



**KTH Industrial Engineering
and Management**

Comparative life cycle assessment of different lithium-ion battery chemistries and lead-acid batteries for grid storage application

Ryutaka Yudhistira
TRITA-ITM-EX 2021:476

Master of Science Thesis

KTH School of Industrial Engineering and Management
Energy Technology EGI-2018-2021
Division of Energy Systems
SE-100 44 STOCKHOLM



**KTH Industrial Engineering
and Management**

**Master of Science Thesis
Department of Energy Technology
KTH 2020**

**Comparative life cycle assessment of different
lithium-ion battery chemistries and lead-acid
batteries for grid storage application**

TRITA: TRITA-ITM-EX 2021:476

Ryutaka Yudhistira

Approved July 2021	Examiner Dilip Khatiwada	Supervisor Dilip Khatiwada
	Commissioner Polarium Energy Solutions AB	Contact person Ryutaka Yudhistira

Abstract

With the rapid increase of renewable energy in the electricity grids, the need for energy storage continues to grow. One of the technologies that are gaining interest for utility-scale energy storage is lithium-ion battery energy storage systems. However, their environmental impact is inevitably put into question against lead-acid battery storage systems. Therefore, this study aims to conduct a comparative life cycle assessment (LCA) to contrast the environmental impact of utilizing lithium-ion batteries and lead-acid batteries for stationary applications, specifically grid storage. The main tools in this study include Microsoft Excel for the life cycle inventory and OpenLCA for life cycle modelling and sensitivity analysis. In this research, a cradle-to-grave LCA for three lithium-ion battery chemistries (i.e. lithium iron phosphate, nickel cobalt manganese, and nickel cobalt aluminium) is conducted. The impact categories are aligned with the Environmental Footprint impact assessment methodology described by the European Commission. The standby grid operation scenario is considered for estimating the environmental impacts, where the batteries would deliver 4,800 kWh of electric energy throughout 20 years. Consequently, the functional unit will be in per kWh energy delivered.

The lead-acid battery system has the following environmental impact values (in per kWh energy delivered): 2 kg CO_{2-eq.} for climate change, 33 MJ for fossil resource use, 0.02 mol H⁺-eq. for acidification, 10⁻⁷ disease incidence for particulate emission, and 8x10⁻⁴ kg Sb_{-eq.} for minerals resource use. Going back to the lithium-ion batteries systems, for the climate change and fossil resource use impact categories, the best performer is found to be the nickel cobalt aluminium (NCA) lithium-ion battery, with 46% and 45% less impact than lead-acid for the respective categories. On the other hand, the nickel manganese cobalt (NMC) was the best for the acidification and particulate emission impact categories with respective 65% and 51% better performance compared to lead-acid batteries. Finally, for the minerals and metals resource use category, the lithium iron phosphate battery (LFP) is estimated to be the best performer, which is 94% less than lead-acid. To conclude, the life cycle stage determined to have the largest contribution for most of the impact categories was the use stage, which then becomes the subject to a sensitivity analysis. The sensitivity analysis was done by varying the renewable contribution of the electricity grids in the use phase. Overall, the lithium-ion batteries systems have less environmental impact than lead-acid batteries systems, for the observed impact categories. The findings of this thesis can be used as a reference to decide whether to replace lead-acid batteries with lithium-ion batteries for grid energy storage from an environmental impact perspective.

Keywords: life cycle assessment (LCA), lithium-ion batteries, lead-acid battery systems, grid storage application.

Sammanfatning

Med den snabba ökningen av förnybar energi i elnäten, fortsätter behovet av energilagring att växa. En av de tekniker som växer intresse för energilagring på nyttan är litiumjon batteriets energilagringssystem. Emellertid, deras miljöpåverkan ifrågasätts oundvikligen mot blysyrabatteri lagringssystem. Därför syftar denna studie till att göra en komparativ livscykelanalys (LCA) för att komparera miljöpåverkan av att använda litiumjonbatterier och blybatterier för stationära applikationer, särskilt för nätlagring. I denna forskning genomfördes en vagg-till-grav-LCA (eller cradle-to-grave i engelska) för tre litiumjonbatterikemi (litium järn fosfat, nickel kobolt mangan, och nickel cobalt aluminium). Effektkategorier anpassades till miljökonsekvensbedömning metoden som beskrivs av Europeiska kommissionen. Det användningsfall scenariot för batterierna var standby läget, där batterierna leverera 4800 kWh elektrisk energi för 20 år. Följaktligen den funktionella unit är i 'per kWh levererad energi'.

Blysyrabatteriet hade följande ungefärliga miljöpåverkansvärden (i per kWh levererad energi): 2 kg CO_{2-eq.} för climate change, 33 MJ för fossil resource use, 0.02 mol H⁺-eq. för acidification, 10⁻⁷ disease incidence för particulate emission, and 8x10⁻⁴ kg Sb_{-eq.} för minerals resource use. Tillbaka till litiumjonbatterierna, för climate change och fossil resource use resursanvändnings kategorier, den bäst presterande var litiumjonbatteriet nickel kobolt aluminium (NCA). Det hade 46% och 45% mindre påverkan än blysyrabatteriet för respektive kategori. Å andra sidan, var nickel mangan kobolt (NMC) bäst för acidification och particulate emission kategorier. De är 65% och 51% bättre än blysyra för kategorierna. Slutligen, litium järn fosfat batteriet (LFP) är det bäst presterande för resource use of minerals and metals kategoriet, vilket det är 94% mindre än blysyra. Avslutningsvis, det livscykelstadier som var bestämt att ha det största bidraget för de flesta av påverkningskategorierna är användningsstadiet, som sedan blir föremål för en känslighetsanalys. I slutändan, litiumjonbatterierna ha mindre miljöpåverkan än blybatterier i detta projekt, för de observerade slagkategorierna. Resultaten av denna avhandling kan sedan användas som referens för att avgöra om bly-syrabatterier ska ersättas med litiumjonbatterier för energilagring ur ett miljöeffektperspektiv.

Nyckelord: livscykelbedömning (LCA), litiumjonbatterier, bilbatteri system, nas lagring applikation.

Acknowledgements

Throughout this research, I have received significant support from various parties. First, I would like to thank my academic supervisor, Dilip Khatiwada, whose insight was invaluable in building the structure and methodology of this thesis project. Second, I would like to acknowledge Polarium Energy Solutions AB, who had supported me in obtaining the required data and environment to conduct the study. Finally, I would like to specifically thank Fernando Sanchez as my direct company supervisor and Anna Aardahl as my manager. Their constant support was key to the success of this project, and their feedback had ensured the quality of this study.

Table of Contents

Abstract.....	i
Sammanfatning	ii
Acknowledgements	iii
Table of Contents.....	iv
List of Abbreviations	vi
1 Introduction	1
2 Literature review.....	3
2.1 Life cycle model of lithium-ion batteries.....	3
2.1.1 Cradle-to-gate phase.....	3
2.1.2 Transportation and use phases	6
2.1.3 End-of-life phase	6
2.2 Lithium-ion batteries in grid storage application	7
2.3 Studies regarding LCA of LIBs used in electric vehicle and grid storage.....	8
2.3.1 Differences in life cycle assessment for lithium-ion batteries.....	8
2.3.2 The Product Environmental Footprint Categorical Rules (PEFCR)	10
2.3.3 Levelized cradle-to-gate inventory of lithium-ion batteries	13
3 Methods and Materials	14
3.1 The life cycle assessment framework.....	14
3.1.1 Goal and scope definition	14
3.1.2 Inventory analysis	15
3.1.3 Impact assessment.....	15
3.1.4 Results interpretation	15
3.2 Goal and scope definition of the thesis.....	15
3.2.1 Product system and boundary of the study.....	16
3.2.2 Functional unit and reference flow.....	18
3.3 Life cycle inventory data source	19
3.3.1 LCI for the cradle-to-gate stage.....	19
3.3.2 LCI for the use stage	20
3.3.3 LCI for the end-of-life stage	22
3.4 Life cycle impact assessment method.....	22
3.5 Modelling tools.....	23
3.6 Results interpretation: sensitivity and comparison with another study.....	24
4 Results and Discussion.....	25
4.1 Comparison of lifecycle environmental impacts of lithium-ion batteries and lead-acid batteries.....	25
4.1.1 Climate Change	25
4.1.2 Acidification, terrestrial and freshwater.....	26
4.1.3 Resource use: energy carriers	27
4.1.4 Resource use, mineral and metals.....	28

4.1.5	Respiratory inorganics.....	29
4.2	Cradle-to-gate impact contribution analysis by process	29
4.2.1	Climate Change: Cradle-to-gate.....	30
4.2.2	Acidification, terrestrial and freshwater: Cradle-to-gate.....	31
4.2.3	Resource use, energy carriers: Cradle-to-gate.....	32
4.2.4	Resource use, mineral and metals: Cradle-to-gate	33
4.2.5	Respiratory inorganics: Cradle-to-gate.....	34
4.3	Results interpretation.....	35
4.3.1	Cradle-to-grave sensitivity analysis of lithium-ion batteries	35
4.3.2	Results comparison with other studies.....	37
4.3.3	Suggested measures to improve the overall environmental impact.....	38
5	Conclusion.....	40
	Bibliography	41

List of Abbreviations

Abbreviation	Definition
BESS	Battery Energy Storage System
BMS	Battery management system (module)
CCF	Circular Footprint Formula
EC	European Commission
EU	European Union
EV	Electric vehicle
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
LMO	Lithium manganese oxide
LTO	Lithium titanate oxide
MWh	Megawatt-hour
NCA	Nickel cobalt aluminium
NiMH	Nickel metal hydride
NMC	Nickel manganese cobalt
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Categorical Rules

1 Introduction

As the investment costs for solar and wind energy continues to decrease, the world continues its transition towards renewable energy (IEA, 2020). Some of the drivers for this cost reduction are government policy, electricity demand growth, and technological progress (Our World in Data, 2020). However, these renewable energy sources are intermittent, and power grids that rely on them would not be able to provide a steady energy supply. These fluctuations can impact the system's frequency and voltage, which translates to the overall power quality. As a result, these systems would require a reliable energy storage system to offset their intermittency. So, energy storage would be a crucial aspect to supplement the growth of renewable energy, especially solar and wind. This is but one of the many functions of energy storage in the electric power grid, and this illustrates the necessity of energy storage to ensure the quality, availability, and reliability of electricity.

