sustainable development of any new technology through the use of LCA.

2.2 Life cycle assessment

Life cycle assessment (LCA) was briefly introduced in Chapter 1.3.1. LCA is part of a family of environmental system analysis tools including material flow analysis, ecological risk assessment, environmental impact assessment and cost-benefit analysis (Baumann and Tillman 2004). ISO 14040 and ISO 14044 Environmental Management - Life Cycle Assessment – Principles and Framework (ISO 14040, 2006b) and Requirements and Guidelines (ISO 14044, 2006c), the cornerstone standards for how to perform LCA, describe its four stages: goal and scope definition, inventory, environmental impact assessment and interpretation; see Figure 4. All stages, except the one for environmental impact assessment, are considered mandatory. The stages are repeated in an iterative way that gradually refines the assessment. In the following, these four key parts of LCA will be described briefly, followed by introductions to comparative assertions, critical review, attributional and consequential LCA, simplified LCA, prospective LCA and uncertainties in LCA.

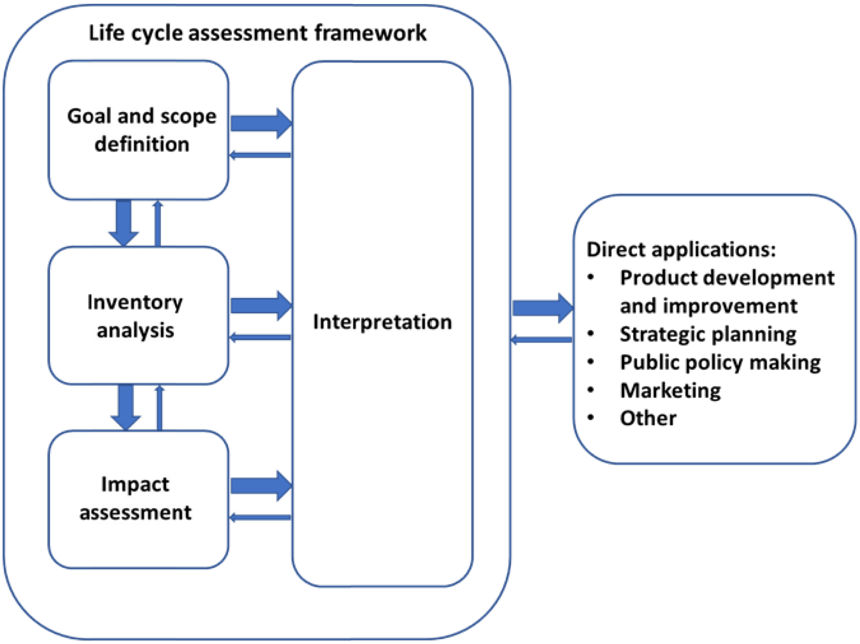

Figure 4: The four stages of life cycle assessment (adapted from ISO 14040 (2006b)).

2.2.1 Goal and scope definition

Defining the goal of the LCA requires describing its intended application, the reasons or driving forces behind carrying out the study and the intended audience. Whether or not the results are intended to be used in comparative assertions for public use should also be included in the goal definition. Defining the scope involves describing the processes to be included in the product system to be studied, as well as defining the service provided by the product system and the associated functional unit. Furthermore, allocation procedures, i.e., how to partition input or output flows between different product systems, environmental impact categories including value choices, data requirements, critical assumptions and limitations, data quality requirements, critical review and report format are considered during the definition of goal and scope, or scoping stage. Usually, at least some of the issues addressed during the scoping stage must be revisited later.

The use of a functional unit, defined in ISO 14044 (2006c) as the quantified performance of a product system for use as a reference unit, underlines the relative characteristic of LCA; it is a tool that aims to handle comparisons between different products performing similar, but rarely the same, functions. For some products, it is relatively easy to find a representative functional unit, e.g., litre refrigerated volume for refrigerators. For other products, like traction batteries, it can be much more difficult, thereby complicating comparisons between studies and ultimately limiting the usefulness of individual datasets. As concluded in Chapter 1.3.2, there is a need for the further examination of the functional unit for traction battery LCA.

2.2.2 Inventory analysis

During the life cycle inventory analysis, data relating to physical flows across system boundaries are collected, validated and normalized to the reference flow of the functional unit. Process flow diagrams including the unit processes belonging to the studied product system are often used to organize the data collection process and obtain an overview of the life cycle (see Figure 5). All inputs and outputs of the product system are compiled in what is often called an ecoprofile, which can consist of hundreds of different emissions and resources.

Many LCA guidelines (but not ISO 14044) distinguish between foreground and background systems and processes. Frischknecht (1998), who was one of the first to use the foreground/background concept, defined it as follows: *"the foreground system consists of processes which are under the control of the decision-maker for which an LCA is carried out. The background system consists of processes on which no or, at best, indirect influence may be exercised by the decision-maker for which an LCA is carried out."* It follows that the data collection techniques used for the foreground and background data can differ. Typically, database data are used for the background system if available. All inputs (resources) and outputs (emissions) of the product system make up the life cycle inventory

(LCI), which usually includes a very long list of substances. Due to the obvious difficulty of interpreting such a list, the life cycle environmental impact assessment stage is, though not obligatory, almost always performed.

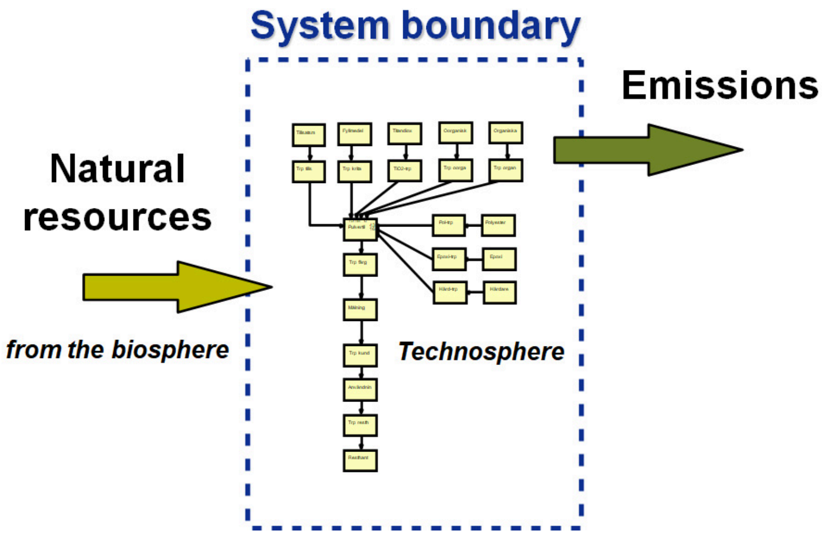

Figure 5: Life cycle inventory analysis involves accounting for physical flows across a product's system boundary.

2.2.3 Impact assessment

Life cycle (environmental) impact assessment (LCIA) facilitates interpretation by aggregating the life cycle inventory. LCIA is established as a fully automated LCA software process of matching input and output substances with the environmental impact characterization factors of the chosen impact categories. An important factor to keep in mind is that the lack of a substance in the life cycle inventory (LCI), the lack of a characterization factor in the used EIA method, or a mismatch in substance names will all result in zero potential impact (Roos 2016). Calculating the characterization factors involves the development and use of models for environmental fate, impact pathways and cause-effect relations (Roos 2016).

Commercial LCA software, like SimaPro (About SimaPro 2021) or Gabi (Gabi Software 2021), contains many different LCIA methods, some addressing single issues, typically for water, energy and toxicity, but most of them containing several impact categories. The International Reference

Life Cycle Data System (ILCD) handbook (JRC 2011) and the Guidance for the Development of Product Environmental Footprint Category Rules (European Commission 2017) provide recommendations on which LCIA methods to use. It should be pointed out that a specific LCIA method is not necessarily implemented exactly the same in all software, which of course is problematic and can require updating by the LCA practitioner. Furthermore, for traction batteries, it is questionable whether resource indicators and toxicity indicators adequately cover the materials present in many battery chemistries. For example, while the interim characterization factors in USEtox include associated factors for some metals, there is still no characterization factor for lithium (UNEP/SETAC 2018). There is a consensus that metals are not well modelled in LCA (Hauschild et al. 2011).

Furthermore, the chemical risks associated with the liquid electrolyte (Lebedeva et al. 2019) in today's lithium-ion batteries are rarely, if ever, modelled in LCAs. The same goes for fluorine containing polyvinylidenfluoride PVDF or $(C_2H_2F_2)_n$, often used as a binder in cathodes. The available LCA emission and impact models for all these toxic chemicals and their possible reaction products are limited to the production phase of the chemicals. As concluded in Chapters 1.2.2 and 1.2.3, there is a need for a further examination of how resources and toxicity are assessed in traction battery LCA.

2.2.4 Interpretation

Life cycle interpretation involves the evaluation of the appropriateness of system boundaries, the functional unit and the data requirements in light of the calculated results and the preliminary conclusions drawn, i.e., revisiting the issues from the initial goal and scope definition stage, but now with added knowledge. To draw final conclusions, the commissioner's team must be involved in part of the interpretation. The outputs of the interpretation phase are the conclusions, limitations and recommendations of the LCA. Writing a scientific article about the LCA and subjecting it to third-party review can be considered yet another iteration of the interpretation.

2.2.5 Comparative assertions

The requirements imposed by the ISO standard on LCA studies involving comparative assertions intended for the public are quite exhaustive. The strict requirements accentuate that LCA is a tool that aims to handle comparisons between different products. ISO 14044 (ISO 2006c) defines a comparative assertion as an *“environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function”*. The requirements for studies intended for public comparative assertions include, among others, the use of a panel of interested parties to conduct a critical review of such studies. This critical review should cover issues like the availability of a sufficiently comprehensive set of environmental impact category indicators that are scientifically and technically valid and internationally accepted.

Environmental product declarations (EPDs), which are often intended for marketing purposes, have similar requirements of the involvement of interested parties in elaborating product category rules (PCRs) for each product (ISO 2006a) and the verification (critical review) of the LCA and the EPD by an independent external party.

Weighting, as part of an impact assessment, i.e., adding up different environmental impacts through the use of weighting factors, is explicitly forbidden for comparative assertions. Comparisons across impact categories are not considered scientifically correct. A comparison should be done category indicator by category indicator, making it more difficult to distinguish one product as environmentally superior to another product since the “winning” product must exhibit the least environmental impact in all used impact categories.

2.2.6 Critical review

A critical review is defined by ISO 14044 (ISO 2006c) as a process ensuring consistency between an LCA and the principles and requirements of the said standard. A critical review may be carried out by an internal or external expert or by a panel of interested parties. Whether and how to conduct a critical review, the type of critical review, and who conducts the review and his/her level of expertise should be defined during the goal and scope definition stage according to ISO 14044 (ISO 2006c). As mentioned above, a critical review is mandatory in some LCA applications. It is, however, considered good practice to always have some form of critical review in all LCA work. The use of an internal but independent expert is often a well-invested resource to check assumptions, data and value choices and increase the quality of any LCA study. The verification of an LCA-based environmental product declaration (EPD), according to ISO 14025 (ISO 2006a), involves data checking to a larger extent than does a critical review of an LCA, according to ISO 14044 (ISO 2006c), which is more focused on the LCA procedure.

2.2.7 Methodological choices

As a consensus document and general framework, ISO 14044 (ISO 2006c) steers around some of the more difficult methodological choices in LCA (Baumann and Tillman 2004). One such issue is whether one should use attributional LCA or consequential LCA. According to Ekvall et al. (2020), the attributional LCA methodology aims to identify the share of the global activities and their environmental burdens that belong to a product, whereas consequential LCA methodology seeks to identify how global burdens are affected by the production and use of the product investigated. Attributional LCA is used by most, if not all, environmental product declaration (EPD) programmes and is characterized by the use of specific or average data (not marginal data) and the solving of allocation problems by allocation (not system expansion and avoided emissions)(EPD International AB 2020). Furthermore, attributional LCA supports the concept of modularity since each product's environmental burden is a share of the total environmental burden. Thus, lower-levels LCAs can be used to build higher-level LCAs. For example, EPDs on vehicle components can be used to build an EPD for a complete vehicle. It should be pointed out that both consequential and attributional modelling can be used in prospective studies, as described in the next Chapter (Arvidsson et al. 2017).

Rebitzer et al. (2004) discussed the need for simplified LCA, especially in the context of SMEs, to keep costs low. Gradin and Björklund (2021) identified ten categories of simplification, of which several are related to inventory data. In many LCA studies, typically, only data from one's own manufacturing process are site-specific. The remaining data are generic, i.e., they are drawn from existing LCA databases and represent average process technology for a country or region. This kind of simplification, denoted as screening LCA below, is, for example, allowed in EPDs under the conditions given in the relevant product category rules and constitutes a major way of making LCA and EPDs affordable. Compare also with the above description of foreground and background systems.

2.2.8 Prospective LCA

Arvidsson et al. (2017) suggested that *"an LCA is prospective when the (emerging) technology studied is in an early phase of development (e.g., small-scale production), but the technology is modelled at a future, more-developed phase (e.g., large-scale production).*" Methodological choices in prospective LCA must be adapted to reflect this goal of assessing the environmental impacts of emerging technologies, which deviates from the typical goals of conventional LCA studies." The main message is thus to somehow model the future state of technology based on the current knowledge. A distinction is made between situations (data) for which there are good reasons to believe that the future will change in a certain direction. In such situations, Arvidsson et al. (2017) recommended the use of *predictive scenarios*, e.g., using engineering-based scaling laws to predict future data. For situations in which future developments are uncertain, Arvidsson et al. (2017) recommended the use of *scenario ranges,* i.e., generating maximum and minimum data based on stoichiometric relationships, laboratory results, expert interviews, scientific articles, etc. The recommendations of Arvidsson et al. have been largely confirmed in other studies (Thonemann et al. 2020). Both predictive scenarios and scenario ranges result in a high value and a low value but with different connotations.

As described above, in LCA, a distinction is made between the foreground and background systems. Arvidsson et al. (2017) cautioned against a temporal mismatch between background and foreground systems. A very important background process that can influence the results in most studies, especially traction battery studies, is electricity generation.

Uncertainty is a major challenge in all LCAs, especially in prospective LCAs (Thonemann et al. 2020). Igos et al. (2019) suggested how to treat uncertainties in LCA at different levels, as described below.

2.2.9 Uncertainty in LCA and in prospective LCA

Walker et al. (2003) defined uncertainty in model-based decision support activities as *"any deviation from the unachievable ideal of the completely deterministic knowledge of the relevant system"*. Uncertainty in LCA can, according to Igos et al. (2019), be related to the following:

- quantity, or the numerical value of a parameter;

- model structure, or the mismatch between the real system and its LCA model; and
- context, or the methodological choices related to the goal and scope definition.

A proper treatment of uncertainty in any LCA consists of the following:

- the identification and characterization of uncertainty sources;
- uncertainty and sensitivity analysis, i.e., propagation of input uncertainty to the results and analysis of their effects; and
- communication about this uncertainty.

As there are many possible uncertainty sources in LCA, efforts should focus on those sources with the highest significance for the results (Wolf and Pant 2012; Igos et al. 2019). Igos et al. therefore outlined recommendations at the following three levels:

- basic, characterized by low efforts with LCA software;
- intermediate, characterized by significant efforts with LCA software; and
- advanced, characterized by significant efforts with non-LCA software.

For the basic recommendations, minimum and maximum values (for quantity uncertainty) and alternative scenarios (for model structure/context uncertainty) are defined for critical (i.e., highly significant) elements to estimate the range of results. Result sensitivity is analysed via one-at-a-time variations (with realistic ranges of quantities) and scenario analyses. Uncertainty should be discussed at least qualitatively in a dedicated paragraph (Igos et al. 2019). Concerning model and context uncertainty, Igos et al. noted that LCA practitioners often compare their results with those of similar LCA studies but conclude that this has more to do with consistency between the studies compared than with the uncertainty of their own study.