There are different types of energy storage, each with its characteristics. They are broadly categorized into thermal, mechanical, magnetic, and chemical storage (Koochi-Fayegh et al., 2020). Battery energy storage systems (BESS), which are a part of chemical energy storage, are now put under the spotlight as prospective utility-scale energy storage. Mainly used for electric vehicle (EV) applications, BESS are starting to enter the grid energy storage market. This is because BESS would be suitable for utility-related applications, such as providing ancillary services, peak shaving, and energy shifting (IRENA, 2017). On another note, it is predicted that Lithium-ion batteries (LIB), specifically, will grow rapidly at least until 2030 (Bloomberg, 2019). Consequently, this study will focus on utility-scale LIB energy storage.

Compared to other types of battery chemistries, LIBs have a higher potential for energy storage (Zubi et al. 2018). This is because lithium is very reactive, which translates to a high potential difference. Also, lithium is extremely light, causing LIBs to have high specific power and specific energy. Now, a typical LIB operates by utilizing graphite as the main material for the anode and a lithium compound for the cathode. They are named after the chemicals that make up their active materials, such as nickel cobalt aluminium (NCA), lithium iron phosphate (LFP), and nickel manganese cobalt (NMC). They also contain other elements such as copper, steel, and plastic. The extraction, processing, and disposal of these materials are resource-intensive (Tivander, 2016), so the growing concern for the environmental impact of LIBs are understandable. Hence, it is imperative that these impacts should be quantified and analyzed, and the study that can do so is called Life Cycle Assessment (LCA).

In an LCA, a product is studied throughout its life: from extracting its raw material to its final disposal. Of course, the extent of an LCA can be adjusted accordingly by changing its scope. Other than obtaining a concrete measure of a product's environmental impact and improving environmental impacts, LCAs have other functions (ISO, 2006). They can be used as an empirical base for decision-making and even for product marketing. In addition, the result of two different LCAs can be compared if they have the same reference unit. For example, it would be possible to measure the impact of using LIBs against conventional lead-acid batteries. The EU itself is also committed to minimizing the environmental impact of batteries, as shown by their Battery Directive (EC, 2006). Thus, conducting an LCA for LIBs should prove beneficial if the share of LIBs in the grid-scale energy storage sector is to rise.

However, more studies conduct LCAs of LIBs for electric vehicle (mobile) application as opposed to grid-scale (stationary) use (Ryan, et al. 2018). Further, only a few of the LCA studies for LIBs in grid application includes the whole cradle-to-grave life cycle (see chapter 2). This makes it difficult to determine how LIBs would impact the environment compared to the conventional and mature lead-acid battery technology. To fulfil these gaps and the motivated by the background in the previous paragraphs, this document will answer the following *research questions*

1. How do the life cycle environmental impacts of LIBs systems are compared to conventional lead-acid batteries systems for grid electricity storage applications?
2. What are the major influencing factors (or most critical processes) in the life cycle of LIBs in terms of environmental impact? And, how do these influencing factors react to different inputs and outputs?
3. What are the measures that can be done to improve the environmental impact results?

The purpose of this study is to *compare* the life cycle environmental impact of LIBs and lead-acid batteries for grid-scale energy storage systems. The LCA for the LIBs and the lead-acid batteries will be cradle-to-grave. Hence, the use and end-of-life stages will also be included in addition to the batteries' manufacturing process and use phase. The environmental impact categories are climate change, acidification potential, resource use of energy carriers, resource use of minerals and metals, and respiratory inorganics. These impact categories are chosen according to the Environmental Footprint 2.0 impact assessment method (Manfredi, et al. 2012). All-in-all, the obtained environmental impact comparison will determine which of the batteries generate the least overall environmental impact and identify the processes which generate the highest environmental throughout the life cycle. Finally, measures for improving the overall environmental impact results will be discussed.

Furthermore, there will also be different scenarios in this study, in which *three different chemistries* of LIBs will be analyzed: LFP, NMC, and NCA. Generally, these batteries differ in terms of the materials used for manufacturing their respective cathode active materials and overall characteristics when operating as an energy storage (see chapter 2). In addition to the scenarios, a sensitivity analysis will also be conducted to see how the environmental impact of a LIB changes with different values in the process input. Consequently, the sensitivity analysis will only be done to the most critical foreground process. To elaborate, critical processes are steps that generate the most impact in the life cycle. With the inclusion of different scenarios and sensitivity analysis, this study should provide a thorough comparative LCA.

Below, Figure 1 shows the general overview of the thesis document:

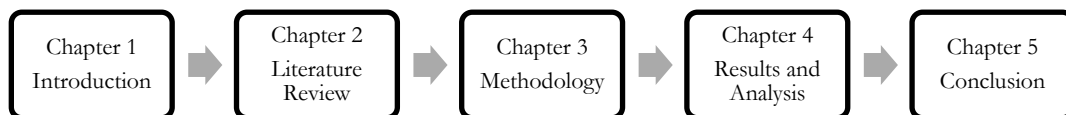


Figure 1, The organization of the thesis document

Starting from Chapter 1, the overall theme and purpose of the thesis are introduced. Then, Chapter 2 presents a summary of different pieces of literature to provide a base for the study. Next, the methodology for obtaining and analyzing the results of this research are written in Chapter 3. Following, the obtained LCA results are compiled in Chapter 4, which will then be analyzed to answer the research questions and study objective. Finally, Chapter 5 will conclude this thesis document.

2 Literature review

Before conducting an LCA on LIBs, a deeper look into the general life cycle of LIB is required. This is to better understand the topic before deriving the research methodology for this thesis. Furthermore, it is crucial to determine how the life cycle of LIBs can be adjusted to fit the LCA framework. For instance, deciding on the scope of the study, how to assess the impacts themselves, and choosing the functional unit for the LIB LCA. To do so, previous LCA studies regarding LIBs should be observed, as they can also serve as references for this project's method. Hence, this literature review section is split into three sub-sections: The general life cycle of LIBs, LIB in grid storages, and the observation result from previous LCAs on LIBs.

2.1 Life cycle model of lithium-ion batteries

LIBs are battery cells that utilize the movement of lithium ions from the negative electrode (anode) to the positive electrode (cathode) through a medium known as electrolytes, hence the name 'lithium-ion battery'. A typical LIB cell consists of five main components: cathode, anode, electrolyte, separator, and cell casing. In a LIB pack, several LIB cells are connected to deliver a specific amount of energy (EPA, 2013). After assembling a pack, the LIBs can then be transported and used for different purposes, such as for small electronics, EVs, and utility-scale energy storage. Finally, the LIB pack is treated and disposed of when it has reached the end of its lifetime. Figure 2 shows a simplified overview of a LIB's entire life cycle.

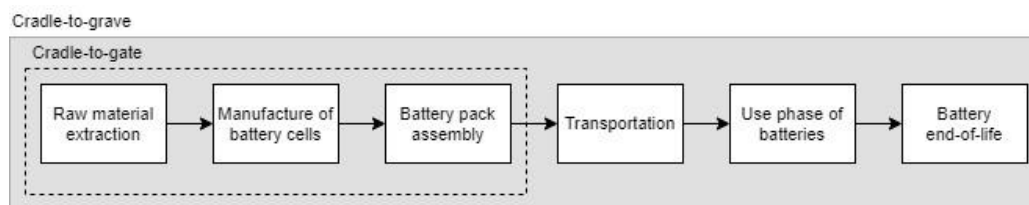


Figure 2, Overview of lithium-ion battery life cycle model

Cradle-to-gate is a term used to denote the processes of raw material acquisition up to product assembly, right before transporting them to the product's user. Meanwhile, cradle-to-grave includes the product's use and end-of-life phases, so it is a more complete overview of a product's whole life cycle (ISO, 2006). Consequently, determining whether a study should include the use and end-of-life phases should be done when stating the scope of the project. Next, the cradle-to-gate, use, and end-of-life stages for LIBs will be discussed further in the following sections.

2.1.1 Cradle-to-gate phase

From Figure 2, there are three main processes in the cradle-to-gate life cycle stage: raw material extraction and processing, creation of battery cells, and assembling the cells into a battery pack. To illustrate these processes better, Figure 3 shows the product system of LIBs for the cradle-to-gate stage. This figure refers to various studies, some of them were conducted by the EPA (2013), Notter (2010), Majeau-Bettez (2013), and Ellingsen (2014)

The life cycle starts by extracting and processing the necessary raw materials. After, the five main components of LIB cells can be manufactured. Typically, the anode is made of graphite (and copper for the negative electrode), the electrolyte by lithium salt, the separator by polymers, and cell packaging by plastic. In the case of the cathode, their material differs according to their chemistry. For this project, three different cathode active material chemistries will be used as different scenarios: Lithium iron phosphate (LFP batteries), lithium nickel manganese cobalt (NMC batteries), and lithium nickel cobalt aluminium (NCA batteries). The difference in these three cathodes' active material is important, as they would generate unique impacts during their processing. These three cathodes use the same material for their electrode, however, which is aluminium. With the components ready, the battery cell can then be synthesized.

After creating the battery cells, they can be put together to create a LIB pack. The number of LIB cells contained in a pack differ according to the target performance, usually expressed in energy capacity. Some important measures that are used to describe the performance of LIBs are specific power, specific energy, and round-trip efficiency. The specific power of a LIB can be obtained by dividing the LIB's rated power by its weight, and this also applies to specific energy. On the other hand, round-trip efficiency quantifies the amount of actual electric energy flowing through the battery for one charge-discharge cycle as a percentage of the ideal amount.