For prospective LCA, which suffers from a general lack of data and data with probability distribution, recommendations at the basic level are suitable.

3 Research methods and techniques

This chapter starts with a historical overview of my research articles, my two research perspectives and their respective units of analysis. After a reflection on my position as an LCA practitioner in relation to my counterparts in our different projects follows a consideration of the LCA process in relation to different philosophical standpoints, research methods and research techniques. Thereafter, I briefly describe how I used literature searches regularly during the 16-year research period. Chapters 3.5.2 and 3.5.3 describe the concrete research methods and techniques used in the five articles. How the validity of the results was assessed is described in Chapter 3.6.

3.1 Research process

The research includes empirical studies from 2004 to 2020; see Figure 6. From 2008 and onwards, the focus was LCA as a support in the development of different battery chemistries. The article about stepwise environmental product declarations (EPDs), an LCA-based eco-label, was part of my licentiate thesis. Its focus is LCA as a support for small businesses in greening any of their products (not necessarily batteries).

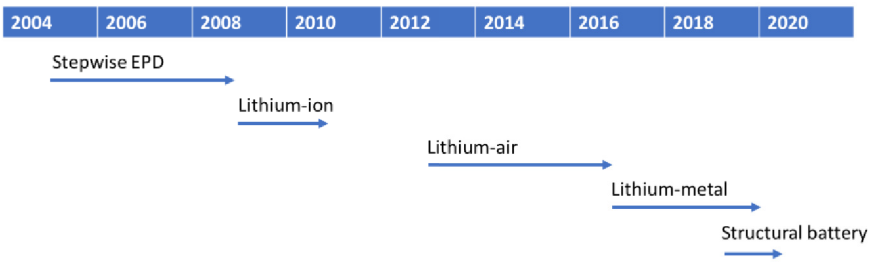

Figure 6: The research was carried out from 2004 to 2020.

The focus on traction battery LCA case studies over the last twelve years has allowed for the gradual improvement of the application of the LCA methodology (see Table 1, page 37). The large number of other LCAs of traction batteries and electric vehicles during this period has also been an inspiration and source of knowledge (Nordelöf et al. 2014)(Temporelli et al. 2020).

3.2 Two research perspectives

Answering all the research questions requires an examination of the results of the LCA case studies from different angles or perspectives.

1. The first research perspective has a narrow focus on the traction battery studied, i.e., the numerical LCA results of the traction battery case studies; it is necessary to answer research questions 1 and 2. The unit of analysis is equal to the functional unit of each battery case study, i.e., kg LIB battery, delivered kWh or vehicle kilometre.
2. The second research perspective has a wider focus on the whole process of using LCA to improve the environmental impact of traction batteries and to further sustainable introduction of any new technology; it is necessary to answer research questions 2 and 3. The unit of analysis is one LCA case study.

As implied above, answering research question 2 may require an examination from both perspectives. Regarding the applicability of the papers, both perspectives apply to all battery-related case studies, whereas only the use of the LCA perspective is relevant for the stepwise EPD paper (A); see Figure 7 below.

The first perspective, the LCA results of battery cases, starts with data that give ideas to hypothesize and ultimately verify theories and is thus inductive (Karlsson et al. 2016). LCA is a quantitative method; thus, data are vitally important. LCA starts with data, is thus inductive and can have an embedded unit of analysis according to Yin (2018), i.e. the functional unit. An example of an inductive research process can be found in the included lithium-ion battery paper (B): the importance of the internal battery efficiency became evident after one-at-a-time calculations with different values.

The use of the LCA perspective (see Figure 7), in general, starts from a hypothesis, seeks data about this hypothesis and develops theories; i.e., it is deductive. Yin (2018) stressed the iterative nature of explanation building within case studies and between multiple case studies, i.e., sometimes deductive, starting with a hypothesis, and sometimes inductive, starting with the data. An example of a deductive research process is the hypothesis in the stepwise EPD paper (A) that LCA is good for the environment and business, that which, through the use of data, was modified to LCA being good for the environment.

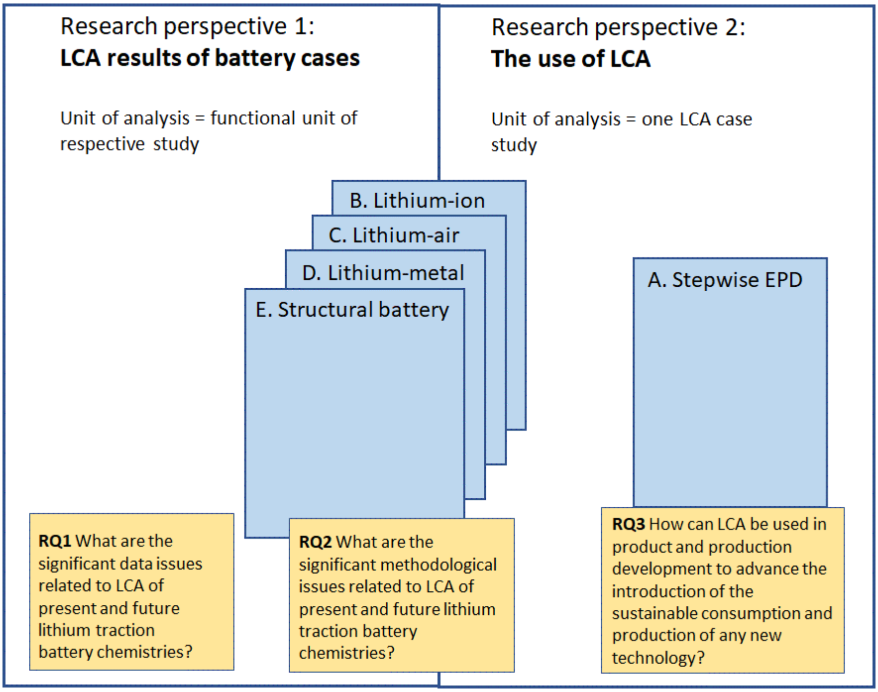

Figure 7: Research perspectives, units of analysis and their relation to the research questions and papers.

Returning to research perspective 1 (the LCA results of the battery cases), the fact that LCA starts with data makes the in-software handling and displaying of data very important. Here, the Sankey display of LCA results in the SimaPro LCA software makes it easy to trace the significant parameters. Figure 8 is from the lithium-ion battery paper, paper B. It shows the use phase of the battery. It becomes immediately obvious that the electricity losses due to the assumed 90% internal battery efficiency are an important parameter for climate impact, much more important than the losses due to battery weight contribution to power demand and definitely much more important than the transport from the vehicle OEM to the user of the vehicle. This finding was not expected and led to questions and discussions in the project group and literature searches on the variation in this parameter, which, in turn, led to the testing of the sensitivity of the results to variations in the efficiency parameter with all other factors being fixed, i.e., one-at-a-time variation in the significant parameter only.

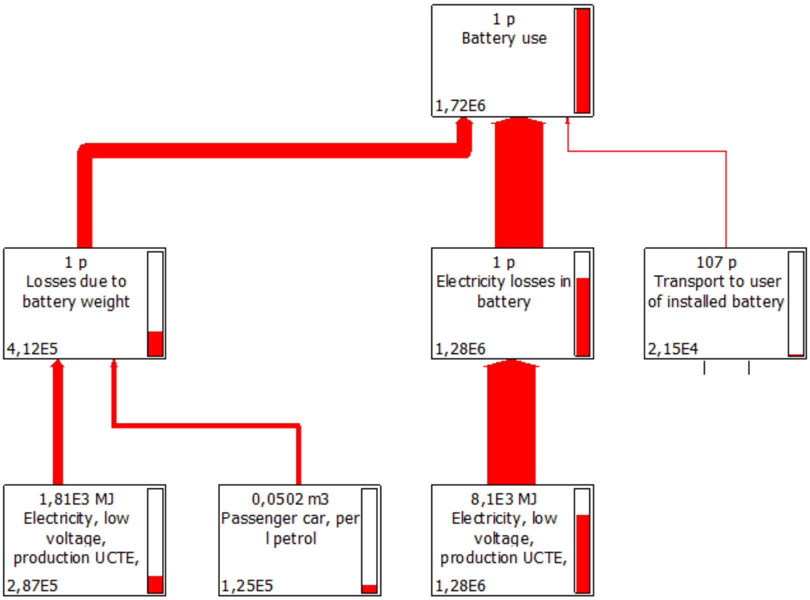

Figure 8: Climate impact in the use phase of a 10-kWh plug-in electric vehicle battery. The Sankey diagram facilitates the identification of significant parameters. The figure is from the lithium-ion battery paper (B). In the lower left corner of each box, gram of CO_2-eq over a 200,000 km life cycle is given.

The ability of the model and LCA software to show the contribution of significant parameters was thus important, as was interacting with specialists and performing literature searches, to develop a realistic variation in the internal efficiency parameter, thus enabling one-at-a-time calculations with different values for the purpose of showing the significance of this parameter.

3.3 Positionality

According to Herr and Anderson (2015), a researcher can investigate his/her positionality by asking the question following: Who am I, as a researcher, in relation to my setting and my participants? The question is partly answered in Table 1, page 37, in the rows describing goal and scope definitions and interpretations, respectively. By viewing myself as an LCA expert and my counterparts as battery experts/scientists, my position was that of an outsider in collaboration with insiders (Herr and Anderson 2015) in all the battery case studies. Note also that my role in the stepwise EPD paper (A) was that of an outsider in collaboration with insiders in three of the case studies but different in the remaining seven case studies. In these seven case studies, I am an outsider in collaboration with outsiders who, in turn, collaborate with insiders.

Knowledge of one's position relative to other project partners and participants is important for several reasons. As researchers, we enter our field of research with a perspective drawn from our own unique experience. We have to be aware of this and counteract the inevitable resulting bias by building a critical reflexivity into the research process (Herr and Anderson 2015). In the LCA process, there are many opportunities to interact with others (see Figure 4) that can balance such inevitable bias. Third-party verification, employed in the stepwise EPD study, is a more formal way of counteracting bias in LCA, as well as finding other mistakes. Furthermore, as an outsider in collaboration with insiders, it is important to recognize and create an understanding of each other's fields of knowledge so that all relevant knowledge is put to use (Herr and Anderson 2015).

3.4 Perspectives from the research on life cycle assessment

3.4.1 Life cycle assessment – both positivist and interpretive

The four stages of LCA contain many different elements in terms of research methodology; different philosophical standpoints necessitate different research methods and techniques in the various stages. The application of the vocabulary of Cecez-Kecmanovic and Dubravka (2011) in Figure 9, to the four stages of LCA gives an idea of the shifting character of practising LCA (see Figure 10).

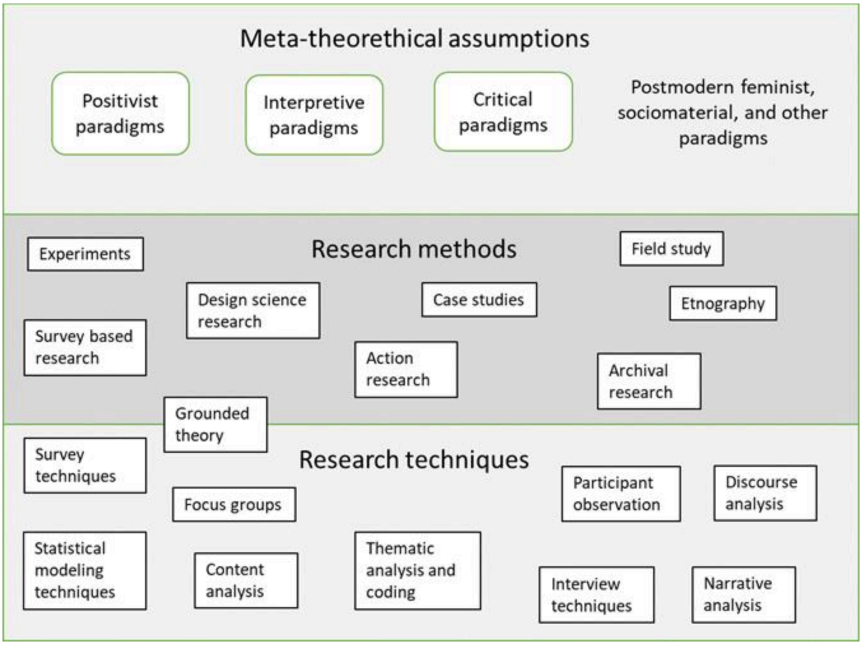

Figure 9: The methodological landscape (adapted from Cecez-Kecmanovic and Dubravka (2011)).

Additionally, the two research perspectives used in the thesis are depicted in Figure 10. Data issues, explored through research perspective 1, may of course emanate from the goal and scope, inventory or impact assessment stages, but their significance will be manifested in the interpretation stage. Research perspective 2, the use of LCA, also includes the application of LCA results.

As mentioned in page 13, defining the goal and scope of the LCA requires describing the intended application, the reasons or driving forces behind carrying out the study and the intended audience. Answering such questions requires interaction with the commissioner of the study in an action-oriented way (Karlsson et al. 2016)(Herr and Anderson 2015). Ideally, the commissioner's staff members contribute their specialist knowledge, very much like a focus group (Yin 2018). It should be noted that the ISO standard (ISO 2006c) only specifies what should be defined, not how to do it and who should do it. In conclusion, there is a need for the further examination of how LCA can be improved by including counterparts with complementary competencies in the process.

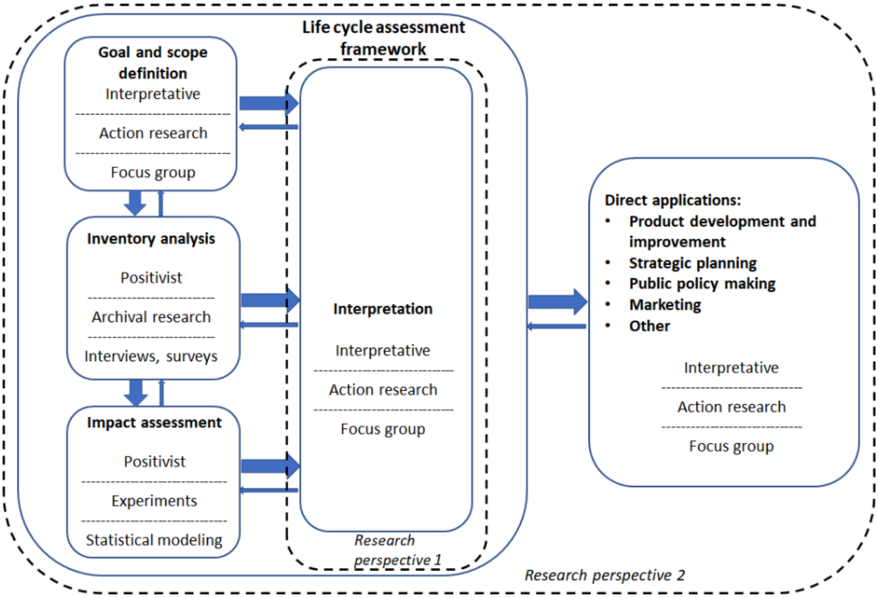

Figure 10: LCA requires different philosophical standpoints and different research methods and techniques in the four stages. The two different research perspectives used in the thesis are also shown.

During life cycle inventory analysis, data relating to physical flows across system boundaries (elementary flows in LCA terms) are collected, validated and normalized to the reference flow of the functional unit as described in page 14. Which unit processes belong to the studied product system is decided in the interpretive goal and scope definition stage, while the data collection itself during inventory requires more of a positivist view on science; a data point, described by its metadata, has only one best numerical data fit, which can be a statistical distribution with an average value. In contrast, the finding of this best fit often involves an interaction between the LCA expert and key staff of the commissioning company. Documents like invoices, annual reports, environmental reports and permits and other archival sources are other usual data sources. Surveys may be used, for example, to produce data about staff transports. Scientific articles and public LCA databases like Ecoinvent (Wernet et al. 2016) can be used as supplements when no case-specific data can be found. A comparison among different secondary sources, triangulation, is performed as much as possible to find the best-fitting data for the model.