Other than the LIB cells, two other components can be found in a LIB pack. The first one is the battery management system (BMS) module, which is responsible for regulating the pack's charge and discharge cycles. The other one is the LIB container, which is usually made of metal. Some battery packs have a built-in thermal regulating system, but since it does not apply to this study's LIBs, it will not be included in the product system. Finally, after assembling the LIB pack, their performance should be measured through a testing and activating process. To note, activating means observing the new LIB pack for one charge-discharge cycle. All in all, the LIB pack should be ready to be delivered and used by the end of this stage.

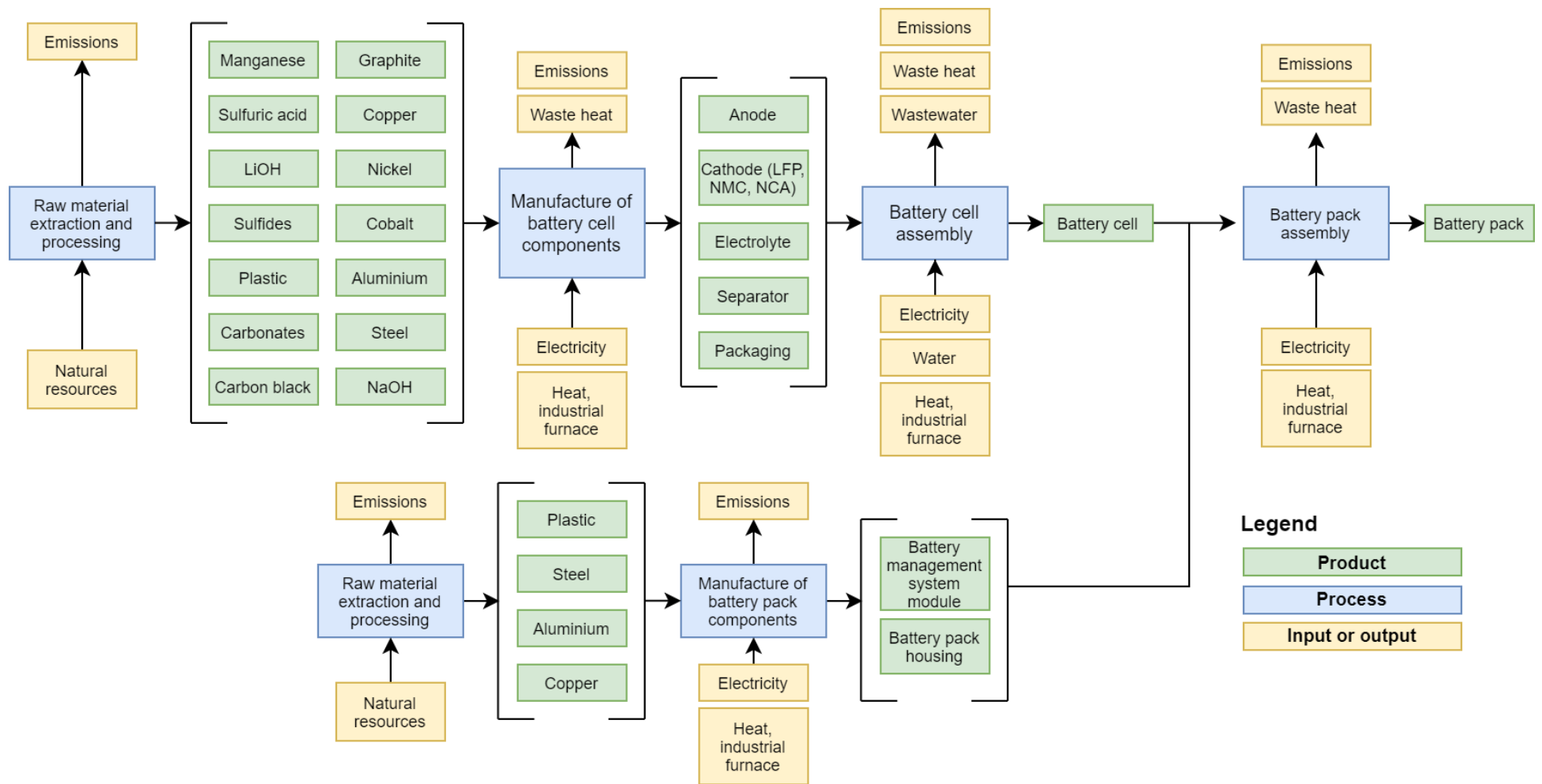


Figure 3, Cradle-to-gate product system for lithium-ion batteries

2.1.2 Transportation and use phases

After completing the cradle-to-gate process, the finished battery pack is then transported to the users. If the transport process utilizes diesel-powered trucks, the only input and output related to this process only concern the combustion of diesel. Next, the battery is used by the users. The purpose of battery packs is to store and deliver electric energy, so the input and output for this process only relate to electricity. Finally, the product of the use stage is the scrap battery pack, which are LIBs that have reached the end of their lifetime. To illustrate, Figure 4 shows the product system for the LIBs’ transportation and use phases.

In the case of using BESS for utility-scale energy storage, there are several different types of applications that can be observed. According to the Asian Development Bank (2018), the different use cases of BESS include frequency regulation, renewable energy integration, and peak shaving (load levelling). In another study, Battke (2013) wrote that the applications of BESS also include seasonal storage, transmission and distribution support, and energy arbitrage. Nevertheless, the main properties the BESS’s use stage is the number of total energy delivered throughout the BESS’s lifetime.

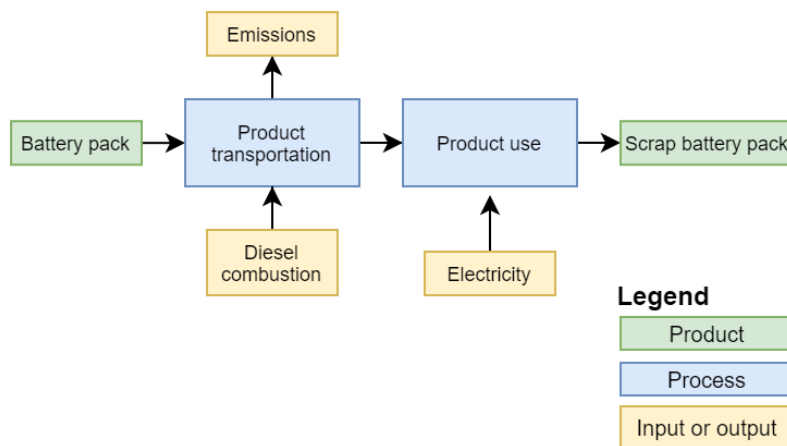


Figure 4, The lithium-ion battery pack transportation and use phase product system

2.1.3 End-of-life phase

When a LIB pack has reached the end of its useful lifetime, it is considered a scrap battery pack. These scraps are collected and transported for recycling. In the Final Product Environmental Footprint Category Rules (PEFCR) document published by the European Commission in 2020, the total battery pack recycling process includes cell recycling, passive parts recycling, EV original equipment manufacturer (OEM) recycling, and rest treatment. However, OEM recycling is not applicable, as it is not included for LIBs that are used for grid energy storage. Rest treatment refers to unsorted materials that cannot be recovered, so they will go directly to the landfill. To clarify, the product system for a LIB pack’s end of life stage can be seen in Figure 5.

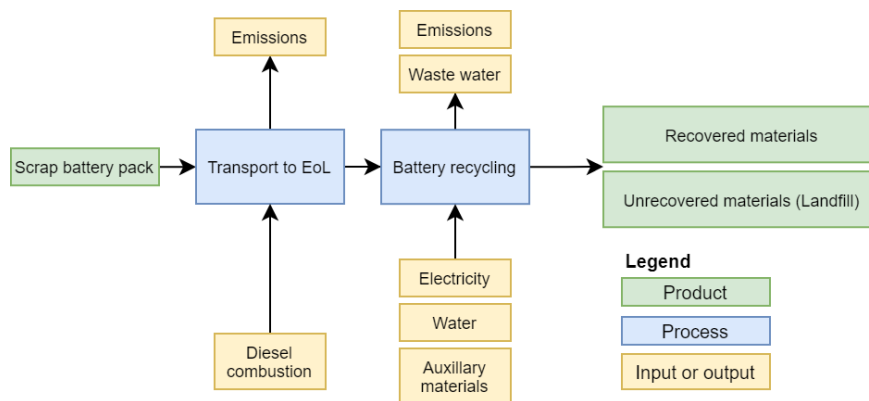


Figure 5, End-of-life product system for lithium-ion batteries

Recycling LIB cells and passive parts in the PEFCR consist of physical recovery and two treatments: pyrometallurgical, followed by hydrometallurgical. The main inputs of this process include electric energy, process heat, and water. There are also auxiliary materials for the pyrometallurgical and hydrometallurgical treatments, which are chemicals used to extract the metals from the cells. On the other side, this process would yield recovered metals, which could then be treated to obtain valuable metals. The unrecovered waste would then be landfilled, as it cannot be recovered further.

2.2 Lithium-ion batteries in grid storage application

There are different types of energy storage technologies that are applicable in power grids. They are broadly categorized as thermal, electromagnetic, mechanical, chemical, electrical, and electrochemical energy storage systems (Tan, et al. 2021). These types of systems are not only different in terms of physical properties, but also energy capacity, energy density, efficiency, and costs. In the case of LIB, they are categorized as electrochemical energy storages as they utilize chemical substances to store and deliver energy in form of electricity. They are characterized by high energy density, high efficiency, and long lifetime. However, their usage in large scale applications (especially for grid energy storage) is scrutinized due to elevated costs (Lima, et al. 2021). Nevertheless, the price of LIB continues to and is projected to decline, as the technology becomes increasingly mature (Pellow, et al. 2020).

Even within grid storage applications, the LIB can be used for different purposes. As mentioned in Section 2.1.2, these different purposes would require specific power and energy ratings, cycling frequency, and discharge duration (Asian Development Bank 2018). Some instances of grid storage application purposes for LIB can be seen in Table 1. For example, LIB application for the area and frequency regulation requires a short discharge interval, as opposed to utility energy time-shift. The different power rating and discharge durations result in different energy rating requirements, which in turn determines the size of the system. Also, the cycle frequency would impact the lifetime of the LIB, since they will degrade faster with increased use.

Table 1, Example application purposes of LIB in grid storage and the specific parameters (Hiremath, 2011)

Application	Power Rating (MW)	Discharge Duration (h)	Energy Rating (MWh)	Cycle per day
Energy management (community scale)	0.1	2.5	0.25	2
Increase of self-consumption	0.0025	4	0.01	0.6
Area and frequency regulation	2	0.25	0.5	34
Support of voltage regulation	1	0.25	0.25	0.68
Transmission and distribution investment deferral	10	5	50	0.68
Utility energy time-shift	100	8	800	1

Determining which LIB application purpose is crucial because it is directly related to the functional unit of the LCA study, especially if the functional unit is in terms of energy delivered. Consequently, this highlights the difficulty of comparing two different LCA studies of LIB, even when the two analyses are in the context of grid energy storage. Therefore, the LCAs of LIBs will only be comparable if the usage purpose is the same. Nonetheless, describing the usage purpose of the LIB is a must when conducting an LCA for the grid storage LIB.

2.3 Studies regarding LCA of LIBs used in electric vehicle and grid storage

As if propelled by the technological development of battery-utilizing devices, various research was done regarding the LCA of LIBs. Most of these studies are comparative LCAs, where batteries with different configurations were analyzed against each other in terms of environmental impact. However, the results of different LCA studies were often difficult to compare. This is due to differences in the life cycle inventory, system boundary, impact assessment method, battery characteristics, battery application, etc. As a result, these discrepancies added up to environmental impacts that vary from each other. Nonetheless, their methodology and data can be used to serve as a reference for this project. The following paragraphs will discuss the differences in previous LCA studies for LIBs, LCAs for grid-scale LIBs, Product Environmental Footprint Categorical Rules (PEFCR) for rechargeable batteries, and the cradle-to-gate environmental impact benchmark values.

2.3.1 Differences in life cycle assessment for lithium-ion batteries

From Table 1, the differences of previous LCAs on LIBs can relate to several aspects. This may include the

Source	Battery Chemistry	Life Cycle Stages Considered	Functional Unit	Battery Application
<i>Zackrisson et al. (2010)</i>	LFP	Cradle-to-grave	Per 10 kWh capacity	Electric vehicles
<i>Notter et al. (2010)</i>	LMO	Cradle-to-grave	Per 1 km driven	Electric vehicles
<i>Majeau-Bettez et al. (2011)</i>	LFP, NMC, NiMH	Cradle-to-gate; Use stage	Per 50 MJ electricity delivered; Per 1 kg battery; Per 1 kWh capacity	Electric vehicles
<i>EPA (2013)</i>	LFP, NMC, LMO	Cradle-to-grave	Per 1 km driven	Electric Vehicles
<i>Ellingsen et al. (2014)</i>	NMC	Cradle-to-gate	Per 1 battery pack; Per 1 kg battery; Per 1 kWh capacity	Electric vehicles
<i>Hiremath et al. (2015)</i>	LFP, NMC, LMO	Cradle-to-gate; Use stage	Per 1 MWh electricity delivered	Grid energy storage
<i>Baumann et al. (2017)</i>	LFP, LTO, NMC, LMO, NCA	Cradle-to-gate; Use stage	Per 1 kg battery; Per 1 kWh delivered; Per 1 kWh capacity	Grid energy storage
<i>Ryan et al. (2018)</i>	LFP, NMC, LMO, NCA	Cradle-to-grave	Per 1 MW reserve capacity for one year	Grid frequency regulation

type of LIB chemistry used, the life cycle stage to be analyzed, chosen functional unit, and the intended application of the LIB itself. Not to mention, the life cycle inventories for these studies might have significant discrepancies, which would mean large differences in impact assessment results. Further, the LCIA method used for each study is not the same, which means the discussed environmental impact categories will vary. As a result, comparing the results of this project with the previous LCAs will not be straightforward.

Then,

Table 2 shows that every observed study includes the cradle-to-gate stage of the LIB, albeit with different chemistries. Thus, each study would have different cradle-to-gate processes as they require unique raw material extraction and processing for their cathode active material. However, the main problem with these

studies is that not all of them provides a publicly available life cycle inventory. So, accurately determining which elements of the inventory made the cradle-to-gate LCA study results differ is impossible. Nevertheless, some studies such as the ones done by Majeau-Bettez (2011), Ellingsen (2014), and Notter (2010) provides supplementary documents to their papers, which includes the life cycle inventory they used. It is worth noting that these inventories are also complemented by *ecoinvent*, a well-known life cycle assessment inventory database.

Next, as shown by the ‘life cycle stages considered’ column, the study boundary for these publications differs from another due to the objectives of each research. The publication by Hiremath (2015), for example, aims to focus on the use phase environmental impact comparison of four battery technologies (lithium-ion, lead-acid, sodium-sulfur, vanadium redox), while Ellingsen (2014) wanted to create a transparent life cycle inventory for NMC battery pack manufacturing. Consequently, Hiremath (2015) analyzed both the cradle-to-gate and the use stage, while Ellingsen (2014) excluded the use stage. Discussions on the environmental impact, however, were often broken down into each life cycle stage. For example, in the study by Hiremath (2015), Majeau-Bettez (2011), and Baumann (2017), the results from the cradle-to-gate stage and the use phase are split into two different figures, so that the readers can determine the contribution of each life cycle stage for the overall environmental impact.

Moving on, the contrast in functional units for each study can also be correlated to the overall objective of each LCA. The most common functional units used for LIBs seem to be LIB capacity (in kWh) and LIB weight (in kg). Though this functional unit would help ease the comparison process of the results within different publications, their main drawback is that they might exclude most of the battery’s characteristics from consideration. These include lifetime, round-trip efficiency, energy density, etc. To counter this, functional units that directly relates to the purpose of the LIBs were used. These include distance driven (in km) for electric vehicle LIBs and by energy delivered (in kWh) for grid storage LIBs, as shown by the publications by Zackrisson (2010), Notter (2010), and Ryan (2018). Of course, it is also possible to show the results in different functional units, such as done by Ellingsen (2014) and Baumann (2017). To conclude, it is important to choose which functional unit to choose by considering each of its drawbacks and advantages.

Table 2, Outlines several studies related to the life cycle assessment of lithium-ion batteries.

Source	Battery Chemistry	Life Cycle Stages Considered	Functional Unit	Battery Application
<i>Zackrisson et al. (2010)</i>	LFP	Cradle-to-grave	Per 10 kWh capacity	Electric vehicles
<i>Notter et al. (2010)</i>	LMO	Cradle-to-grave	Per 1 km driven	Electric vehicles
<i>Majeau-Bettez et al. (2011)</i>	LFP, NMC, NiMH	Cradle-to-gate; Use stage	Per 50 MJ electricity delivered; Per 1 kg battery; Per 1 kWh capacity	Electric vehicles
<i>EPA (2013)</i>	LFP, NMC, LMO	Cradle-to-grave	Per 1 km driven	Electric Vehicles
<i>Ellingsen et al. (2014)</i>	NMC	Cradle-to-gate	Per 1 battery pack; Per 1 kg battery; Per 1 kWh capacity	Electric vehicles
<i>Hiremath et al. (2015)</i>	LFP, NMC, LMO	Cradle-to-gate; Use stage	Per 1 MWh electricity delivered	Grid energy storage
<i>Baumann et al. (2017)</i>	LFP, LTO, NMC, LMO, NCA	Cradle-to-gate; Use stage	Per 1 kg battery; Per 1 kWh delivered; Per 1 kWh capacity	Grid energy storage

Ryan <i>et al.</i> (2018)	LFP, NMC, LMO, NCA	Cradle-to-grave	Per 1 MW reserve capacity for one year	Grid frequency regulation
---------------------------	--------------------	-----------------	--	---------------------------

The different applications for LIBs are for electric vehicles and grid-scale energy storage. These applications require different power and energy ratings from the LIBs, as the source of the energy demand is not the same. Baumann (2017) noted that only a small amount of LIB LCAs relate to LIB for stationary applications. To corroborate, in this thesis project, there are only three publications that discuss LIB for grid storage (Hiremath, 2015; Baumann, 2017; Ryan, 2018). In these studies, it was shown that it is important to decide which grid storage scenario to choose when conducting an LCA for stationary application LIBs. The scenarios include LIB applications for primary regulation, community-scale energy management, energy time-shift, etc. (Hiremath, 2015). It is important to determine the chosen LIB application scenario because the energy demand of each case is different, which would in turn vary the final life cycle environmental impact.

With these discrepancies, a thorough comparative study focusing on previously done LCAs on LIBs would be needed to obtain a generalized picture of the environmental impact of LIBs. Peters (2018) had researched to levelized the inventories used in previous LCAs of LIBs. The process of the research was to first identify the key inventory data differences in existing LIB LCAs and then unify the inventories into one common document. As a result, a common dataset for future LCAs on LIBs was created. To note, this publication has attached a supplementary file that contains this unified life cycle inventory. Unfortunately, this study only covers the cradle-to-gate stage of the LIB's life cycle. Therefore, Peters' study is different from this thesis since it did not include the use and end-of-life stages.