As described in page 15, life cycle (environmental) impact assessment (LCIA) facilitates interpretation by aggregating the life cycle inventory. LCIA is implemented in LCA software as a process of matching input and output substances with environmental impact characterization factors. The calculation of the characterization factors involves developing and using models for environmental fate, impact pathways and cause-effect relations (Roos 2016), implying a positivist view of science.

Life cycle interpretation, described in page 16, involves the evaluation of the appropriateness of system boundaries, the functional unit and the data requirements in light of the calculated results and the preliminary conclusions drawn, i.e., revisiting the issues of the goal and scope definition stage but, now, with added knowledge. Completeness, sensitivity and consistency should also be evaluated. Ideally, this interpretation should include an interpretive action-oriented exercise, carried out with the commissioner's team acting much like a focus group, just like in the goal and scope definition stage. Idea generation workshops can be seen as an additional iteration of the interpretation. The workshop format allows for the participation of a larger focus group. The outputs of the interpretation phase are the conclusions, limitations and recommendations of the LCA. Idea generation workshops often focus on ideas for improving product environmental performance based on the LCA results. It should be noted that just as for the goal and scope definition phase, the ISO standard does not specify who should take part in the interpretation phase. In conclusion, there is a need for the further examination of how to involve the commissioner and his/her staff in the interpretation phase.

3.4.2 LCA and action research in the literature

Literature searches in Science Direct and Scopus in spring 2020 led to the identification of seven research articles that had LCA and action research in the title or among the keywords. One of these was only concerned with life cycle costing (LCC), two were concerned with social LCA, and two were from the same study, leaving three studies that were concerned with quantitative LCA and action research. These three, (Testa et al. 2017) (Romain et al. 2015)(Bonou, Skelton, and Olsen 2016), used action research more to implement the use of LCA, i.e., to install LCA procedures, than in the actual carrying out of the LCA work.

In her dissertation, *Marketing life cycle thinking,* Rex (2008) focussed on organizational processes, including how life cycle goals influence internal sensemaking about green actions and how consumer and customer interest in environmental matters are perceived and acted on. Her results indicated that both life cycle thinking, and green marketing are greatly shaped by the perceptions and sensemaking of people adapting their application to local contexts. She concluded that both internal and external marketing are possible keys to facilitating the spread of life cycle thinking in industries and can align with the business rationales of a company.

Bobba et al. (2020) considered the involvement of different expertise key in updating both the modelling and the input data to provide reliable information for the identification of circular economy aspects in the context of batteries for e-mobility. No mention of action or interpretive research in the keywords or titles indicated that there could be more articles linking LCA with interpretive research techniques than were found in the search performed.

3.5 Research methods and techniques used

3.5.1 Literature search

Literature searches were carried out regularly during the 16-year research period. Sometimes, they were carried out as structured keyword searches in Scopus and Science Direct, typically when starting projects leading to papers and when starting to write a paper. In addition, suggestions from research repositories like Research Gate, Mendeley and Google Scholars based on internet algorithms provide increasingly good coverage of my subject areas of interest. Furthermore, acting as a reviewer for various scientific journals during the last ten years also helped me stay up to date with the current literature in my field of knowledge.

3.5.2 Stepwise EPD method and project design (paper A)

The main objective of the stepwise EPD project behind the stepwise EPD paper (paper A) was to develop and test a method for stepwise environmental product declarations (EPDs) suitable for small and medium-sized enterprises (SMEs). The context was a European project including ten SMEs in Denmark, Latvia, Portugal and Sweden (contract number 513045). The author designed the project and acted as a project leader and LCA practitioner for the Swedish case studies. To create more value and increase suitability for SMEs, LCAs were used not only for EPDs but also for eco-design.

The stepwise EPD paper (A) contains case studies of LCA-based EPDs carried out in a stepwise order in ten small or medium-sized European enterprises (European SMEs). The research methods employed in relation to the stepwise EPD paper can best be described as action research (Herr and Anderson 2015) in case study form (Yin 2018). For each case, at least one stepwise EPD was developed, entailing goal and scope definition, data collection, LCA calculations, LCA interpretation, the drafting of the EPD and the verifying of the EPD. The EPD development itself involved numerous meetings and reviews of data and drafts. These actions were carried out by experts in LCA, working in the involved research organizations, in cooperation with SMEs' experts in production, sales, design, etc. The mandatory verification of the stepwise EPD at the end of the EPD development process can be seen as a form of validation.

The main motivation for the SMEs to participate in the stepwise EPD project was an anticipation of a demand for EPDs from their customers and clients and a willingness to test new approaches and methods in environmental work. Willingness to spend time and effort developing and making use of the EPDs was the main criterion for the selection of the case study companies. According to Yin (2018), each case in a multiple case study must be carefully selected so that the individual case studies either (a) predict similar results (a literal replication) or (b) predict contrasting results but for anticipatable reasons (a theoretical replication). The willingness to spend time and effort developing and making use of EPDs in relation to the hypothesis that EPDs are good for the environment and for business represents a literal replication.

After finalizing the EPDs, a series of workshops and meetings were carried out, aimed at using stepwise EPDs (and underlying LCAs) in marketing and as a basis for eco-design. Surveys among potential users were also carried out. Draft meeting notes of all workshops and meetings were sent to participants for internal validation. National conferences were also held to discuss and disseminate the results. Such workshops and meetings extend beyond regular EPD use.

In parallel to the development and utilization of stepwise EPDs, the stepwise EPD concept or method was defined. The research method employed was to discuss, among experts, the experiences from practical work with the EPDs and draft guidelines within the framework of relevant standards and norms, such as the EPD standard ISO 14025 (ISO 2006a) and ISO 14044 (ISO 2006c). Throughout the project, experiences were discussed among SMEs, research organizations and other partners at several meetings at the company, national and project levels. Draft minutes of all meetings were sent to participants for confirmation. The concept discussions also extended to experts and forums outside the project.

At the end of this two-year project, each SME was interviewed by their research partner to evaluate the results, i.e., the impacts of stepwise EPD work on design, market communication and sales. The same semi-structured evaluation questions were used in Sweden, Portugal and Latvia. In Denmark, a more open and less structured approach was used. The impact of performing stepwise EPDs was documented in confidential impact reports. These impact reports, together with the stepwise EPDs and all the discussions from the meetings held, form the basis of the stepwise EPD paper (A).

3.5.3 Methods and techniques applied in papers B-E

This thesis includes four papers focussed on LCA as support in the development of traction batteries. The inspiration is partly from the findings in the stepwise EPD paper (A) that LCA can instigate environmental improvements in product design. Similar to the stepwise EPD paper, the battery papers are also using action research (Herr and Anderson 2015) in case study form (Yin 2018). However, as elaborated above, LCA also contains many positivist research elements. These become more pronounced as the research perspective is narrowed to focus on the numerical results of the LCAs, i.e., research perspective 1 (see Figure 7). The papers, in chronological order in Table 1, are all about LCAs of future lithium traction battery chemistries: lithium-ion $LiFePO_4$ battery with water as a solvent, lithium-air, lithium with a metal anode, and structural $LiFePO_4$ chemistry batteries. They all share the confidence in LCA displayed in the stepwise EPD paper (A).

LCA of lithium-ion batteries for plug-in hybrid electric vehicles, paper B

The LCA was carried out at the Swedish research institute RISE IVF as a form of internal study. The LCA model was partly based on data from the literature and partly on in-house laboratory trials with tape casting of $LiFePO_4$ cathodes using water instead of N-methyl-2-pyrrolidone (NMP) as a solvent in the cathode slurry and the nanospinning of the separator. The main objective of the study was to identify and highlight critical issues regarding the life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles to facilitate the use of LCA when designing such systems.

This LCA followed the general four-stage ISO 14044 methodology described in Figure 4. To obtain more guidance, the general rules of the International Environmental Product Declaration EPD® system (EPD® 2008) were followed. Goal and scope definitions as well as data inventory and the final interpretation were made with support from other researchers at RISE IVF.

The LCA system model was built around a theoretical design of a battery with 10-kWh capacity for a plug-in hybrid electric vehicle (PHEV). The functional unit was defined as this 10-kWh battery, capable of sustaining 3,000 charge cycles at 80% maximum discharge, allowing for 150,000 km of electric operation during the vehicle design lifetime. The PHEV was assumed to operate 75% in electric mode and 25% in combustion mode. Thus, all figures for resource use, emissions and environmental impact are related to one such battery weighing 107 kg, corresponding to an energy density of 93 kWh/kg at the battery level.

The study focuses on the battery, and the production phase model includes only the battery and its casing. The battery charger, electric engine(s) and other hardware in the electric power train are outside the system boundary. In the use phase, only electricity related to internal battery efficiency and the extra electricity and fuel needed to carry the weight of the battery are included (30% of propulsion energy assumed depending on weight). The combustion engine and rest of the vehicle are outside the system boundary. The transportation of the battery between the vehicle manufacturer and the user of the vehicle is included in the use phase. Following the EPD system guidelines (EPD® 2008), which stipulate cut-off as the allocation method, only transportation to a scrap yard was included in the ensuing recycling phase.

In line with the recommendations in the EPD system (EPD® 2008), five widely accepted impact categories were calculated and reported: global warming, acidification, ozone depletion, photochemical smog, and eutrophication.

As mentioned above, the production phase was modelled based on the scientific literature and recipes used in laboratory work in the development of a $LiFePO_4$ cell with water as the solvent. The data collection process included mass balance of inputs and outputs. All laboratory data were scaled to represent industrial-scale production. The detailed description of the estimates, calculations and assumptions of the data made in the modelling of the 10-kWh battery system is a major contribution and strength of paper B.

LCA of lithium-air battery cells, paper C

The research in the lithium-air battery paper (C) was carried out in the context of the EU project STable high-capacity lithium-Air Batteries with Long cycle life for Electric Cars (STABLE; grant agreement number 314508). The stated purpose of the lithium-air battery paper was to highlight the environmental hotspots linked with lithium-air batteries to guide their improvement at the full-cell level and to illustrate the potential benefits of the adaption of lithium-air batteries in vehicles. Theoretically, lithium-air technology can achieve at least ten times better energy density than can lithium-ion technology and is therefore very interesting for mobile applications.

The LCA work was specifically designed to fit a technology development project. A literature survey and streamlined LCA were carried out during the first of the four years of the project cycle. The results of the literature survey and streamlined LCA based on a limited set of inputs were presented in an idea generation workshop at the first-year meeting. This setup aimed to feed ideas and information into the cell design work. Due to the low technology readiness level (TRL) of lithium-air technology, the focus was much more on achieving a working prototype than on streamlined production on a large scale; efficiency and optimization were not achievable/in focus at this stage of development.

Material and energy needs were determined based on the best prototype achieved in the project. The data collection process included mass balance of inputs and outputs. Laboratory data were scaled to reflect industrial-scale production in Europe. Furthermore, LCA database background data, academic literature, engineering rules, stoichiometric calculations and estimations were also used. Material safety data sheets were collected, and all participating laboratories were obliged to perform a chemical risk assessment of their laboratory work, the aim of which was primarily to minimize chemical risks during project execution but also to complement the LCA data. The estimate of cell assembly energy first developed for the lithium-ion battery paper (B) was also used for the modelling of the assembly of the lithium-air battery cell.

To put the battery in the application context of a vehicle, the results were presented as the environmental impact per vehicle kilometre and per delivered kWh. The system boundary was essentially the same as that in the lithium-ion battery paper, i.e., only the production, use and recycling of the lithium-air battery cell was inside the system boundary, and everything else was outside. In the use phase, only electricity related to internal battery efficiency and the extra electricity needed to carry the weight of the lithium-air battery cell were included. Recycling data were estimated from a review of the sparse number of available articles on the subject but modelled with system expansion (or end-of-life (EOL) recycling to use the terminology of Nordelöf et al. (2019)), i.e., not modelled with cut-off as in the lithium-ion battery paper.

To assess the trade-offs between tailpipe emissions from internal combustion vehicles (ICVs) with material resource use and toxicological impacts from electric vehicles (EVs), climate impact, resource depletion and toxicity were considered suitable environmental impact categories. A need to develop LCA toxicity impact methods to properly assess lithium was noted. Furthermore, a recent change in the abiotic depletion method made external validation, i.e., comparisons with other studies, difficult. The choice of an abiotic depletion method is discussed further in Chapter 5.2.1.

The use of the predictive scenarios and scenario ranges recommended by Arvidsson et al. (2017) is combined by calculating both current achievement and long-term goal for lithium-air battery cells. The ranges used are, thus, results in and of themselves and are presented in Chapter 4.3.

Perspectives on environmental and cost assessment of lithium metal negative electrodes in electric vehicle batteries, paper D

The context of this contribution was a Swedish national technology development project, TriLi - Longlife lithium electrodes for EV and HEV batteries. The aim was to guide cell producers and battery pack designers on how to decrease the cost and improve the environmental performance of cells with lithium-metal negative electrodes.

Cells with lithium-metal negative electrodes were designed and tested in silico in a Nissan Leaf and a Tesla Model S battery pack, which were created by cells connected in series to fulfil the system voltage requirements and in parallel to fulfil energy and power requirements to match those of the current lithium-ion battery packs in the respective vehicle. The same cell-to-pack weight ratio as the original lithium-ion batteries (LIBs) was used in the lithium-metal batteries (LMBs), and the same energy consumption per km and mass of vehicle as the original vehicles was assumed. Two different positive electrode chemistries were involved in the in-silico design: lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP).

As in the lithium-air battery project, a very distinct twofold iteration of the four-stage ISO 14044 cycle was used. An immediate result of this iteration was that a much thinner lithium foil was used than initially planned, thus significantly reducing the climate impact. As mentioned above, the Sankey diagrams provided in SimaPro enable the easy identification of significant contributions, thus increasing internal validity.

Compared to the lithium-ion and lithium-air battery papers, the model of use phase losses due to the transport of mass was improved by the use of an energy reduction value related to the new European driving cycle, enabling the dynamic modelling of the battery mass; i.e., any change in battery weight results in a change in vehicle electricity consumption. The model of the production phase was developed as in the lithium-air battery paper (C); i.e., laboratory data were scaled to the industrial scale in interaction with researchers at the Ångström Laboratory at Uppsala University.

The data collection techniques included in this contribution were LCA database background data, scientific literature, laboratory trials, engineering rules, stoichiometric calculations and estimations made with the assistance of battery researchers involved in the project. The lithium-metal battery paper (D) models the existing battery packs in a Nissan LEAF and a Tesla Model S, with improved cells and with current technology cells, to make the comparisons more realistic. This makes the paper much more useful for benchmarking purposes and increases the external validity of the results.

Prospective life cycle assessment of a structural battery, paper E

The research in the structural battery paper (E) was a cooperative effort between RISE IVF and the Department of Aeronautical and Vehicle

Engineering at the Royal Institute of Technology (KTH) under the Swedish national XPRES initiative. The purpose was to predict environmental hotspots in a structural battery with LCA and chemical risk assessment (CRA) to improve the environmental performance of the battery.

The iterative four-stage ISO 14044 LCA approach was followed. The cooperation lasted approximately one year and included several smaller iterations between stages. Goal and scope definitions and interpretations were carried out together with counterparts and comprised expertise in LCA, chemical risk assessment and composite materials.

The interpretation was complemented with an idea generation workshop with eight staff members from KTH's Department of Aeronautical and Vehicle Engineering. The idea generation workshop consisted of four steps:

1. the presentation/discussion of life cycle assessment of a structural battery;
2. the brainstorming of ideas for the environmental improvement of structural batteries. All participants are made aware that no negative critique is allowed during this step;
3. the categorization of ideas (informal, maybe during coffee break), often followed by some additional brainstorming; and
4. the evaluation of ideas based on the criteria for environmental improvement and realizability. Critique is encouraged during this step.

The data collection techniques were the same as in the other battery-related papers. In addition to climate impact and abiotic depletion, ozone formation was quantified.