In the end, Peters had determined that implementing his levelized life cycle inventory, which is a common inventory that can be used for cradle-to-gate LCA for LIBs, resulted in more comparable environmental impact results. Hence, implementing this inventory would be useful in the absence of primary data. Nevertheless, data from other sources will be needed for the use and end-of-life stages

2.3.2 The Product Environmental Footprint Categorical Rules (PEFCR)

Due to the wide array of differences in LCA of LIB described in section 2.3.1, the European Commission has drafted a document to attempt to standardize LCA for LIB from a whole cradle-to-grave perspective. They use the Product Environmental Footprint (PEF) Guide as the basis for doing so. The PEF is a document created by the European Commission to describe a methodology to measure the overall environmental footprint of a product throughout its life cycle adhering to the ISO 2006 series of LCA standards (Manfredi, et al. 2012). The PEF is then tailored for different product categories, such as metal sheets, wine, water pipe systems, etc. These specific PEFs are described in Product Environmental Footprint Categorical Rules (PEFCR) documents.

In 2020, a pilot PEFCR document for high specific energy rechargeable batteries was published. In its scope, the PEFCR for batteries considers the use of batteries in three different applications: cordless power tools, information and communication technologies, and e-mobility (electric vehicles). The application that is most analogous for batteries in stationary storage use would be e-mobility, as they both require large-sized batteries with high capacity. To add, this PEFCR considers two types of battery technology: lithium-ion and nickel-metal hybrid (NiMH).

The batteries PEFCR compiles its inventory data by using primary information from various sources. This inventory can then be used by other parties as a reference when they do not have specific data, albeit with adjustments that they deem necessary. Also, the inventory provided by the batteries PEFCR encompasses the cradle-to-grave life cycle of batteries, as shown in Table 3. This proves that the PEFCR can be used as a default inventory reference when conducting an LCA for batteries if the study is similar to the PEFCR.

Table 3, Life cycle stages included in the batteries PEFCR (EC, 2020)

Life Cycle Stage	Included Processes
Raw material acquisition	Mining, pre-processing, manufacturing of cells and battery components
Main product production	Assembly of battery packs
Distribution	Transport to consumer
Use phases	Electricity usage during the use phase
End-of-life	Scrap collection and processing

The batteries PEFCR uses *energy delivered* as its functional unit. This is because the intended function of batteries is to supply electricity, so it would be preferable since the environmental impact can then be related directly to the application. Regarding the environmental impact categories, the batteries PEFCR consequently follows the Environmental Footprint (EF) mid-point method. The impact categories considered in the EF method are shown in Table 4. In the case of the batteries PEFCR, the five most relevant impact categories are determined to be *Climate Change, Terrestrial and Freshwater Acidification, Energy Carriers Resource Use, Minerals and Metals Resource Use, and Respiratory Inorganics*. These five categories contribute to approximately 90% of the total impact for batteries in the e-mobility application. The contribution to the total impact was obtained by normalizing and weighting the results from each impact category by using the factors as provided in Annex 1 of the batteries PEFCR. Nevertheless, the five impact categories are deemed most relevant in the batteries PEFCR.

Table 4, Impact categories for lithium-ion battery life cycle assessment (EC, 2020)

Impact category	Indicator	Unit	Recommended default LCIA method
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE)	mol N eq.	Accumulated Exceedance (Seppäälä et al. 2006, Posch et al, 2008)
Cancer human health effects	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model (Rosenbaum et al, 2008)
Climate Change	Radiative forcing as Global Warming Potential (GWP100a)	kg CO ₂ eq.	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox model (Rosenbaum et al, 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq.	EUTREND model (Struijs et al, 2009b) as implemented in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq.	EUTREND model (Struijs et al, 2009b) as implemented in ReCiPe
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq.	Accumulated Exceedance (Seppäälä et al. 2006, Posch et al, 2008)
Ionising radiation, human health	Human exposure efficiency relative to U-235	kBq U-235 eq.	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)
Land Use	Soil quality	Soil quality index	LANCA (Beck et al. 2010)
Non-cancer human health effects	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model (Rosenbaum et al, 2008)
Ozone depletion	Ozone depletion potential (ODP)	kg CFC-11 eq.	Steady state ODPs 1999 as in WMO assessment
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq.	LOTUS-EUROS model (Van Zelm et al, 2008) as implemented in ReCiPe
Resource use, energy carriers	Abiotic resource depletion - fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinee et al., 2002 and van Oers et al, 2002)
Resource use, mineral and metals	Adiabatic resource depletion (ADP ultimate reserves)	kg Sb eq.	CML 2002 (Guinee et al., 2002 and van Oers et al, 2002)
Respiratory inorganics	Impact on human health	Disease incidence	UNEP recommended model (Fantke et al, 2016)
Water scarcity	User deprivation potential (deprivation-weighted water consumption)	m ³ world eq.	Available WATER Remaining (AWARE) Boulay et al, 2016

2.3.3 Levelized cradle-to-gate inventory of lithium-ion batteries

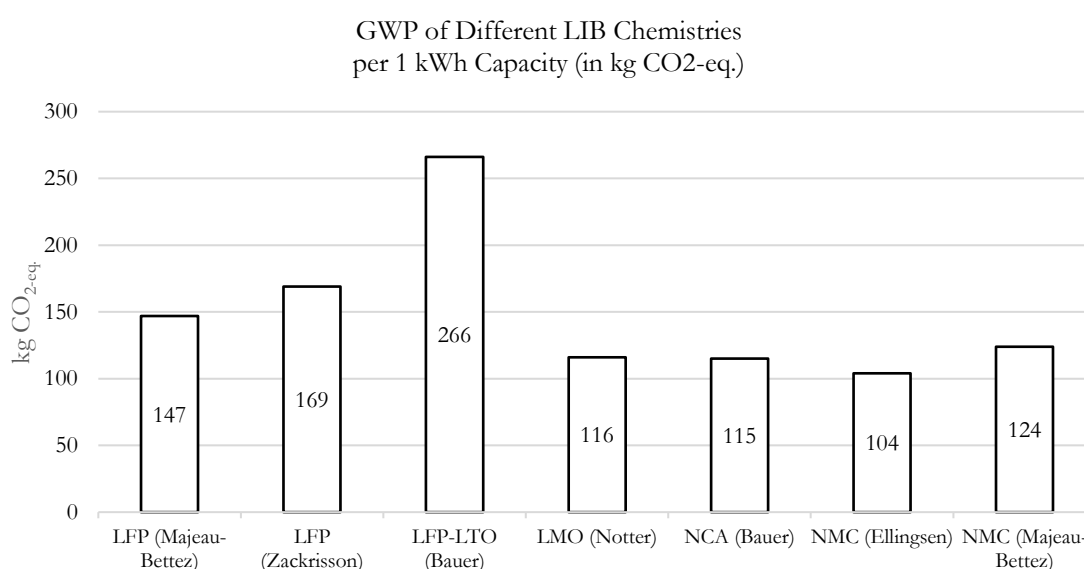
As described in Section 2.3.1, there are differences in every LCA study related to LIBs and to thoroughly compare them with one another, a levelized LCI would be needed. Peters (2018) addressed this problem by compiling different publications related to LCA on LIBs. Then, the discrepancies between the compiled datasets were identified and levelized. Finally, a common, unified inventory was then published to serve as a basis for future LCA studies on LIBs. The references used for the common LCI can be seen in Table 5 below: Note that this levelized inventory only covers the cradle-to-gate process

Table 5, Studies referred to for compiling the common life cycle inventory for lithium-ion batteries (Peters and Weil 2018)

Lithium-Ion Battery Chemistry	Sources
Lithium Iron Phosphate (LFP)	Zackrisson et al. (2010) Majeau-Bettez et al. (2011)
Lithium Titanate Oxide (LTO)	Bauer (2010)
Nickel Manganese Cobalt (NMC)	Majeau-Bettez et al. (2011) Ellingsen et al. (2014)
Lithium Manganese Oxide (LMO)	Notter et al. (2010)
Nickel Cobalt Aluminum (NCA)	Bauer (2010)

In addition to creating a common inventory for LIBs, this study had also compared the resulting environmental impact from this LCI. The impacts that were considered include global warming potential (GWP), Particulate Matter Formation (PMF), Acidification Potential (AP), Human Toxicity Potential (HTP), and Photochemical Ozone Formation (POF). To give an example, the resulting GWP from the levelized inventory can be seen in Figure 6.

Figure 6, The resulting GWP from the levelized life cycle inventory (Peters and Weil 2018)



Since this is the result from a levelized inventory, the results obtained from this thesis should be comparable to Figure 6, albeit only for the *cradle-to-gate* phase. Further, this publication could serve as a source of secondary data in the absence of the primary ones. All-in-all, this study will serve as an important reference thorough this thesis research

3 Methods and Materials

To iterate, this thesis will refer to the ISO 16040:2006 standard for LCA guidelines and requirements. This thesis will also refer to the PEFCR for rechargeable batteries document, which was described in Section 2.3.2. However, the implementation of the PEFCR will only be limited to the end-of-life inventory, impact assessment method, and chosen functional unit. This is because the batteries that are in the focus of the PEFCR document are intended for electric vehicle application, so it will have a different use phase as compared to LIB application in grid storage.

Now, this chapter of the document will start with an overview of the LCA framework. Then, explanations on how the LCA framework is implemented in this thesis project is described. Hence, the overall methodological framework of the LCA will be compiled with an overview of the scope and boundary definition, life cycle inventory, and life cycle impact assessment of this thesis.

3.1 The life cycle assessment framework

The LCA principles, framework, and requirements, and guidelines are thoroughly described by the International Organization for Standardization (ISO) in two documents: ISO 14040 and ISO 14044. Here, it is stated the main feature of an LCA is that LCA is a study that observes the whole environmental aspects and impacts for the studied subject, from raw material extraction to its final disposal. The extent of an LCA can be adjusted accordingly to the project's goal. Now, before considering the method of this thesis, the LCA concept will be summarized in this section. There are four phases in conducting an LCA project: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the results interpretation phase. These phases are iterative, as illustrated in Figure 7.