Toxicity was not quantified with regular and established LCA methods. Instead, it was investigated with a novel semiquantitative chemical risk assessment (CRA) from a life cycle perspective. A four-step procedure was followed to qualitatively assess chemical hazards and legal risks:

1. the collection of material safety data sheets (MSDS), retrieved from chemical suppliers.
2. the identification of hazard statements of the chemical mixture as well as the individual components from the MSDS, according to the Classification, Labelling and Packaging (CLP) regulation (European

Commission 2008b); in addition, the chemical abstract service (CAS) and registry number for classified individual components were listed.

3. the identification of any legal requirements, restrictions, or unharmonized classifications. To do this, CAS numbers were investigated using the European Chemical Agency's (ECHA's) database; and
4. the evaluation of risk as low, moderate or high in each life cycle phase according to the criteria developed in the project.

The CRA was carried out by experts in both chemical risk and LCA, not by the author. All evaluation results went through an internal review.

Overview of the aspects involved in battery-related papers (B – E)

An overview of the important aspects involved in the battery-related papers is given in Table 1. Some aspects related to the methodology have already been mentioned above, and some will be referred to in Chapter 4.

Table 1: Overview of the important aspects involved in battery-related papers.

<table>
<tr><th>Aspect/Paper</th><th>2008-2010
..lithium-ion</th><th>2012-2016
..lithium-air</th><th>2016-2020
...lithium-metal</th><th>2019-2020
..structural</th></tr>
<tr><td>Total ISO 14044 LCA duration[a]</td><td>1 year</td><td>Two cycles in 4 years</td><td>Two cycles in 3 years</td><td>1 year</td></tr>
<tr><td>Goal and scope definition</td><td>With IVF internal project partners/ production experts</td><td>With internatio-nal project part-ners/battery and production experts</td><td>With national project partners/ battery experts</td><td>With national project partners/ composite mate-rial and chemical experts</td></tr>
<tr><td>Functional unit</td><td>10-kWh battery weighing 107 kg</td><td>1 vehicle km
1 delivered kWh</td><td>1 vehicle km</td><td>1 structural battery roof</td></tr>
<tr><td>Inventory</td><td colspan="4">LCA database background data, academic literature, laboratory trials, engineering rules, stoichiometric calculations and estimations made with the assistance of experts in batteries and/or production and/or chemicals</td></tr>
<tr><td>System model, production</td><td colspan="2">Battery cell and some casing</td><td>Battery cell and 50% rest-of-pack</td><td>Structural bat-tery incl. battery cell and 50% rest-of-pack</td></tr>
<tr><td>System model, use</td><td colspan="2">Electricity related to battery efficien-cy and battery weight (based on 30% proportionality)</td><td colspan="2">Electricity related to battery efficien-cy and battery weight (based on ERVs)</td></tr>
<tr><td>System model, recycling</td><td>Only transport to recycling</td><td colspan="2">Rough estimate of recycling burdens</td><td>Based on PEFCR (Recharge 2018)</td></tr>
</table>

Aspect/Paper	*2008-2010 ..lithium-ion*	*2012-2016 ..lithium-air*	*2016-2020 ...lithium-metal*	*2019-2020 ..structural*
EIA categories	Climate impact, ozone formation, eutrophication, acidification, ozone depletion	Climate impact, abiotic depletion, ecotoxicity	Climate impact, abiotic depletion, toxicity	Climate impact, abiotic depletion, ozone formation
Electricity mixes (bold= =base case)	**Western European** Swedish Chinese	**Western European** Swedish		
Variation in other critical parameters	Internal battery efficiency, weight induced losses	Current achievements and long-term goal of lithium air battery cell	Vehicle size, battery chemistry, internal battery efficiency[b], weight induced losses[b], cycle life[b]	Initial design or target design of structural battery
Comparison with other studies	Yes	Yes	Yes	Yes
Interpretation	With IVF internal project partners/ production experts. Interpretation after 1 year. No idea generation.	With international project partners, battery and production experts. Idea generation after 1 year. Normal interpretation after 4 years.	With national project partners/ battery experts. Idea generation after 1 year. Normal interpretation after 3 years.	With national project partners/ composite material experts. Idea generation after 1 year just after normal interpretation.
Chemical risk assessment	CRA pinpointed NMP and PVDF as problematic (Posner 2009)	Obligatory for all laboratories involved in the project. Used as input data for the LCA	Not part of the LCA study	Chemical risk assessment with a life cycle perspective developed and used

[a] not including a critical review of the article

[b] not quantitatively included in the paper but an important part of the project and qualitatively discussed in the paper

3.6 Validity in LCA

External validity describes to what degree the findings of a study are valid in general (Trochim 2006). Research questions 1 and 2 are concerned with the environmental improvement of traction battery systems. External validity in LCA relates to what Igos et al. (2019) called context uncertainty; i.e., it relates to the goal and scope of the LCA. A general approach used in the battery-related papers (B-E) is to investigate and discuss external validity (or context uncertainty) by scenario analysis via one-at-a-time variations in the critical data. In *Table 1*, electricity mixes and the variation in other critical parameters are relevant for external validity and context uncertainty.

External validity will also be discussed in relation to how the lessons learned for battery technology development can be applicable for the development and introduction of any new technology.

Construct validity is related to the degree of generalization in the sense that everyone must uniformly understand the concepts or terms that are the subjects of generalization (Trochim 2006). LCA is a relatively well-defined concept, while some of the descriptors discussed above, like consequential LCA, attributional LCA, accounting LCA, retrospective LCA, prospective LCA and streamlined LCA, are more diffuse, with different interpretations in different contexts. The examples and discussions in this thesis refer to prospective attributional LCA (Arvidsson et al. 2017), which refers to LCA about technology studied in an early phase of development but modelled for a future more developed implementation by projecting the current data to this future more developed phase. Construct validity in LCA can also relate to what Igos et al. (2019) called model uncertainty, i.e., the mismatch between the real system and the LCA model. Construct validity (or model uncertainty in LCA) is very difficult to assess; if I knew which LCA model assumptions are wrong, then I would correct them if I could, and if I had a different understanding of an important concept, I would try to align my understanding with reality. However, until I know it, I am, by definition, unaware of it, and assessing something that one is not aware of is, by definition, impossible. In the LCA work, model uncertainty was investigated and discussed by scenario analysis via one-at-a-time variations in the critical data in the sense that the awareness of its existence instigated extra robustness in the scenarios, i.e., a greater difference between the lowest and highest value. Comparing the models, results and conclusions with those of other studies is also a way to minimize the adverse effects of model uncertainty.

Internal validity is the approximate truth about inferences regarding cause-effect or causal relationships (Trochim 2006). Thus, internal validity is only relevant in studies that try to establish a causal relationship. It is not relevant in most observational or descriptive studies, for instance. The key question in internal validity is whether observed changes can be attributed to the examined intervention (i.e., the cause) and not to other possible causes (Trochim 2006). Since this thesis is concerned with the environmental improvement of traction battery systems, primarily how to conduct (a more and better) eco-design of traction battery systems, whether or not it was the tested inferences, e.g., less thickness of the lithium-metal foil in the lithium-metal battery paper (D), that actually caused the examined effects is a very important issue.

4 Summary of appended papers

In this chapter, the main results from the respective papers are presented. In addition, the final subsection will present comments concerning limitations in the results and introduce recent developments since the publication of the papers, as are further discussed in Chapter 5.

4.1 Paper A: Stepwise EPD

As described in Chapter 3.5.2, the main objective of the stepwise EPD project described in the stepwise EPD paper (A) was to develop and test a method for stepwise environmental product declarations (EPDs) that is suitable for small and medium-sized enterprises (SMEs). The context was a European project including ten SMEs in Denmark, Latvia, Portugal and Sweden. Research institutes in the respective countries provided assistance to the SMEs in terms of the life cycle assessment and elaboration of the declaration. To create more value and increase suitability for SMEs, LCAs were designed to also be used for eco-design and not only for environmental product declarations (EPDs). In EPDs that are largely based on generic data, the underlying LCAs do not necessarily carry the same eco-design potential.

The assumption that producing the stepwise EPD, or rather performing the underlying life cycle assessment, can be used as a basis to identify eco-design options was verified in eight out of the ten case studies. Many improvement options were generated, and some, on average, 1.5 options per product, were also implemented within the 27-month project timeframe.

The assumption that the stepwise EPD can be used to communicate a product's environmental profile to potential customers, thereby creating demand for such improved eco-efficiency products, could not be verified. All case study companies were disappointed by the lack of appreciation for stepwise EPDs in normal marketing activities. More in-depth discussions with selected clients focussing on the LCA rather than the EPD had more success, but only a few of the case study companies tried this approach.

Finally, the third assumption that customer demand and the identified improvement options would bring about actual improvement in product eco-efficiency could not be verified since no customer demand was created. However, 15 (out of 162) environmental improvement ideas or options were implemented. It seems, therefore, that explicit customer demand is not always necessary for implementing environmental improvements.

In summary and important for this thesis, it was confirmed that LCA is very useful in the eco-design context; the results display the power of LCA for generating and implementing environmental improvements related to products as well as production, without any explicit customer demand for such improvements.

4.2 Paper B: Lithium-ion battery

The LCA in this paper was carried out at the Swedish research institute RISE IVF as an internal study with the participation of experts in batteries, materials and production. The LCA model was partly based on data from the literature and partly on in-house laboratory trials with the tape casting of $LiFePO_4$ cathodes using water instead of N-methyl-2-pyrrolidone (NMP) as a solvent in the cathode slurry and nanospinning of the separator. NMP is included in the candidate list of substances of very high concern (SVHC) and officially recognized in the EU as toxic to reproduction. The main objective of the study was to identify and highlight critical issues regarding the life cycle assessment of lithium-ion batteries intended for plug-in hybrid electric vehicles to facilitate the use of LCA when designing such systems.

As an example of the contribution of this paper, the estimate of cell assembly energy from data in battery producer Saft's annual report in 2008 (Saft 2008), which was 74 MJ/kg battery, has attracted much attention and has been challenged, partly because cell assembly energy was found to be significant and partly because data from manufacturing sites has proven very difficult to obtain.

The calculated results focus on climate impact after concluding that the other considered environmental impact categories follow the same trend as that of climate impact. An important result was that the climate impact in the production phase of the $LiFePO_4$ cell with water as the solvent was much less than that of the same cell using NMP as the solvent. The contribution analysis pointed to cell assembly energy, the supply of electronics and cathode precursors as major sources of climate impact during the production phase. Note that the contribution analysis was facilitated by Sankey diagrams in SimaPro; see Chapter 3.2.

Two conclusions related to the water-based cell were investigated in more detail: 1) use phase and production phase impacts being on the same order of magnitude and 2) internal battery efficiency causing three times more losses than did battery weight. The robustness of these results was tested by using extreme but not unrealistic data for the electricity mix, internal battery efficiency and vehicle weight. It was concluded that 1) when the vehicle is driven with a coal-rich electricity mix are the impacts at a similar level for all five impact categories in both life cycle phases. With a coal-lean electricity mix like in Scandinavia, use phase impacts are lower than production-related impacts. It was further concluded that 2) the climate impact from internal battery efficiency losses is two to six times that from losses due to battery weight worldwide; i.e., the 2nd conclusion above was confirmed in more detail. See the appended lithium-ion battery paper (B) for other data details.

As one of the first traction battery LCAs, the referenced lithium-ion battery paper has been extensively cited in the academic literature (439 times according to Google Scholar as of 7 April 2021). It shares the objective of this thesis to inspire and assist industries in using LCA to improve the environmental performance of traction batteries.

4.3 Paper C: Lithium-air battery

The research in the paper on the life cycle assessment of lithium-air battery cells was carried out in the context of the EU project STable high-capacity lithium-Air Batteries with Long cycle life for Electric Cars (STABLE), as described in page 33. The stated purpose was to highlight the environmental hotspots linked with lithium-air batteries to guide their improvement at the full-cell level and to illustrate the potential benefits of the adaption of lithium-air batteries in vehicles.

The scenarios range from achieved cell performance to achievable in terms of energy density (2700 versus 10800 Wh/kg), internal efficiency (66 versus 80%), longevity (50 versus 200 cycles) and depth of discharge (20 versus 80%). The range of the scenarios shows the inherent potential of lithium-air technology to decrease climate impacts and the distance to realizing that potential. The results also highlight that low internal efficiency, even at the long-term goal level, may create a heat problem that requires further energy to be alleviated.

The paper includes a complete bill of material of a functioning prototype lithium-air battery cell, explaining how its production was modelled with mostly Ecoinvent processes (Wernet et al. 2016). The contribution analysis pointed to cell assembly energy, cathode precursors and lithium foil/metal as major sources of climate impact during the production phase. The data have been used as benchmarks in a more recent study of lithium-air technology (Fenfen Wang and Yelin Deng 2020).

4.4 Paper D: Lithium-metal battery

The context was a Swedish national technology development project, TriLi - Longlife lithium electrodes for EV and HEV batteries, as described in page 34. The aim was to guide cell producers and battery pack designers in terms of how to decrease the cost and improve the environmental performance of cells with lithium-metal negative electrodes.

The climate and cost impacts (using Western European electricity) largely show a similar pattern: the use phase has more climate and cost impacts than does the production phase; existing battery packs based on lithium-nickel-manganese-cobalt-oxide (NMC) cells show lower climate impact and cost than do existing battery packs based on lithium-iron-phosphate (LFP) cells, and both lithium-metal batteries (LMBs) show clear cost and environmental impact advantages over the existing lithium-ion battery (LIB) packs. The main reason is the higher energy density obtained, which lowers the battery weight and thus the amounts of all materials and, most importantly, the electricity consumption losses.

The paper also demonstrates that climate impacts from production and use phase propulsion impacts can be reduced considerably by producing and using battery cells in locations with carbon-lean electricity; see the discussions in Chapters 5.1.1 and 5.1.2. The climate impact of the electric vehicle use phase confirms the conclusions from other studies that electric vehicles driven using European (or global) average electricity have indirect climate impacts at the same level as the current European tailpipe CO_2 regulation at 95 g of CO_2/km; compare this with Figure 1. This makes the climate impacts of the vehicle use phase (with global average electricity) account for approximately 80% of the total life cycle impacts of the battery. Using a more carbon-lean electricity mix can reduce these impacts by 90% or more. Conversely, electricity generation based only on coal will almost double CO_2 emissions from electric vehicles in the use phase. Altogether, six battery packs with different cell chemistries were modelled and compared.

Paper D involved the first LCA of a technology, LMBs with liquid electrolytes, which is predicted to become the next mass-produced traction battery technology (Motavalli 2015)(Wu and Kong 2018). As such, it meets the aim of guiding cell producers and battery pack designers in terms of how to decrease the cost and improve the environmental performance of cells with lithium-metal negative electrodes.

4.5 Paper E: Structural battery

The research in the structural battery paper (Mats Zackrisson et al. 2019) was a cooperative effort between RISE IVF and the Department of Aeronautical and Vehicle Engineering at the Royal Institute of Technology under the Swedish national XPRES initiative, as described in page 35. The purpose was to predict environmental hotspots in a structural battery with LCA and chemical risk assessment (CRA) to improve the environmental performance of the battery.

The LCA results indicate that a structural battery in a passenger car can avoid environmental impacts in substantial quantities and that improvement efforts should be focussed on saving energy and/or improving the electricity mix for both cell production and carbon fibre production. The CRA with a life cycle perspective pinpointed two chemicals for substitution.

The interpretation was complemented with an idea generation workshop with eight staff members from the Department of Aeronautical and Vehicle Engineering. It resulted in 35 ideas aimed at improving the environmental performance of a structural battery. Four of the 35 ideas were of an exclusively production-oriented nature. Most ideas concerned material substitution, which would indirectly affect production. The three ideas that were deemed the most easily implemented were the use of bio-based binders for batteries plus the use of eco-friendly electrolytes; the application of structural batteries in insulating panels of refrigeration trucks; and the investigation of bio-based carbon fibre precursors, e.g., lignin. The top three ideas from an environmental improvement perspective were car architecture based on the structural battery concept, simpler architecture of the structural battery for easier recycling, and the replacement of lithium with sodium.