3.1.1 Goal and scope definition

Like other studies, the goal and scope definition of an LCA serves as a boundary to ensure the project's clarity. The goal of an LCA should clearly state the intended use and the reason for the study. On the other hand, the scope of an LCA is directly related to the depth and details of the project. This includes defining the assessed product system, functional unit, system boundary, study assumptions (and limitations), and impact assessment method. Although the LCA study is an iterative process, these two aspects should be conducted first as it helps clarify the study. Of course, as changes occur, the goal and scope can be adjusted to cater to the reality of the project.

In an LCA, the functional unit is used as a quantitative reference to relate the inputs and the outputs of the studied product system. It is also used to make different LCAs comparable. Some examples of functional units are kilograms of mass, meters of length, and megajoules of energy. The amount of the outputs required to fulfil the functional unit is called the Reference flow. Next, the system boundary clarifies what processes in the product system should be included in the study. For instance, deciding if the end-of-life of a product be analyzed or excluded from the analysis should be done when determining the system boundary. Ideally, the output and input of the processes at the system boundary should only consist of elementary flows to help guarantee the thoroughness of LCA. Nevertheless, it is not a requirement as the LCA's conclusion should focus on fulfilling the goal and scope of the project.

Other important terms for an LCA study are background and foreground systems. Background systems consist of processes that the decision-maker has none or indirect influence on, while foreground systems have processes that are directly related to the decision-makers (Frischknecht, 1998). As such, it is important to denote which processes are in the background, or foreground, when discussing the LCA project's scope.

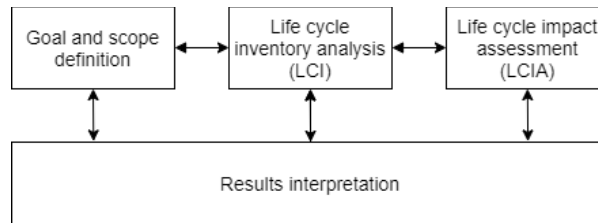


Figure 7, The phases of an LCA study (ISO, 2006)

3.1.2 Inventory analysis

The life cycle inventory (LCI) is a phase that is focused on building an inventory. The inventory is a compilation of all data used in the LCA. Hence, this step is analogous to the data gathering step of a research methodology. Items in the inventory could include energy inputs, material flows, and emissions. When collecting the inventory, the data can be obtained from a combination of primary and secondary data. Of course, the validity of the information will directly relate to the LCA project's degree of confidence. In the case of studies with multiple products, allocation procedures should be properly done to divide the attribute the inventory accurately. Once again, the LCI step is iterative since more information might be obtained, or limitations might be noticed, when conducting the study.

3.1.3 Impact assessment

After completing the LCI stage, the life cycle impact assessment (LCIA) is conducted to evaluate the environmental impact (EI) of the items in the inventory. These EIs can be obtained by connecting the inventory with EI categories and category indicators. This 'connecting' process is formally known as the characterization step, where different types of emissions are quantified and associated with their relevant impact category indicator. The numerical sum of all emissions in the same category indicator is then put into their impact category. Examples of impact categories include acidification potential, climate change, and human toxicity, while their respective category indicators are kg SO₂-eq., kg SO₂-eq., and kg 1,4-DCB-eq. (Hischier, 2010). Note that the EI categories and category indicators to be used is related to different types of impact assessment methods. Impact assessment methods thoroughly describe which categories and indicators are used to obtain the EI results. In the end, the results from the LCIA serves as the basis for the life cycle interpretation step.

3.1.4 Results interpretation

The purpose of this step is to interpret the results obtained from the LCIA stage. This step has three features: significant issue identification, study evaluation, and conclusion. The LCIA itself is used to determine the significant issues of the LCA. Then, the overall study is evaluated against the goal and scope of the LCA. Here, the correctness of the definitions of the system functions, functional unit, and system boundary must be validated. The resulting evaluation can then be iterated back to adjust the three other steps: goal and scope definition, inventory analysis, and impact assessment. In addition, complementary observations can be done, such as conducting a sensitivity analysis for the LCIA. Finally, after the results are obtained, the conclusion of the LCA can be drawn and recommendations can be made. The conclusion can then be used to fulfil the LCA's goal. However, there will be environmental impacts that can be reduced with improvement measures. Scenarios and sensitivity analysis can also be done to further understand the system. Therefore, the LCA is ultimately an iterative process, which can be repeated as many times as necessary.

3.2 Goal and scope definition of the thesis

The goal of this study has been discussed in Chapter 1. To underline, *this is a comparative LCA study between LIBs and lead-acid batteries*. Also, three scenarios will be analyzed. These scenarios will inspect the environmental impact of three different LIB battery *chemistries*: LFP, NMC, and NCA will be observed. Now, to clearly define the scope of the project, several topics will be discussed in this sub-section: the product system, the boundary of the system, the functional unit, and the reference flow. Defining these

aspects clearly will be crucial to ensure that the results of this study stay relevant and to help comparability with other literature. Nevertheless, stating a clear goal and scope of an LCA study is a required by the ISO (2006) standard.

3.2.1 Product system and boundary of the study

This section will clarify which processes will be included in the study. Further, the processes will be clarified as background and foreground processes. Not only by where the decision-makers influence, the separation between the background and foreground would also be determined by the availability of data related to each process. If primary data is available, the process might be put in the foreground of the study, while using secondary data will categorize the process to the background. Now, an overview of the life cycle of LIBs, the system boundary, and the division between background and foreground processes for this LCA study can be seen in Figure 8.

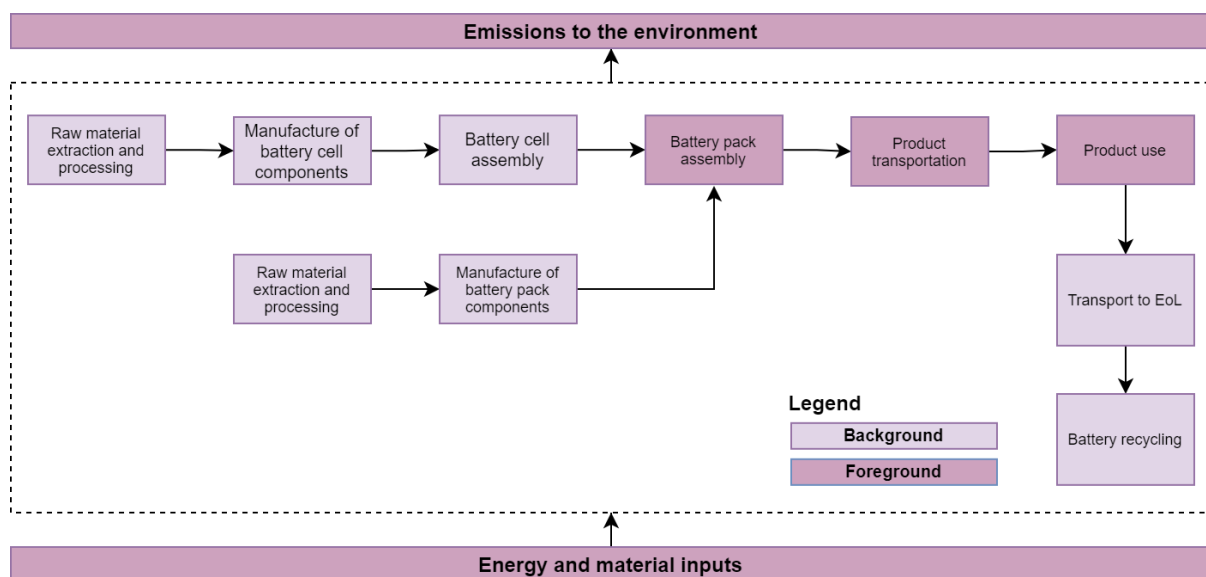


Figure 8, System boundary for the LCA study

- Foreground processes: Battery pack assembly, product transportation, product use, energy and material inputs, and emission to the environment
- Background processes: Raw material extraction and processing, manufacture of battery cell components, battery cell assembly, manufacture of battery pack components, transport to EoL, and battery recycling.

The foreground processes, which this thesis study has an influence on, was decided because primary data for them are available. Meanwhile, the lack of primary data and stakeholder influence has put the other processes in the background, but it does not mean that they are excluded from the study. Further, the dashed line in Figure 8 denotes the boundary of the system. Hence, the two blocks: Energy and materials inputs and the emissions to the environment, are the generalized inputs and outputs into the product system, respectively.