4.6 Comments on the papers

There are some comments to be made on the papers described in the previous chapters. Here, two specific areas are covered before the full discussion is presented in Chapter 5: comments on uncertainty in the data and corresponding sensitivity, as well as limitations related to the lack of data and/or lack of guidelines, and an introduction to how these limitations have been further managed.

4.6.1 Uncertainty in the LCA data

As described in Chapter 2.2.9, a general approach used in LCA to investigate and discuss the uncertainty and sensitivity of the results to the uncertainty is scenario analysis via one-at-a-time variations in the critical data. A very important background process in traction battery studies is related to electricity generation. In battery-related papers (B – E), a Swedish average electricity mix was used to simulate current battery production and battery use in Sweden and a possible future global mix after the widespread adoption of energy policies. The average Western European mix was used to simulate the European and average global current conditions. In some cases, the Chinese mix, with a high share of hard coal, was used to simulate the current worst-case scenario (see Table 1).

Here should also be emphasized the importance of beginning uncertainty treatment with dominance analysis, in order to identify which parameters are significant and thus targeted for one-at-a-time variations. In SimaPro, dominance analysis is facilitated by default Sankey diagrams; see Figure 8. Before starting one-at-a-time variations, the plausible variation in the dominant data must be assessed somehow, e.g., by comparing them with those of other studies. Thus, in battery-related papers (B – E), the sensitivity of the results to the uncertainty of the significant parameters was carried out by the following steps:

1. dominance analysis, facilitated in SimaPro by the Sankey diagram, to identify the significant parameters;
2. an assessment of the variation in the significant parameters; and

3. one-at-a-time variations in the significant parameters.

As an example of foreground quantity uncertainty, both the lithium-air battery (C) and structural battery (E) papers calculate current achievement or initial design and long-term goal or target design for a lithium air battery and a structural battery, respectively. Another example is that the lithium-ion battery (B) paper varies the internal battery efficiency, weight-induced losses and electricity mix one at a time. To analyse the sensitivity of the base case conclusions, see Variation in other critical parameters in Table 1. In fact, most of the discussion and conclusion sections in the lithium-ion battery paper (B) relate to sensitivity to the uncertainty of the critical data. The recommendation of Igos et al. (2019)(see Chapter 2.2.9) that uncertainty should be discussed at least qualitatively in a dedicated paragraph, is well adhered to as most of the discussion and conclusion sections in the lithium-ion battery paper relate to sensitivity to the uncertainty of the critical data. This pattern of dedicating most of the discussion section to uncertainty and sensitivity analysis, to understand the results, is the same in all the battery-related papers. A comparison with other studies, as was done in all the battery-related studies (see Table 1) is also very important for understanding the LCA results (checking for missing data, differences in model and assumptions, etc.), even if Igos et al. (2019) did not regard this as part of uncertainty.

Paper A, about stepwise environmental product declarations (EPDs), conversely, does not even mention uncertainty, sensitivity, data quality or reliability. The required third-party verification is assumed to vouch for the quality of the results. Furthermore, the LCAs of the EPDs cannot be considered prospective at all; they are specifically designed for existing products. It appears to be that the lack of data in prospective LCA calls for extensive qualitative discussion and reflection on uncertainty but that this same lack of data prohibits the use of more sophisticated quantitative uncertainty and sensitivity analysis (Igos et al. 2019).

As pointed out by Thonemann et al. (2020), data and uncertainty are considered two main challenges to performing prospective LCA. Other challenges when performing prospective LCA are further discussed in Chapter 5.3.2.

4.6.2 Limitations and recent developments

There are of course several limitations in the battery-related papers (B – E) described in the previous chapters. Most of them relate to a lack of data and/or lack of guidelines. This lack of data also has repercussions on methodological issues; i.e., it is difficult to formulate good guidelines without essential data.

There is a general lack of primary or specific data about battery cell manufacturing. In particular, this was the case in 2009 when the lithium-ion battery paper (B) was written. The lack of data is also an inherent characteristic of prospective studies. The amount of energy needed to produce traction battery cells is a case in point. The energy needs for large-scale cell production will be further explored in Chapter 5.1.2, and some new data will be suggested and presented.

The focus on cell production has drawn attention away from the fact that with most electricity mixes, the largest climate impact over the life cycle will occur during the use phase of the battery. This makes the battery internal efficiency and the charging efficiency very important parameters. The importance of keeping a system perspective and not omitting the use phase and the efficiency parameter is highlighted in Chapter 5.1.1.

Chapter 5.2.1 stems from the lithium-metal battery paper (D), in which it was noted that the lithium-iron-phosphate (LFP) battery scored higher in abiotic resource depletion than did a similarly sized lithium-nickel-manganese-cobalt-oxide (NMC) battery. The use phase contributions to abiotic depletion, due to the higher electricity consumption of the LFP system, hide the fact that the production phase contributions are higher from the LFP system, which is not what one would expect since both nickel and cobalt have been pinpointed as scarce materials (but not iron or phosphate)(Olivetti et al. 2017). This contradiction is further explored in Chapter 5.2.1.

Whether characterization factors for LCA toxicity impact include the materials present in many battery chemistries in an adequate way was questioned already in the introduction. Furthermore, the available LCA emission models for toxic chemicals used in lithium-ion batteries (LIBs) and their possible reaction products are limited to the production phase of chemicals. As an example, the tetraethylene-glycol-dimethyl-ether (TEGDME) electrolyte and the organic N-methyl-2-pyrrolidone (NMP) solvent used in the manufacturing of the lithium-air cell cathode in the lithium-air battery paper (C) are both considered toxic. Due to a lack of data, the potential emissions of these substances were not modelled in any phase. This caused the normal LCA toxicity evaluation to be misleading. To my knowledge, potential toxic emissions during cell manufacturing, the use of batteries and battery recycling are normally not modelled in vehicle LCAs; thus, most vehicle LCAs are misleading regarding toxicity assessments. To improve this situation, the idea of using chemical risk assessment (CRA) from a life cycle perspective, as in the structural battery paper (E), is further explored in Chapter 5.2.3.

When using LCA for eco-design purposes, it is desirable to minimize the number of environmental impact categories since they cannot be compared in a scientifically fully correct way and are difficult to communicate. However, a full picture of the environmental impact, not only the climate impact, is also desired. Table 1 shows the different environmental impact categories chosen in the battery-related papers. Chapter 5.2.4 discusses the choice of impact categories for traction battery LCA and presents a ranking list of the indicators.

The need for many different functional units for traction battery LCA studies due to different study objectives hampers comparisons between studies and the use of data from other studies. Table 1 shows the different functional units used in the battery-related papers. The point made in Chapter 5.2.2 is that there is often more than one relevant way to calculate the chosen functional unit and that presenting results calculated with several functional units facilitates comparisons and reflection and makes the study more useful for others.

The first two aspects in Table 1 on page 37, the total ISO 14044 LCA duration and with whom the goal and scope definition were decided, relate to the context in which the LCA work was done and the LCA process; that is, the research perspective is now the whole LCA process (research perspective 2), not the functional units in the respective LCA. The lithium-air (C) and lithium-metal (D) battery papers were larger projects and therefore allowed for several iterations of the ISO LCA cycle, starting with screening LCA, including an idea generation workshop at an early stage. The more time and iterations there are, the more participatory interactions are possible. However, the absence of an interested, demanding and paying commissioner was felt in all the projects. Therefore, fixed programs for LCA activities were introduced already in the description of work including: 1) screening LCA and safety study, 2) idea generation workshop on how to use results of screening LCA in technology development, and 3) full LCA to verify the environmental performance of the developed technology. Chapters 5.3.1 and 5.3.2 discuss how to improve the LCA process by engaging more personal categories and competencies in the process.

5 Discussion

In this chapter, the LCA results of the battery case studies (research perspective 1) will be used to discuss some key parameters and issues pertaining to the LCA of traction batteries. Then, the LCA methodology (research perspective 2) will be discussed in relation to traction battery LCA. The European project behind the lithium-air battery paper (C) bridges to the findings and discussions about the use of LCA in technology development in general.

This chapter is structured according to the three research questions. However, the questions and subsections are interrelated and, to some extent, contribute to answering the research questions in multiple ways, as shown in Table 2.

Table 2 Relation between the research questions and the following subsections.

Research question / *Subsection*	RQ1. What are the significant data issues related to LCA of present and future lithium traction battery chemistries?	RQ2. What are the significant methodological issues related to LCA of present and future lithium traction battery chemistries?	RQ3. How can LCA be used in product and production development to advance the introduction of the SCP of any new technology?
5.1.1 Keep a system perspective - do not forget efficiency	X		(X)[c]
5.1.2 Energy use for large-scale traction battery manufacturing	X		
5.2.1 Use two abiotic depletion measures to reflect scarce materials	(X)[a]	X	(X)[c]

Research question / *Subsection*	RQ1. What are the significant data issues related to LCA of present and future lithium traction battery chemistries?	RQ2. What are the significant methodological issues related to LCA of present and future lithium traction battery chemistries?	RQ3. How can LCA be used in product and production development to advance the introduction of the SCP of any new technology?
5.2.2 Calculate results for all relevant functional units		X	(X)[b]
5.2.3 Chemical risk assessment (CRA) from a life cycle perspective	(X)[a]	X	(X)[b]
5.2.4 Environmental impact categories for traction batteries		X	(X)[c]
5.3.1 Bring participatory action into LCA			X

[a]Example of the overlap between RQ1 and RQ2 in that the lack of data (RQ1) disqualifies certain methods (RQ2) and makes other methods (RQ2) more suitable.
[b]General applicability.
[c]General applicability with adaptation.

5.1 Data issues of traction battery LCA

In this chapter, the LCA results of the battery case studies (research perspective 1) will be used to discuss the importance of studying the whole life cycle of a traction battery, not only its production, so as not to ignore system efficiency, as well as the energy use for battery cell production. These two aspects primarily concern the first research question.

> RQ1. What are the significant data issues related to LCA of present and future lithium traction battery chemistries? Significant data issues refer to both what data are significant for the total life cycle results, i.e., the hotspots, and what specific data are missing or show large variability.

5.1.1 Keep a system perspective - do not forget efficiency

Assuming a global average electricity mix, the internal efficiency of a battery system is a key parameter from an environmental perspective. The associated environmental impact is neglected in battery LCA studies that do not include the use phase.

The climate impacts of the use phase for a traction battery vary greatly depending on the electricity mix. The carbon content can typically vary from 50 g of CO_2/kWh_{el} electricity in Sweden over the Western European (and global) average of 500 g of CO_2/kWh_{el} to well over 1,000 g of CO_2/kWh_{el} in China, Eastern Europe and parts of the United States. With the Swedish mix, the climate impacts during the use phase can be on the same order of magnitude as those of production and recycling. However, with the global average electricity mix, the climate impacts of the use phase account for approximately 80% of total impacts for an electric vehicle (EV); see, e.g., the lithium-metal battery paper (D). Approximately the same distribution applies to toxicity and ozone formation since all three impact categories are strongly linked to the burning of fossil fuels to generate electricity. Recycling has the potential to recover 10-20% of the production phase burdens (Cusenza et al. 2019)(Mats Zackrisson 2019), i.e., 2-4% of the total climate, toxicity and ozone formation burdens. To illustrate the discussion, a schematic diagram of the environmental burdens of an average EV is shown in Figure 11. The figure is constructed from data for a Nissan LEAF with a 24-kWh lithium-nickel-manganese-cobalt (NMC) battery and a Tesla Model S with an 85-kWh lithium-nickel-cobalt-aluminium (NCA) battery used as benchmarks in the lithium-metal battery paper (D). Note that the production and recycling phases only include the battery, while the use phase includes the electricity consumption of the whole vehicle. Abiotic depletion, which is discussed below, does not follow the same distribution of burdens over the life cycle compared to climate, toxicity and ozone formation. Figure 11 can be compared to the *European Union average* column in Figure 1 on page 2. One major difference is that *Other manufacturing* is not included in Figure 11. Judging from Figure 1, the manufacturing of the rest of the vehicle can be of the same magnitude as *Production of battery* in Figure 11. Another major difference is that in Figure 1, *Lithium battery* production is approximately half of *Fuel cycle*, whereas *Production of battery* is only a quarter of *Use of BEV* in Figure 11. The main reason for this difference is that Figure 1 distributes production burdens over

150,000 km of service life, whereas Figure 11 distributes production burdens of calculated service life considering both the depth of discharge and battery capacity, resulting in much longer service life and, thus, less production burdens per kilometre.

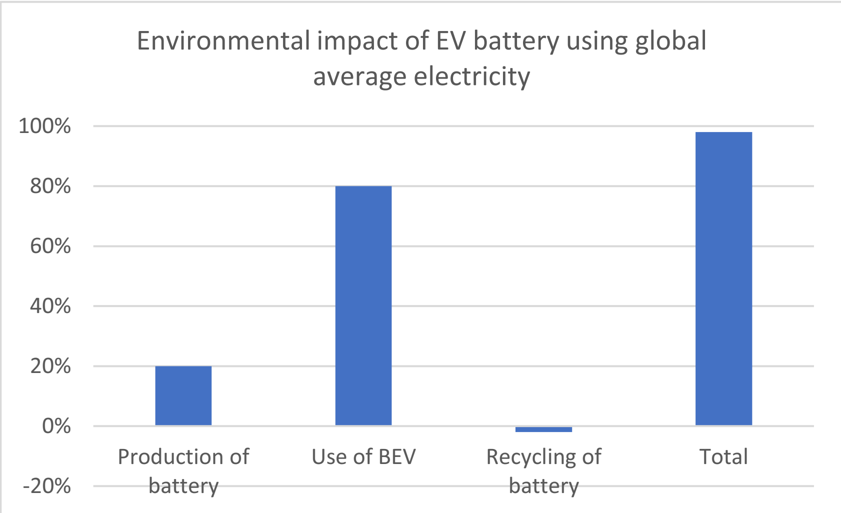

Figure 11: Schematic diagram comparing the environmental impacts of battery production and recycling with the use phase of battery electric vehicles (BEVs) driving on average European electricity.

Some examples of how different changes will affect the environmental impact of the total life cycle are as follows:

- One hundred percent improvement in battery life, i.e., doubling battery life, means that the environmental impacts from production and recycling (18%) decrease by 50% since the impacts are distributed at double distances, i.e., 9% less total environmental burdens. However, since Figure 11 assumes a long service life (227,000 and 593,000 km), 100% improvement will be difficult to achieve. It is more realistic to achieve 100% improvement in the 150,000-km service life used in Figure 1; thus, Lithium battery and Other manufacturing burdens will be distributed at double distances and thus halved. For the European Union average column, this will mean a reduction in Lithium battery and Other manufacturing burdens from 57% to 40% of the total burdens. Approximately half of that, i.e., 8.5%, is from the battery, which compares well with the 9% improvement calculated using Figure 11.

- Reducing battery weight by 20% means 2% less electricity consumption for a Nissan Leaf and 3.3% less electricity consumption for a Tesla model S[1], and thus also the same decrease in climate, toxicity and ozone formation impact in the use phase. If the heavy vehicle battery becomes 20% lighter, then it will most likely lead to secondary weight savings in the vehicle of at least the same magnitude. Thus, we can expect, on average, 5% less vehicle electricity consumption due to 20% battery weight savings; 5% of 80% is 4%; thus, total environmental burdens are reduced by only 4%.

The two examples above are from the Horizon 2020 call *LC-BAT-10-2020: Next generation and realisation of battery packs for BEV and PHEV*, in which 20% overall life cycle improvement was to be achieved by 20% reduced battery system weight and 300,000 km of battery life. As 9% plus 4% is way off the target of 20%, additional innovations had to be envisaged, two of which are described below:

- If the driver of the EV can be induced to use more solar and wind power electricity, say, for 10% of the mileage, then it will reduce total impacts with 10% x 90% x 80%=7% because solar and wind power electricity has approximately 90% less impact than does global average electricity and the use phase is 80% of total impacts. This was to be achieved by a GPS- and cloud-connected battery management system that could, among other abilities, steer the driver towards vacant charging stations with green electricity in a timely manner. Ten percent is a very low estimation of the potential of such a device. Fifty percent more solar and wind power would mean 50% x 90% x 80%= 36% less total environmental impacts.
- It is important to keep in mind that from an environmental perspective, the charge/discharge efficiency is more important than the energy density (Peters et al. 2015). Thus, efforts to increase the energy density of the pack must not be to the detriment of the charge/discharge efficiency. Every percent decrease in the charge/discharge efficiency will give the same percentage increase in use phase electricity consumption and climate, ozone formation and toxicity impacts and almost the same total increase (80%). Since the LC-BAT-10-2020 project envisaged innovations related to both the thermal management

[1] 20% x 294 kg x 0.65 kWh/100 kg 100 km/0.1863 kWh/km=2% for the Nissan Leaf; see the lithium-metal battery paper for data on the vehicles and (Forell, Busa, and Wilbert 2016) for an energy reduction value of 0.65 kWh/100 kg 100 km.

and the battery management system, the charge/discharge efficiency was under scrutiny.

The importance of the charge/discharge efficiency was highlighted in the lithium-ion battery paper (B) and further accentuated in the lithium-air battery paper (C), which highlights the importance of losses during the use phase due to the low efficiency of the lithium-air cell. The low efficiency of lithium-air cells has been confirmed by Fenfen Wang and Yelin Deng (2020), but many LCA studies of future battery chemistries neglect the use phase; e.g., Santos et al. (2020) studied only the production phase of a zinc-air battery cell, Raugei and Winfield (2019) neglected the use phase in their prospective LCA of a novel lithium-cobalt-phosphate chemistry, Wang et al. (2020) found the lowest ecological, carbon and water footprint in lithium-air cells compared to lithium-sulphur and sodium-ion cells, and Mcmanus (2012) omitted the use phase in a comparison of lead acid, nickel cadmium, nickel metal hydride, lithium ion, and sodium sulphur batteries. Thus, such "LCA" studies miss examining the most important life cycle stage related to environmental impact.

Another example of an omission is the system boundary applied in all the battery-related papers, which neglects the losses in external chargers, which can amount to 15% according to Lam et al. (2019). In comparisons with internal combustion vehicles (ICVs), not including 15% charging losses is definitely wrong; in comparisons between batteries or electric vehicles (EVs), a large improvement potential is left unexamined. Fifteen percent of use phase impacts equals 12% of the total impacts of an EV in a global context; thus, external losses during charging deserve to be paid much more attention and be highlighted in future research and development.

As the world moves more towards renewable sources of electricity production, closer to the current Swedish mix, the 20/80% distribution of environmental burdens between the production and use of an EV will move towards a 50/50% distribution. In a 50/50% setting, production improvements are just as important as use phase improvements.

5.1.2 Energy needs for large-scale battery manufacturing

There is a general lack of primary, or specific, data about battery cell manufacturing. The amount of energy needed to produce traction battery cells is a case in point. The triangulation of data from several recent sources suggests that 60 +/- 10 kWh_{el}/kWh_c is reasonable to assume for the large-scale manufacturing of lithium-ion batteries (LIBs) if no plant- and chemistry-specific values are available.

Two recent studies by Dai et al. (2019) and Kurland (2020) have provided primary or semi-primary data about large-scale LIB manufacturing. Dai et al. presented life cycle inventory (LCI) data representative of cell production and pack assembly in 2017 at one of the world's top ten automotive LIB producers in China. Kurland looked at the application for the environmental permit for the NorthVolt Ett LIB plant in Skellefteå, Sweden, and the electricity and gas franchise fees for Tesla Gigafactory 1 in Nevada, USA. Kurland triangulated the studies and adjusted the data from Dai with respect to cell formation energy (Kurland 2020). These three data points were numerically quite similar, and they all referred to the modern large-scale industrial production of lithium-nickel-manganese-cobalt (NMC) battery cells. Modern in this context means new, large-scale means a production capacity between 3 and 35 GWh_c/year, and NMC is presently the most common chemistry for traction batteries. Note that upstream energy needs for the mining and production of cell raw materials are not included in what is here referred to as battery manufacturing. Upstream burdens may, according to Dai et al, (2019), constitute 80% of the total cradle-to-gate energy needs.

Table 3: Energy for large-scale NMC cell production.

Source	Reference	Value[a] (kWh_{el}/kWh_c)
Leading Chinese LIB manufacturer	(Dai et al. 2019)	60
Northvolt Ett	(Kurland 2020)	50
Tesla Gigafactory 1	(Kurland 2020)	65
Northvolt	(Linda Nohrstedt 2018)	60-80
Suggested in absence of a specific value		60 +/-10

[a]Note that cell production energy is approximately 20% of total battery pack production (Dai et al. 2019).
kWh_{el} is kilowatt-hour electricity.
kWh_c is kilowatt-hour battery capacity.

Considering that previous industrial figures are 2-3 times higher (Kim et al. 2016; Ellingsen et al. 2013; Ellingsen et al. 2017), the lithium-ion battery paper (B), and the fact that Northvolt itself had estimated the electricity need to be 60-80 kWh_{el}/kWh_c (Linda Nohrstedt 2018), it seems reasonable to assume 60 +/-10 kWh_{el}/kWh_c for large-scale manufacturing in future LIB studies if no plant- and chemistry-specific values are available. Most of the energy during cell production is used to create dry room conditions, cure or dry the electrodes and formation of the battery cells (Dai et al. 2019; Kurland 2020). Electricity can be used for all these processes, but the first two can also use heat (from gas, steam, or hot water). However, in the absence of specific data, electricity is the best approximation (Kurland 2020). Note that specific data are always preferred and can differ greatly. A recent study reported 763 kWh process energy/kWh_c for pilot plant production (Thomitzek et al. 2019). Conversely, an even more recent study of large-scale Chinese LIB production claimed 20 kWh of electricity and 9 kWh of steam per kWh of battery capacity (Sun et al. 2020).

The assembly of cells in modules and battery packs is considered to need negligible extra amounts of energy compared to that needed for cell production (Dai et al. 2019). Thus, the value suggested can also be used as an approximation for cell production followed by battery assembly; i.e., 60 kWh_{el} per kWh cell is approximately equal to 60 kWh_{el} per kWh battery. Note that raw material extraction and preparation upstream cell and battery manufacturing are not included in this figure but should, of course, be part of the complete model of cell production.

5.2 Methodological issues of traction battery LCA

In this chapter, how to measure abiotic depletion and toxicity in battery LCA studies and the utility of calculating results for several functional units will be discussed. These two aspects concern the second research question.

RQ2. What are the significant methodological issues related to LCA of present and future lithium traction battery chemistries? Methodological issues refer to the process or way of carrying out LCA. There is an overlap between RQ1 and RQ2 in that the lack of data (RQ1) disqualifies certain methods (RQ2) and makes other methods (RQ2) more suitable.

5.2.1 Use two abiotic depletion measures to reflect scarce materials

To both follow the current guidelines and reflect the current criticality issues, it is recommended that two measures for abiotic depletion potential be used.

In the lithium-metal battery paper (D), it was noted that the lithium-iron-phosphate (LFP) battery scored higher in abiotic depletion compared to a similarly sized lithium-nickel-manganese-cobalt (NMC) battery. The cause was higher electricity consumption in the use phase due to a heavier LFP battery. Nevertheless, this contradicts the pinpointing of cobalt and nickel as scarce materials that can limit the production of the currently most popular NMC technology (Olivetti et al. 2017)(Greim, Solomon, and Breyer 2020). Additionally, in the lithium-air battery paper (C), difficulties in interpreting the results of abiotic depletion were noted because of a recent change in the method used. Peters and Weil (2016) found that very different results are obtained with the existing abiotic depletion impact assessment methodologies in the context of EV batteries, which hinders their clear interpretation.

To better understand which abiotic depletion method should be used, a contribution analysis was carried out with the three different life cycle abiotic depletion impact methods available in the CML impact assessment method in SimaPro. The CML method was developed by the Institute of Environmental Science of the Faculty of Science of Leiden University in the Netherlands and is recommended in the ILCD Handbook (JRC 2011) for the measurement of abiotic depletion.

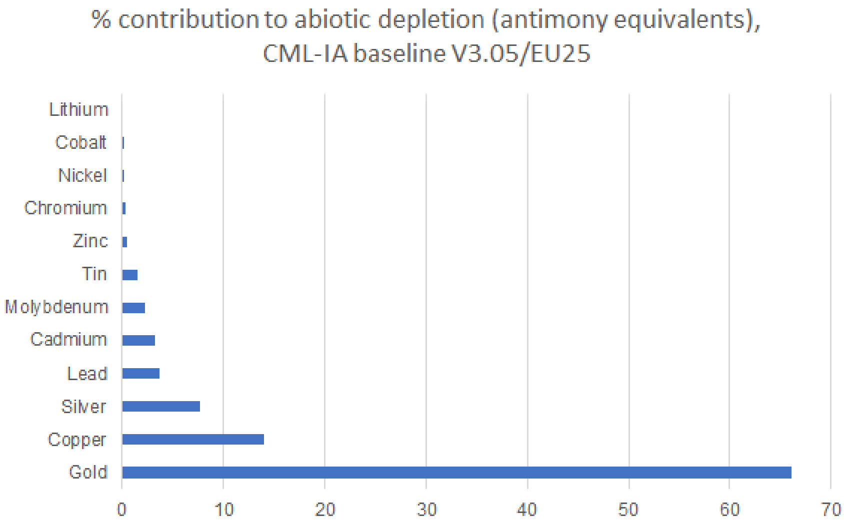

Figure 12: Life cycle contribution to abiotic depletion as antimony equivalents of an NMC333 traction battery, method CML-IA baseline V3.05/EU25, ultimate reserves. Own analysis based on paper D.

With the CML-IA baseline V3.05/EU25 method, most of the abiotic depletion, 66%, stems from gold in the electronics of the battery system, i.e., not from the cell. Lithium, nickel and cobalt together contribute less than 0.5% to abiotic depletion according to this method. It is clear that this method used to assess resource depletion, the CML-IA baseline version 3.05, does not pinpoint the materials currently being pinpointed as critical in the context of traction battery production. However, the non-baseline versions of the same method do; see Figure 13 and 14. Thus, it seems important to use the non-baseline versions to obtain LCA results that can relate to today's issues of criticality.

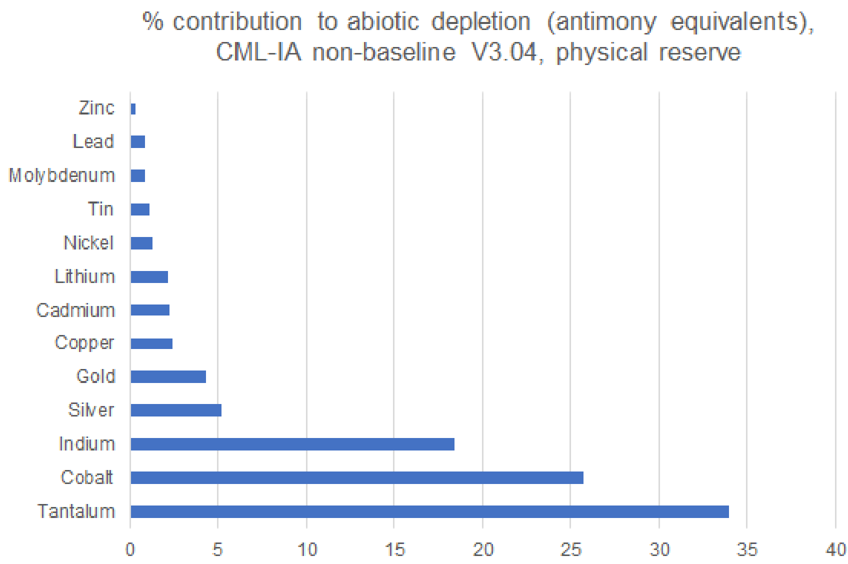

Figure 13: Life cycle contribution to abiotic depletion as antimony equivalents of an NMC333 traction battery, method CML-IA non-baseline V3.04 / EU25. Own analysis based on paper D.

Tantalum and indium are used primarily in the electronics in the rest of the battery pack. Cobalt, lithium and nickel stem from the cell.

The non-baseline version comes in two versions: abiotic depletion (elements, reserve base/physical reserve) and abiotic depletion (elements, economic reserve). Berger et al. (2020) argued that the choice of method depends on what should be quantified:

1. “the changing opportunities of future generations to use mineral resources due to the current mineral resource use” or
2. “potential mineral resource availability issues for a product system”.

Criticality issues are closer to question 2; thus, the method used should preferably be based on the physical or economic reserve rather than on the ultimate reserve. Another way of describing the difference between ultimate reserve and economic reserve is that using the ultimate reserve as the basis reflects long-term criticality issues, while using the economic or physical reserve as the basis reflects short-term criticality issues. Figure 14 shows the abiotic depletion calculated with the non-baseline CML method based on economic reserves.

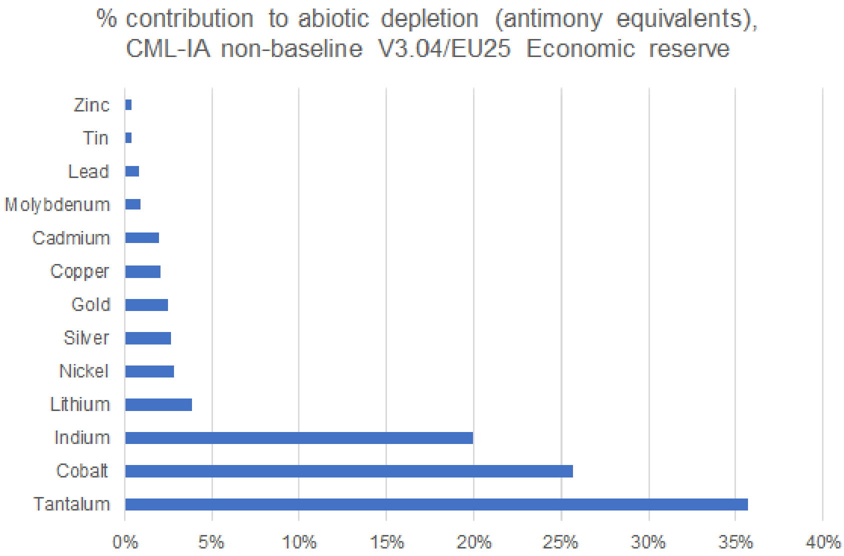

Figure 14: Life cycle contribution to abiotic depletion as antimony equivalents of an NMC333 traction battery, method CML-IA non-baseline V3.04 / EU25 Economic reserve. Own analysis based on paper D.

Both non-baseline versions capture the short-term criticality issues of NMC cells much better than the baseline version. Cobalt is the second most critical material for both non-baseline methods. Lithium and nickel are the number four and five most critical materials for the non-baseline method based on economic reserves and the number eight and nine most critical materials with the non-baseline version based on physical reserves, respectively. Therefore, to reflect the current scarcity in the context of electric vehicles, the non-baseline CML versions of abiotic depletion potential must be used.

The ILCD handbook (Wolf and Pant 2012) actually recommends using the reserve base version of the CML method for calculating abiotic depletion. However, it fails to point out that this version of the method is only available in the non-baseline version, which is not where you expect to find a recommended method. More recent guidelines, like the general PEF guidance (European Commission 2017), recommend, however, the ultimate reserve version. Furthermore, (Oers 2020) recently updated the ultimate reserve version and concluded that “using the ultimate reserve based on the crustal content gives a better and more robust indicator of reserve". The updated indicators (Oers 2020) for lithium, cobalt and nickel have the same relation to, for example, copper as in the non-updated indicators used in the figures above, i.e., a factor 100 to 1,000 times smaller. Thus, following the PEFCR for batteries (Recharge 2018)(Niklas Hill, Samantha Morgan-Price 2020) concerning the choice of method for measuring abiotic depletion will not reflect the current resource concerns related to batteries. To follow the current guidelines and reflect the current criticality issues, it is therefore recommended that both the ultimate reserve version (to follow the guidelines and reflect long-term criticality issues) and the economic reserve version (to reflect short-term criticality issues) of abiotic depletion be calculated.