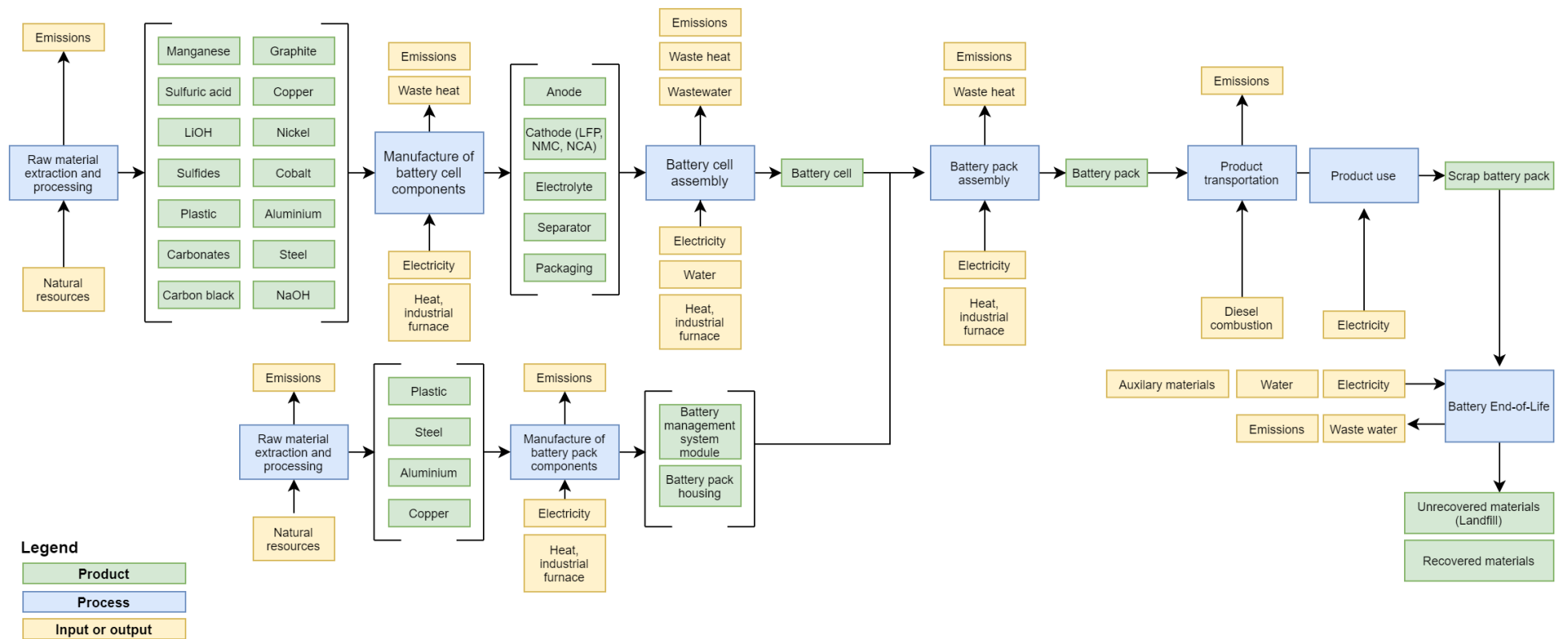


Figure 9 The product system of the lithium-ion battery life cycle assessment study

To have a more detailed view of the whole life cycle of LIBs, Figure 9 illustrates the complete product system used in this study. Note that Figure 9 is the merged form of Figure 3, Figure 4, and Figure 5, so it provides a complete illustration of the LIB life cycle. Zooming into the manufacturing processes for battery cell components and battery pack components, the sub-processes that are considered in this LCA study can be expanded further. These include the following:

1. Battery cell assembly:
 - a. Anode manufacturing
 - b. Cathode manufacturing for LFP, NMC, and NCA chemistries
 - c. Electrolyte manufacturing
 - d. Separator manufacturing
 - e. Cell packaging manufacture.
2. Manufacture of battery pack components:
 - a. Battery management system module
 - b. Battery pack housing.

Once again, since these processes are in the background, the related inputs and outputs are obtained from secondary data sources: databases and literature. More details on which references were used will be explained in the life cycle inventory section of this report.

3.2.2 Functional unit and reference flow

Referring to the literature review, there is a wide array of different functional units that can be used for a cradle-to-grave LCA for LIBs. However, the functional unit of this study will follow the PEFCR for Rechargeable Batteries (2020). This is because as the function of BESS in utility storage is to supply electric energy, it would be intuitive to define the functional unit as *per kWh of the total energy delivered over the lifetime of the battery*, which will be symbolized as kWh_D (shorthand for kWh energy delivered) from now on. Now, there are three necessary parameters required to calculate the total energy delivered throughout the battery's lifetime: average energy delivered per cycle in kWh (kWh_{D-cycle}), the total amount of cycles throughout the battery's lifetime (n_{cycle}), and the average capacity per cycle in percent (c_{cycle}) (Hiremath et al., 2011 and EC, 2020). The relationship between the three parameters can be seen in equation (1).

$$\text{kWh}_D = \text{kWh}_{D\text{-cycle}} \times n_{\text{cycle}} \times C_{\text{cycle}} \quad (1)$$

Now, to relate the batteries to the functional unit, the mass of the battery must also be considered. By dividing the battery mass with the total energy delivered throughout the lifetime, a reference flow can be obtained. The unit of this reference flow will be *kg of battery per kWh energy delivered throughout the battery lifetime* (kg/kWh_D), as shown in equation (2). The life cycle inventory would then refer to this reference flow, as it directly relates the battery packs with the functional unit. The reference flow was determined to be descriptive of the LIB's environmental impact when the LIB is at work (EC, 2020), so this reference flow will also be used in this thesis project.

$$\text{Reference flow} = \frac{\text{kg}}{\text{kWh}_D} \quad (2)$$

However, there is an important aspect to be considered when using this functional unit. While it is true that using the 'energy delivered' term as the functional unit (and reference flow) might seem to enable the comparability of this LCA study to other related publications, it is not that straightforward. This is because the total energy delivered by the battery packs would be different for each usage scenario (Hiremath et al, 2015, Baumann et al., 2017, and Ryan et al., 2018). As described in Section 2.1.2, there is a wide array of usage methods for LIBs in grid storage systems. In essence, because of the different usage scenarios, the total energy delivered throughout the lifetime of the battery will be different, which would in turn result in a different reference flow. To note, the use phase scenario used in this thesis study will be explained in the life cycle inventory further into this report.

3.3 Life cycle inventory data source

To clarify, the processes in this LCA project are grouped into three main stages: cradle-to-gate, use, and end-of-life. In turn, the cradle-to-gate stage is mainly about the manufacturing of components for battery cells and battery packs. Then, recalling Figure 8, only the manufacturing process of battery packs (which is at the end of the cradle-to-gate stage) and the use phase are in the foreground, which means that other processes are classified as background processes. As they are in the background, these processes will rely on secondary data that are adjusted to suit this thesis project. It is important to know from where the secondary data comes from, for the accountability of this study. Therefore, Table 6 summarized the general information related to the life cycle inventory of this study. Then, in the following sub-sections, the inventory for each life cycle stage will be discussed individually. In addition, an inventory for a generic lead-acid battery is needed for comparison with the LIBs. For this, the cradle-to-gate LCI provided by Spanos (2014) will serve as the reference benchmark against LIBs. Note that primary data used in this study are all provided by Polarium Energy Solutions AB.

Table 6, Details on data sourcing and location for each life cycle stage of the project

Life Cycle Stage	Process	Location	Data Source (material flows)	Data Source (Emission factors)
Cradle-to-gate	Raw materials acquisition and processing	Rest-of-world	Ecoinvent 3.71	Ecoinvent 3.71
	Manufacture of battery cells	China	Peters (2018)	Ecoinvent 3.71
	Manufacture of battery pack housing	China	Peters (2018), Primary	Ecoinvent 3.71
	Manufacture of BMS module	Belgium	Peters (2018)	Ecoinvent 3.71
	Assembly of battery packs	Mexico	Primary, Peters (2018)	Ecoinvent 3.71
Use	Transportation and electricity delivery	United States	Primary	Ecoinvent 3.71
End-of-life	Battery recycling and disposal	United States	Rechargeable batteries PEFCR (2020)	Ecoinvent 3.71

3.3.1 LCI for the cradle-to-gate stage

Although all secondary data regarding the cradle-to-gate stage comes from the study conducted by Peters and Weil (2018), it can be traced one step further as the components in the levelized inventory refer to different literature. Going deeper, since three different LIB chemistries would be considered as the scenarios in the study, they also have different references within the publication. As such, Table 7 goes one step further from Table 6, where the main data sources for each process in the cradle-to-gate stage are described.

Table 7, Main data sources for each process within the cradle-to-gate phase

Process	Location	Transportation Method	Main source for material flow
Raw materials acquisition and processing	Rest-of-world	n.a.	Ecoinvent 3.71
Manufacture of battery cells - LFP	China	Sea freight	Zakcrisson et al. (2010)
Manufacture of battery cells – NMC	China	Sea freight	Ellingsen et al. (2014)
Manufacture of battery cells – NCA	China	Sea freight	Bauer et al. (2010)
Manufacture of battery pack housing	China	Air freight	Bauer et al. (2010), Primary
Manufacture of BMS module	Belgium	Sea freight	Ellingsen et al. (2014)
Assembly of battery pack	Mexico	n.a.	Primary, Peters and Weil (2018)

The acquisition and processing of raw materials are entirely according to the Ecoinvent 3.71 database since it can provide the most detailed inputs and outputs. The location for it is put as ‘rest-of-world, as there is no primary data regarding where the process took place. The term rest-of-world refers to the globally averaged value, as described in EcoInvent 3.71. Next, the manufacturing of all types of battery cells is conducted in China, by utilizing the levelized datasets from Zackrisson et al. (2010), Ellingsen et al. (2014), and Bauer et al. (2010). Similarly, the battery pack housing is also made in China and is modelled by using the dataset provided by Bauer et al. (2010). The inventory for the battery pack casing is also adjusted accordingly by referring to the available primary data. Finally, the BMS module is created in Belgium, while referring to the data provided by Ellingsen et al. (2014). Each of these components has its complex product systems, so it would be more informative to refer to the sources directly if more details are needed. As an important note, Peters and Weil (2018) had *aggregated all energy consumption* to the battery pack manufacturing level, so that double-counting the energy use in the cradle-to-gate stage is avoided. The electricity mix is then chosen to be the Chinese mix because battery cells, which accounts for most of the battery packs weight, are manufactured in China. Of course, this is only applicable to this study.

Now, since the battery packs themselves are built in Mexico, all these components must be transported to Mexico from their respective location. Table 7 provides the list of locations and transportation methods for each component. The transportation distance is estimated by using an online freight distance calculator tool, ‘sea-rates.com’. In contrast with the components, a bill-of-material (BOM) is available for the battery pack, so primary data can be used for the inventory. Thus, Table 8 breaks down the materials contained in the battery pack, which is also the inventory used for this study. The mass composition is then used to model the battery pack assembly process, adjusted to the reference provided by Peters and Weil (2018). Nonetheless, since almost all the data used in the cradle-to-gate phase are from literature, the results of this study will be limited to provide an estimation, which is impossible to be determined as perfectly descriptive of the real conditions.