5.2.2 Calculation of the results for all relevant functional units

The plethora of functional units recommended by different guidelines for LCA of traction batteries is a barrier for comparisons between studies, yet unavoidable since the choice of functional unit depends on the purpose of the study. It is strongly recommended to provide results relative all functional units or reference flows that are relevant for the study.

As described in the introduction, there are several LCA guidelines applicable for traction batteries, and their recommendations concerning functional units differ because the guidelines have different objectives. A dividing line is if the guideline is meant for comparisons of different vehicles or if its purpose is to compare or label batteries. The former uses *vehicle km,* and the latter uses *delivered kWh*. In addition, there are LCA studies with the main purpose of discussing and supplying LCA data, in which *kWh battery capacity* or even *kg battery* is used. Philippot et al. (2018) characterized these four functional units as measured in distance, in delivered energy, in energy content, or in battery weight. Dolganova et al. (2020) investigated over one hundred LCAs on electric vehicles performed between 2009 and 2018 and found that most studies used a functional unit related to the battery capacity in MJ or kWh but that kilometres was also a common functional unit.

Considering that some studies report results per vehicle life or battery life, which is then the sum of all the kilometres assumed, all the kWh delivered or the whole X kg or Y kWh battery, at least eight different units are commonly used in LCA traction battery studies. This plethora of functional units is a barrier to comparisons between studies, but since the choice of functional unit depends on the purpose of the study, it is not possible to suggest any one of them as being superior to the others.

However, it is strongly recommended that results relative to all functional units or reference flows, which are relevant for the study, be provided. For example, the lithium-ion battery paper (B) presented results for one 10-kWh battery weighing 107 kg. Then also providing the results per kWh battery capacity and per kg battery is relevant and uncomplicated and facilitates comparisons. However, it is not relevant to present results per km since this plug-in hybrid electric vehicle (PHEV) battery only covered 75% of the mileage, with the rest of the mileage being supplied by an internal combustion engine (ICE) outside the system boundary. This also illustrates one problem with PHEVs: they need two systems, and if these systems are designed to maximize output power to attract affluent customers, then their environmental impact will increase; see Chapter 1.1.1.

The preferred functional units for traction batteries applied in BEVs are distance (Andrea Del Duce et al. 2013)(Hill et al. 2020) and/or delivered energy (Recharge 2018). Just as weight is linked to energy content through a battery's energy density, distance is linked to delivered energy through vehicle electricity consumption and total life cycle mileage; i.e., delivered energy equals vehicle electricity consumption multiplied by the total life cycle mileage. The lithium-air battery paper (C) presents results both in relation to distance (vehicle km) and in relation to delivered energy (delivered kWh).

For comparisons of vehicles, distance is the preferred functional unit (Andrea Del Duce et al. 2013). The total life cycle climate impacts of an electric vehicle (EV) battery can then be benchmarked against the European passenger car fleet standards of 95 g of CO_2-eq/km by 2021 (European Commission 2009). Even if this standard only applies to tailpipe emissions today, life cycle standards are mandated in Regulation 2019/631 (European Commission 2019) and can thus be expected in the future.

It should be noted that the life cycle system boundary in the battery-related papers was limited to the production, use and recycling of the battery. The reason for this was to focus on the main part of an electric vehicle. By gradually including more parts of the electric power train and the vehicle body, an increasingly complete electric vehicle LCA can be achieved while keeping the same basic LCA calculation model.

5.2.3 Chemical risk assessment from a life cycle perspective as a way of developing LCA

Most vehicle LCAs are misleading regarding toxicity assessments for several reasons. To improve the situation, it is suggested that chemical risk assessment (CRA) from a life cycle perspective be used as a temporary remedy and a way to develop robust within-LCA methods to measure toxicity.

Traction battery LCA, which tries to assess toxicity, ignores many toxic effects due to a lack of LCA toxicity characterization factors as well as emission data in the different life cycle stages. Metals (particularly lithium), electrolytes, fluorine-containing binders and toxic production solvents (e.g., N-methyl-2-pyrrolidone) are all examples of this. Since a lack of LCA data results in zero impact, it is often also interpreted this way, which can lead to a false sense of security. The abovementioned substances can lead to risks during precursor preparation, in cell manufacturing, during transport, in the use phase, and during recycling and disposal (Lebedeva et al. 2019; Pinegar and Smith 2020; Larsson et al. 2017; Hamuyuni and Tesfaye 2019). As a temporary remedy and way of developing LCA in this context, it is proposed that the current LCA toxicity measures be replaced with chemical risk assessment (CRA) from a life cycle perspective, as described in the structural battery paper (E).

In technical development projects and industrialization projects, CRA is legally mandatory in many countries; i.e., it is done irrespective of any LCA being done. The knowledge gained in a normal CRA, preferably extended to a life cycle perspective, can also be used in LCA. Therefore, chemical experts, who do not necessarily need to be LCA experts, can be engaged and bring knowledge to the specific LCA and to LCA practice in general. Considering that many LCA practitioners are not chemical experts and therefore find it difficult to develop the currently inadequate LCA toxicity assessment of traction batteries, using CRA in this context can eventually lead to the development of LCA methods and data to be "good enough for the life cycle toxicity assessment of traction batteries". Normal CRA is not quantitative and standardized, as is LCA, but CRA uses all available information on toxicity and covers all known toxic effects.

These features also make CRA suitable for the development of standardized[2] LCA.

CRA, from a life cycle perspective, as described in the structural battery paper (E), is a way of developing the capability of LCA to cover toxicity issues with traction batteries in an adequate way. However, this development will not happen by itself simply by using CRA from a life cycle perspective in LCA traction battery studies. In addition, a concerted effort to translate and transfer the knowledge gained by conducting CRA in battery studies into LCA battery datasets and LCA impact methods is needed, similar to what has been done in the textile sector by Roos (2016).

CRA was also used in relation to the lithium-ion battery paper (B) and the lithium-air battery paper (C). In the lithium-ion battery paper, a separate CRA report was issued pointing towards N-methyl-2-pyrrolidone (NMP) and polyvinylidenfluoride (PVDF) as problem chemicals (Posner 2009). Neither of these substances were used in the water-based lithium-iron-phosphate (LFP) cell that was the focus of the paper and were only used in the LFP cell used to compare them with the water-based LFP cell.

In relation to the lithium-air battery paper (C), CRA was made obligatory for all laboratories involved in the project. The main argument for performing CRAs was to lower and control chemical risks at the respective laboratory, but these CRAs were also used to engage project staff to contribute inputs to the screening LCA carried out early in the project (see a further description below). As mentioned above, since CRA is legally mandatory in many production contexts, it makes sense to use the information gained from it to strengthen the toxicity part of any LCA being carried out in the same context.

5.2.4 Environmental impact categories for traction batteries

When using LCA for improvement purposes, it is desirable to minimize the number of environmental impact categories. For traction battery LCA, climate impact, abiotic depletion, respiratory inorganics, acidification, ozone formation and eutrophication are ranked as the most important impact categories to include (in that order).

As noted in Table 1, the battery-related papers have used/reported different sets of environmental impact categories in all the studies. Table 4

[2] LCA is standardized in ISO 14040 and ISO 14044, but, here, it refers to more implicit standardization in the form of the development of best practice, concerning the characterization factors in life cycle impact assessment methods.

summarizes the recommendations in the relevant guidelines and shows the choices made in the battery-related papers.

Table 4: Environmental impact categories for traction battery LCA.

Impact category/Guideline	**1**	**2**	**3**	**4**[a]	***5***	***Battery related papers in this thesis***
Climate change	X	X	X	X	X	B, C, D, E
Ozone depletion	X				X	
Human toxicity	X	X		X[b]	X	C, D
Respiratory inorganics	X		X	X[c]	X	
Ionizing radiation	X				X	
Photochemical ozone formation	X	X		X[d]	X	B, E
Acidification, land	X	X			X	B
Acidification, water	X			X		
Eutrophication, land	X					B
Eutrophication, water	X	X		X	X	
Ecotoxicity	X	X		X	X	C, D
Land use	X				X	
Resource depletion, mineral	X	X	X		X	C, D, E
Resource depletion, energy	X	X	X		X	
Water scarcity					X	

1. Guidelines for the LCA of electric vehicles by Andrea Del Duce et al. (2013)
2. LCA guidelines for electric vehicles by Loon et al. (2018)
3. PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications (Recharge 2018)
4. Preparatory Study on Ecodesign and Energy labelling of Batteries (Lam et al. 2019)[a]
5. Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA - Interim Report (Hill et al. 2020)

[a]The ecodesign directive has its own 13 categories, many of which are emissions or waste that does not fit into any LCA impact category and therefore not listed.
[b]Persistent organic pollutants (POPs), heavy metals to air, polyaromatic hydrocarbons (PAHs).
[c]Particulate matter (PM), dust.
[d]Volatile organic carbon (VOC).

There is a general desire to minimize the number of impact categories since they cannot be compared in a scientifically fully correct way and thereby limits the possibility of drawing conclusions in terms of how to improve environmental performance. In this context, it should be noted that the PEFCR guidelines (Recharge 2018) base their recommendation on normalization and weighting; i.e., they claim that climate impact, respiratory inorganics and resource depletion are the most important environmental indicators to include in the battery context.

It is questionable to include an impact category knowing that important impact characterization factors or emission data are missing. As discussed above, this can lead to a false sense of security. Additionally, fair comparisons with ICVs should be facilitated. The standard (ISO 2006c) mentions many criteria for selection (relevance, international acceptance, comprehensiveness, etc.) but does not rank them. Based on Table 4 and the above discussion, a ranking list for impact categories for traction batteries is suggested in Table 5.

Table 5: Ranking list for impact categories for traction batteries.

Rank	Impact category	Motivation
1	Climate impact	Relevant for both internal combustion vehicles (ICVs) and electric vehicles (EVs). International consensus on science and urgency. Strongly linked to fossil fuel combustion for electricity or in ICVs.
2	Resource depletion, mineral and metals	Very relevant for EVs. Choose the *ultimate reserve* as the base to follow the current guidelines and/or the *economic reserve base* to reflect current scarcity of battery metals; see Chapter 5.2.1.
3	Respiratory inorganics/particulate matter	Relevant for both EVs and ICVs. Dust from tyres, brakes and combustion.
4	Acidification	Strongly linked to fossil fuel combustion for electricity but not so much for vehicle fuel combustion due to regulations.
5	Ozone formation	Strongly linked to fossil fuel combustion for electricity and in ICVs.
6	Eutrophication	Strongly linked to fossil fuel combustion for electricity and in ICVs.

Toxicity is not listed since the recommendation is to cover toxicity with chemical risk assessment (CRA) from a life cycle perspective in LCA of traction batteries; see Chapter 5.2.3. It can be argued that since climate impact somehow “covers” the link to fossil fuel combustion for electricity or in ICVs, ozone formation and eutrophication are less needed. Acidification is slightly different since sulphur is removed in most vehicle fuels but less so in electricity production fuels. Respiratory inorganics or particulates “cover” health issues stemming from combustion emissions of ICVs and increased particulate emissions of EVs due to increased weight

(Hooftman et al. 2016). Resource depletion measures the scarcity of metals, which is very relevant for EVs. Three or four indicators plus CRA from a life cycle perspective is manageable and will cover the current issues of EVs and ICVs reasonably well. All indicators can be calculated with the "ILCD 2011 Midpoint+" method available in SimaPro.

5.3 Technology development and LCA

In this chapter, some more battery related LCA methodological issues (requiring research perspective 2) will be discussed. Early in technology development projects, at low technology readiness levels (TRLs), there is a lack of data, and environmental issues are rarely a top priority. Chemical risk assessment, screening LCA and idea generation workshops are suggested as ways to engage different experts in LCA work and improve it. These aspects relate to the third research question.

RQ3. How can LCA be used in product and production development to advance the introduction of the sustainable consumption and production of any new technology?

5.3.1 Bring participatory action into LCA

There is room for more participatory action in LCA. Companies looking to build LCA into their product development cycles can benefit from simplified LCA early on in technology development projects and the engagement of key staff to interact with LCA experts in defining the goal and scope, inventory of data, idea generation workshops and chemical risk assessments from a life cycle perspective.

Nordelöf (2017) found that *"LCA studies covering electrified vehicles generally fail to report the goal and scope definition in accordance with ISO standard"* and argued that this is a main cause for the results in the research field appearing to be divergent and inconsistent. While discussing whether stricter guidelines, like those of the PEFCR (Recharge 2008), can improve goal and scope reporting, Nordelöf settled *on "if only the existing ISO standard* (ISO 2006c) *is brought into use as intended"*. Presumably, the correct use of the ISO standard will lead to the goal and scope being correctly reported.

According to ISO 14044, defining the goal of the LCA requires describing its intended application, the reasons or driving forces behind carrying out the study and the intended audience, as mentioned in page 13. Furthermore, it includes deciding whether the results are intended to be used in comparative assertions for public use. Defining the scope involves describing the product system to be studied, including the system boundaries, its function and the associated functional unit. Allocation procedures, environmental impact categories including value choices, data requirements, critical assumptions and limitations, critical review and report format are also considered during the defining of the goal and scope. Deciding on such questions naturally requires close interaction with the commissioner of the study, but the standard does not provide any guidance on who should participate in defining the goal and scope. In many instances, it is still obvious that the commissioner that ordered the study and holds all the knowledge and data about the study object must take part in defining the goal and scope. In other instances, e.g., in large EU projects, it is less clear who the commissioning party should be. The LCA is there to verify environmental improvements because the call text demands it, but there is no clear commissioner within the project consortium. EU project officers do not have the time to be intensely involved in projects.

The lithium-air battery paper (C), developed in an EU technical development project, used three tasks to build engagement for the LCA among project partners: 1) screening LCA and safety study, 2) an idea generation workshop on how to use the results of the screening LCA in technology development, and 3) full LCA to verify the environmental performance of the developed technology. One iteration of the goal and scope definition is accomplished within tasks 1 and 2, followed by another iteration in task 3. The three-task procedure was developed from experiences with the stepwise environmental product declaration (EPD) project in the stepwise EPD paper (A), in which the following stepwise process was used:

1. Goal and scope definition together (an LCA expert and an expert from a small and medium-sized enterprise (SME)). A short day's exercise including also an introduction to LCA and stepwise EPD, analysing and deciding which product or product group to focus on, and introducing the data collection procedures.

2. Inventory by the SME of the resources and emissions from their own production associated with the target product with support from the LCA expert.
3. LCA calculations and outlined stepwise EPD by the LCA expert.
4. Examination of LCA and drafting of the EPD together (SME and LCA expert).
5. Critical review of the stepwise EPD by another LCA expert.
6. Idea generation workshops to brainstorm environmental improvement opportunities, including additional SME staff.

Note that all steps, except for step 3, involve active cooperation between LCA expert(s) and SME counterpart(s) and that the ISO cycle (goal and scope; inventory; impact assessment; and interpretation) is followed, with steps 4 and 5 counted as interpretation and step 6 counted as idea generation bridging over to application; see Figure 10 in page 27. It should be noted that the critical review of the LCA according to ISO 14044 (ISO 2006c) is very much focused on the LCA procedure, while the verification of an EPD according to ISO 14025 (ISO 2006a) also involves data checking to a large extent. The verification of an EPD therefore requires more presence of the commissioner's staff, whereas the critical review according to ISO 14044 is more an affair between the critical reviewer and the LCA practitioner. Thus, EPD verification can provide alternative interpretations of the result and possibly initiate alternative applications.

Idea generation workshop

The ten idea generation workshops presented in the stepwise EPD paper (A) resulted in 162 product improvement ideas, 23 of which were evaluated as significant (from an environmental perspective) and 15 of which were implemented within the time frame of the two-year project. Seven of the ten companies identified their main environmental impact during production and three during the use phase. It is expected that most improvement ideas will be found in the dominant phase, but this was not analysed. Typically, half a day was used for these workshops that involved a mix of staff functions. The companies involved were generally very enthusiastic about the findings. Many of them described the main benefit of the whole project as one of learning more about their product's environmental performance and how it could be improved. The idea generation workshops together with the examination of the LCA (step 4 of the stepwise process described above) were the main activities for achieving this learning. Idea generation workshops have since been offered routinely by the author as part of any normal LCA project involving a single client company. The LCA results are embraced by the commissioning company's staff, and the number of ideas generally runs very high. The psychology behind this finding seems to be that to take part in idea generation, one must embrace the results, and no one wants to be left out. Often, ideas are not new but have been hiding in someone's desk waiting for the right time to be implemented.

In an idea generation workshop, as described here, the LCA results are presented to and perceived/interpreted by individuals with experiences and knowledge other than those involved in the LCA up to this point. This could possibly lead to the emergence of alternative interpretations of the results. However, the main benefit of idea generation, as described here, is to spread the LCA results and engage the staff of the commissioning company to improve the product's environmental performance, i.e., to bridge it with direct applications; see Figure 10 in page 27.

The engagement potential of idea generation was the main reason for using it in the EU project to develop lithium-air battery cells (the lithium-air battery paper (C)). One problem with this kind of technology development project, or any technology development project for that matter, is that environmental issues do not have top priority. Thus, to raise environmental awareness early in the project, before all design parameters are decided on and difficult to change, LCA screening followed by idea generation was carried out. At the end of the four-year project, a full LCA to verify technology development achievements was carried out. Thus, two complete ISO LCA cycle iterations were carried out. Companies looking to build LCA into their product development cycles can benefit from this experience. The key learnings/advice are as follows:

- perform screening or simplified LCA early on in technology development projects,
- engage key staff to interact with the LCA expert in the goal and scope, inventory and interpretation phases,
- use idea generation workshops to broaden engagement among staff and generate ideas to improve product environmental performance, and

- engage health and safety staff in chemical risk assessment from a life cycle perspective.

5.3.2 Prospective LCA challenges

There seems to be a broad consensus (Thonemann et al. 2020)(Bergerson et al. 2020)(Tagliaferri et al. 2016)(Cucurachi et al. 2018) around the definition by Arvidsson et al. (2017) that "an LCA is prospective when the (emerging) technology studied is in an early phase of development (e.g., small-scale production) but the technology is modelled at a future, more-developed phase (e.g., large-scale production)". There is no guidance in ISO 14044 on how to compare new or immature technology with old and mature technology. However, the attention and rigour put forth by the standard to comparisons and comparative LCA seems to have created a best practice very close to the definition of Arvidsson et al. (2017). Thus, LCA practitioners struggle with scaling the laboratory data of emerging technologies to industrial-scale production to compare them with the present technology, as LCA results are best understood when they are compared.

It should be noted that only the structural battery paper (E) was recognized as prospective by Thonemann et al. (2020) in their extensive search of prospective LCAs, although the lithium-air battery paper (C) and the lithium-metal battery paper (D) are just as prospective as the structural battery paper. The obvious reason for not being recognized as prospective is the lack of that (or similar) word in the title and among the keywords. This is an indication that prospective LCAs are much more common than suggested by Thonemann et al. (2020), who found only 44 prospective LCA studies, of which the structural battery paper (E) was included. As noted by Buyle et al. (2019), *"Every decision-oriented life cycle assessment entails, at least to some extent, a future-oriented feature"*.

LCA has been mandatory in EU technology development projects for verifying environmental improvement since the seventh framework programme was launched in 2007 (European Commission 2020a). A good reason for performing LCA at an early stage of technology development is to identify potential environmental hotspots at low technology readiness levels (TRLs) when they are much easier and less expensive to rectify (Buyle et al. 2019). However, at very low TRLs, there are hardly any data at all, which makes LCA difficult. A way of dealing with this lack of data at early stages was described in the previous chapter: start with a screening LCA, supported by chemical risk assessment (CRA), and follow-up with an idea generation workshop. Screening or simplified LCA is suggested because there is not much else that can be done with little quantitative data. CRA needs to be done anyway and will bring data and engagement to the LCA process. Idea generation creates a common understanding of the LCA results and challenges, builds engagement among project partners and is a platform for bringing forward eco-design ideas. At the end of the project, regardless of the TRL, a full LCA, complemented with a CRA from a life cycle perspective, should verify the performance of the implemented eco-design.

Returning to research perspective 1, the LCA results, determining the energy needs for cell production is a good example of the difficulties involved in scaling data correctly. Dunn et al. (2014) noted estimations of average values between 1-400 MJ/kg battery for battery assembly (including cell production and cell assembly). Average values simply do not vary that much. It is important to scale as correctly as possible: if the value is too low, then a potential hotspot can remain undetected, while if the value is too high, then it may lead to the abandonment of the emerging technology; too much variation can make it impossible to draw any conclusions from the data. Additionally, scaling can benefit from the increased participation of other experts in the LCA, in this case, production/industrialization experts.

6 Conclusions and recommendations

This chapter reflect on the generalizability of the conclusions and recommendations. The chapter ends with the conclusion that future research needs in the expansive field of traction batteries are enormous. The mitigation of the environmental impacts of battery charging and charging infrastructure as well as during the recycling of different LIB chemistries are presented only as examples of the author's own research interests.

6.1 Main conclusions and recommendations

The main objective of this thesis and the research behind it is to facilitate the use of LCA for improving the environmental performance of electric vehicle traction batteries. This was achieved primarily by making inventory data available for future battery chemistries but also by highlighting the critical parameters and methodological issues pertaining to electromobility. This thesis also aims to contribute to sustainable industrial and societal change at large by paving the way for the increased and improved use of LCA by industries. To meet these aims, three research questions (RQs) were formulated (see Chapter 1.4 or Table 2 in page 51).

This thesis includes five papers over a 15-year period, each of them with their own unique conclusions and recommendations formulated at the time of writing the respective paper; see Chapter 4. Furthermore, this thesis brings forth additional conclusions and recommendations described in Chapters 5.1 and 5.3, based partly on the limitations and shortcomings of the papers (see Chapter 4.6.2) and on the conclusions of and experiences from the papers. These additional conclusions and recommendations (Chapters 5.1 and 5.3) can thus be said to be the main conclusions and recommendations of this thesis. Table 2 outlines how the research questions relate to the main conclusions and recommendations of this thesis. Furthermore, the generalizability of the conclusions is examined.

6.1.1 Recommendations primarily targeting LCA data

Keep a system perspective - do not forget efficiency

The importance of the efficiency was first noted in the lithium-ion battery paper (paper B). It was difficult to find an authoritative reference of an exact value of the efficiency parameter. Therefore, 0.90 and 0.975 internal efficiencies were used to test the robustness of the conclusions. In the lithium-air battery paper (paper C), it was noted that the low internal efficiency expected, even in the long term, could be a serious barrier to the technology. The lithium-metal battery paper (D) highlighted that both climate impact and costs are larger in the use phase than in the production phase, thus making the internal efficiency a very important parameter. Therefore, the general recommendation is to keep a system perspective and do the following:

- always include the use phase in LCA traction battery studies,
- improve battery energy density but not to the detriment of battery internal efficiency, and
- investigate efficiency or losses related to the use phase.

Cradle-to-gate LCAs that omit the use phase, for reasons of no control or knowledge about the use phase, abound, not just concerning traction batteries. Such LCAs always run the risk of ignoring the most environmentally significant phase. The recommendation to include and investigate a use phase scenario is universal and general; even in situations where the use phase is largely unknown and out of the control of the manufacturer, modelling and investigating this phase builds knowledge.

Energy use for large-scale traction battery manufacturing can be approximated to 60 +/-10 kWhel/kWhc if no specific data are available.

The estimate of energy needs for battery manufacturing from the data in battery producer Saft's annual report in 2008 (Saft 2008) in the lithium-ion battery paper (B) has attracted much attention, partly because data from manufacturing sites have proven very difficult to obtain. Due to the lack of other or more specific data, the same data from Saft's annual report in 2008 (Saft 2008) were used in all the ensuing battery papers:

the lithium-air (C), lithium-metal (D) and structural battery (E) papers. This is, of course, a weakness, and it is therefore an advantage to be able to present data in this thesis from studies that collected them from large-scale manufacturing sites and that correlate well. These data can be used as a basis in LCA traction battery studies when no site-specific data are available. The general recommendation is of course to use study- and site-specific data but, in the absence of such data, to use 60 +/-10 kWh_{el}/kWh_c for the large-scale manufacturing of lithium-ion batteries. These data are hardly generalizable to any other production but traction battery cell production and battery assembly.

6.1.2 Recommendations primarily targeting the LCA methodology

Use two abiotic depletion measures to reflect scarce materials in the short and long term

In the lithium-metal battery paper (D), it was noted that the lithium-iron-phosphate (LFP) battery scored higher in abiotic depletion than did a similarly sized lithium-nickel-manganese-cobalt (NMC) battery. The cause was higher electricity consumption in the use phase due to a heavier LFP battery. Nevertheless, this finding contradicts the pinpointing of cobalt and nickel as scarce materials since the LFP chemistry does not contain these materials at all. Since the current guidelines recommend a method that does not identify nickel, cobalt and lithium as scarce materials, the recommendation is to include one that does to calculate two abiotic depletion measures in traction battery LCA studies. This recommendation is probably also relevant for some other product categories, but this should be investigated for each individual product category by means of a contribution analysis, like those in Figure 12, 13 and 14.

Calculation of the results for all relevant functional units facilitates comparisons and reflection

The calculation of the results for all relevant functional units increases the possibility for comparisons with other studies. This can provide access to alternative data and improved opportunities for reflection on models and assumptions. Thereby the quality of the current study can be improved, and future studies may reap the same benefit. The lithium-air battery paper (C) reported two functional units: vehicle kilometres for comparisons in a vehicle context and per delivered kWh electricity to facilitate comparisons between batteries. However, the other three battery-related papers in this thesis all used one functional unit, and each of the three studies used a different functional unit from those of the others. A lack of funds and time for work that does not give an immediate research payback is an explanation but not an excuse for this situation. The recommendation to calculate the results for all relevant functional units is generally applicable for all LCA studies.

Use of chemical risk assessment from a life cycle perspective

Traction battery LCA, which tries to assess toxicity, ignores many toxic effects due to a lack of LCA toxicity characterization factors and data on toxic emissions in many life cycle stages. This can lead to a false sense of security. Chemical risk assessment (CRA) from a life cycle perspective, as applied in the structural battery paper (E), is suggested as an alternative to calculate within-LCA toxicity indicators in the short term. In the long term, such use of CRA from a life cycle perspective may help improve within-LCA toxicity assessment methods. CRA, but not from a life cycle perspective, was also used in the lithium-ion and lithium-air battery papers. As CRA is legally mandatory in many industrial contexts, the recommendation can be phrased as follows: integrate the CRA results as much as possible in LCA. This approach brings alternative competence to the LCA and can improve LCA data, methods and overall quality. This recommendation is applicable for all products with chemical risks in any life cycle stage.

Ranking list of environmental impact categories for traction batteries

The battery related research papers have all used/reported different sets of environmental impact assessment (EIA) categories. This reflects that the choice of EIA categories is difficult. Too many EIA categories limit the possibility of drawing conclusions in terms of how to improve environmental performance since they cannot be assessed together. Conversely, the impact categories used must comprehensively reflect the environmental burden of the traction battery or electric vehicle and the internal combustion vehicle in comparative studies. Climate impact, abiotic depletion, respiratory inorganics, acidification, ozone formation and eutrophication are ranked as the most important impact categories to be included in traction battery LCA (in that order). They can be complemented by chemical risk assessment from a life cycle perspective to cover toxicity issues.

The ranking list presented above is of course only valid for LCA studies involving traction batteries and/or electric vehicles. However, developing such ranking lists for other products is recommended since it facilitates the possibility of drawing conclusions in terms of how to improve the environmental performance within studies and compare and reflect between studies.

6.1.3 Recommendations primarily targeting LCA use in technology development

Use of screening LCA, chemical risk assessment (CRA), idea generation and full LCA in technology development

All the projects in the referenced papers used some parts of this recommendation; see Table 1. As mentioned above, both CRA and idea generation help build engagement, competence and, in the end, the data necessary for full LCA. The recommendation to start with screening LCA, CRA and idea generation early on in technology development projects and then complement them with full LCA at the end is valid for all types of technology development projects.

6.2 Future research

The needs of future research in the expansive field of transportation, environmental impact and lithium-ion batteries are enormous. Here, I will only mention a few issues that are close to my own findings and future research interests. These are the use of LCA to minimize environmental impacts in the development of charging infrastructure and novel battery systems and, in particular, their chemistry-specific recycling routes. Chemical risk assessment (CRA) from a life cycle perspective should be used to assess chemical risks, particularly those related to recycling.

The lack of charging infrastructure is one of the main obstacles for the electrification of vehicle fleets. If you cannot charge at home because you live in a flat, or there is nowhere to charge at work, or it is too far between the charging stations to your summer house, then an electric vehicle with a reasonably sized battery and price may not be an option. Thus, charging infrastructure must be built, but there are very little data available about the efficiency of different charging technologies. If 15% of the electricity is lost before it enters the battery, as claimed by Lam et al. (2019), then this is equal to an extra 15 g of CO_2/km with European and global average electricity, 500 g of CO_2/kWh. Conversely, if the source is a surplus of renewable energy, then charging efficiency is less important. Research efforts at the European level have so far focused on dynamic or wireless charging (Tsakalidis et al. 2020). Research on the environmental impact of charging infrastructure should be done in conjunction with its development and build-up, and it is time to start now.

With smart charging infrastructure, electric vehicles can become an important part of a future energy system in which renewable but intermittent sources, like wind and solar energy, play a large role (Muratori et al. 2021)(Fachrizal et al. 2020). A renewable electrical energy system needs system services like peak shaving and load levelling, which can be provided by a battery, standalone (stationary) or in a vehicle. Since renewable electricity generation is a prerequisite for electrification having less of a climate impact, this facet of charging infrastructure research, sometimes called vehicle-to-grid, should be both encouraged and supported.

Many of the ingredients in modern lithium-ion battery (LIB) chemistries are toxic, irritant, volatile and flammable. In addition, traction LIB packs operate at high voltage, which creates safety problems throughout the life cycle of the LIB. In the production and use phases, these safety issues must be solved and managed as they are discovered; otherwise, the technology will fail to be introduced. However, safety issues in the recycling phase are rarely investigated fully since the recycling phase lies 10-20 years in the future. The safety issues and environmental impact in the recycling phase are a research gap that needs to be filled for every new type of LIB chemistry (Mohr et al. 2020) and LIB design. Chemical risk assessment (CRA) from a life cycle perspective has a role to play, both to identify and mitigate risks and to improve within-LCA methods for chemical toxicity risks. The LIB circularity problem, as a whole, should ideally be approached with a design for recycling (Kriwet et al. 1995) or remanufacturing (Sundin and Lee 2012) or a circular economy (Baars et al. 2020) perspective; i.e., the battery and cell should be designed for the safe and easy recycling and reuse of the materials in new cells and batteries if that is environmentally and economically justified. The recycling of today's cells is seen as a necessity to have enough resources in the future (Greim et al. 2020) to supply electrified transportation. Finally, the new EU Sustainable Batteries Regulation (European Commission 2020b) will establish a comprehensive framework covering all types of batteries and addressing their whole life cycle, from production processes, design requirements and second life, recycling and incorporating recycled content in new batteries.

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Part II Appended Papers