Table 8, Materials composition of different battery packs used in the study (Source: Polarium Energy Solutions AB)

Battery Chemistry	Material	Share of total
LFP	Battery cell	79.6%
	Packaging	17.4%
	BMS Module	2.8%
NMC	Battery cell	66.8%
	Packaging	29.3%
	BMS Module	3.8%
NCA	Battery cell	80%
	Packaging	17.6%
	BMS Module	2.3%
NCA-b	Battery cell	75.9%
	Packaging	20.9%
	BMS Module	3.1%

3.3.2 LCI for the use stage

As seen from Table 6, the location of the use phase in this LCA study is in the United States. Since the end process of the cradle-to-grave stage, battery pack assembly, is located in Mexico, the product must first be transported to the United States. This time, the product is transported using lorries via a land route, since

Mexico and the United States are not separated by sea. The distance is once again estimated using the online freight distance calculation tool (SeaRates, 2021).

Then, an important factor for the use stage is the usage scenario for the BESS. As explained in Sections 2.1.2 and 3.2.2, the main parameter required would be the total energy delivered throughout the lifetime of the batteries. The total energy delivered is the energy required for the system that is powered by the batteries, which is also known as the total energy demand. To obtain this, several factors must first be determined. First, the energy rating of the system is required. The energy rating is basically how much electric energy does the system need, per cycle, and it can be determined by the power rating and total hours of operation per cycle. Second, the number of cycles must be known. The number of battery cycles (or charge-discharge cycles) should be considered for the whole lifetime of the system. Finally, the lifetime of the electric system is also important. This is different from the lifetime of the batteries because this lifetime is related to the whole system itself. The system's lifetime can also be considered as the 'simulation time, as it will be the same for both the LIB and the lead-acid battery. In this LCA study, the batteries are operating at a 'standby state', where it operates solely to back up the system in case of blackouts. The system is connected to the power grid, so the battery does not operate much. To summarize, the energy delivered parameters for this standby state can be obtained by using the numbers seen in Table 9. The system is assumed to be operating for 20 years. Therefore, the number of cycles in Table 9 refers to the total during 20 years of operation. Note that for the standby scenario, the C_{cycle} will be assumed as 100%.

Table 9, Summary of the parameters required to determine the use phase energy delivered (Source: Polarium Energy Solutions AB)

Use phase scenario	Power rating (kW)	Discharge duration (hrs.)	Energy rating (kWh _{D-cycle})	Number of cycles for 20 years (n _{cycle})	Total energy delivered (kWh _D)
Stand-by	5	4	20	240	4,800

In addition, another important consideration would be the performance of the battery packs themselves. The performance of the batteries is necessary to determine the reference flow of the use phase, as described in Section 3.1.2. To obtain these parameters, several data must be extracted from the batteries. These parameters are the energy density and the battery lifetime. The energy density is the amount of energy the battery can deliver per unit of weight, usually in kilograms. On the other hand, the lifetime of the battery refers to how long will the battery be able to operate. Batteries have two different lifetime parameters: calendrical life and cyclical life. However, since the batteries used in the stand-by scenario are not charged and discharged that often, they will reach the end of their calendrical life first. All in all, Table 10 shows the parameters of the batteries used in this study. Note that the three different chemistries are included in the table and that these parameters are obtained from primary data.

Table 10, Summary of the reference flow of the batteries (Source: Polarium Energy Solutions AB)

Battery type	Reference flow (kg/kWh _D)
LFP	0.064
NMC	0.037
NCA	0.025
Lead-acid	0.501

Notice that in Table 10, the reference flow for lead-acid batteries is much higher compared to the LIBs. This is directly related to the differences in both the energy density and lifetime. On another note, it is clear from Table 10 that the parameters for battery performance will differ for different battery products. As such, it is important to cross-check with the product datasheet of the batteries to validate the data every time a similar LCA study is conducted. Similarly, the total energy delivered will differ depending on the

chosen use phase scenario. Once again, this emphasizes the difficulties of comparing two different cradle-to-grave LCA studies on LIBs when the use phase is not completely identical. Therefore, the inventory and the subsequent obtained environmental impact is limited to this specific study and cannot be replicated in one or more of the parameters are to be changed.

3.3.3 LCI for the end-of-life stage

As previously mentioned in Table 6, the end-of-life stage of this study will rely on the inventory provided by the PEFCR for rechargeable batteries document (EC, 2020). The inventory includes the processes necessary to treat the waste battery cells, passive parts, OEM parts, OEM electronic parts, and unsorted fractions. Once again, since the OEM parts are related to the use of LIBs in EVs, they will be excluded from this study. However, it is important to note that the inventory used will be assumed to be the same as the default amounts for e-mobility, as they are the closest proxy available for LIBs for stationary applications. Also, the PEFCR document utilizes the Environmental Footprint database as its default instead of Ecoinvent 3.71, so adjustments are necessary to align the model if the Ecoinvent 3.71 database is to be used.

Since there are materials recovered in the end-of-life stage, *credits* will be necessary to attribute the avoided environmental impact due to the recycling processes. However, in this study, no secondary materials are introduced as input materials for the cradle-to-gate stage. This is also why the study is cradle-to-grave instead of cradle-to-cradle, as the material flow is not circular. Therefore, the credits from recycling the materials will be given straight away to the end-of-life stage, as a discount to the total burden from treating the scrap battery packs. The credits and burdens at the end-of-life stage are calculated according to the Circular Footprint Formula (CFF), which can be obtained from the PEF guide document (Manfredi, et al. 2012). Fortunately, the CFF is already integrated into the PEFCR inventory, so no manual calculation was needed. Of course, the geographical references in the PEFCR inventory must be modified since the process is conducted in the United States instead of the European Union. Nevertheless, the default amounts are assumed to be the same although the location is changed. Also, the transportation from the use phase location to the end-of-life stage is assumed to be zero, since no data are available for this process.

Finally, an important limitation of the PEFCR dataset is that although it is usable for all types of LIBs, the inventory it provides is focused on NMC batteries. As a result, the main recovered materials from recycling the battery cells are Nickel, Manganese, and Cobalt. Therefore, assumptions must be made when modelling the end-of-life of LFP and NCA batteries. These assumptions of recovered materials are highlighted in Table 11. As can be seen, there are no materials recovered for the LFP model. Unfortunately, it was difficult to find a reliable source for the end-of-life model of LFP batteries, since the study related to it are few (Melin, 2019). Therefore, the study uses the limited dataset provided by the PEFCR for the end-of-life stage of LIBs. Nevertheless, it is recommended to use a more specialized inventory for the end-of-life stage of each specific LIB chemistry to get a clearer picture. On another note, the end-of-life treatment of lead-acid batteries is provided by the Ecoinvent 3.71 database, as it has already been modelled.

Table 11, Assumed recovered materials for each scenario of battery chemistries, compared to the PEFCR

Material Recovered	PEFCR	NMC Model	NCA Model	LFP Model
Nickel	Included	Included	Included	Excluded
Cobalt	Included	Included	Included	Excluded
Manganese	Included	Included	Excluded	Excluded

3.4 Life cycle impact assessment method

Similar to determining the functional unit of this study, the LCIA method used for this LCA would follow the guidelines set by the PEFCR for rechargeable batteries (EC, 2020). The impact assessment method of the PEFCR was the Environmental Footprint methodology, whose impacts were listed in Table 4 in Section

2.4.2. Recall that there were five most relevant impact categories as determined by the PEF CR. To ensure that this study is thorough and descriptive, only these five impact categories will be observed in this LCA study. Consequently, the impacts of the LIBs will be compared to lead-acid batteries in these categories and will be expressed in terms of per cent difference from the lead-acid batteries. Of course, the scenarios with different LIB chemistries will be included in the comparison. This should provide enough comparative assessment between the LIBs and lead-acid batteries. For reference, Table 12 shows the environmental impact categories that are considered in this report.

Table 12, *Environmental impact categories used in this report (EC, 2020)*

Impact category	Indicator	Unit	Recommended default LCIA method
Acidification, terrestrial and freshwater	Accumulated Exceedance (AE)	mol N eq.	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Climate Change	Radiative forcing as Global Warming Potential (GWP100a)	kg CO2 eq.	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Resource use, energy carriers	Abiotic resource depletion - fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinee et al., 2002 and van Oers et al, 2002)
Resource use, mineral and metals	Adiabatic resource depletion (ADP ultimate reserves)	kg Sb eq.	CML 2002 (Guinee et al., 2002 and van Oers et al, 2002)
Respiratory inorganics	Impact on human health	Disease incidence	UNEP recommended model (Fantke et al, 2016)

3.5 Modelling tools

To help understand the life cycle of a product (or service) better, LCA studies often employ computer software to help with data logging, system visualization and result calculation. This would in turn help reduce the costs of conducting an LCA and increase transparency (PRé Sustainability, 2020). However, these software would usually require data, which consist of the inputs and outputs of the system, to operate. The data is then obtained from can come various sources, such as databases (EcoInvent, ELCD, GaBi, etc.), literature, and primary observation. Note that the sources of data for this thesis project are listed in Table 6. Nevertheless, the usage of software in an LCA would considerably help the practitioner.

In this project, the life cycle inventory is listed and categorized in Microsoft Excel. This helps increase the readability of the dataset, which in turn would make it easier for the system to be modelled. In addition, Microsoft Excel was also used for visualizing the obtained environmental impact results. Then, for modelling the LIB lifecycle, two different software could be used to model the life cycle: SimaPro and OpenLCA. These two software are almost identical in terms of operation. From this thesis and other literature, the SimaPro software was simpler to use than OpenLCA and was utilized in different LCA for LIB (Hiremath et al., 2015, Liang et al., 2017, and Lima et al., 2021). On the other hand, only one study (Peters, et al., 2018) used OpenLCA for LCA on LIB, though there are several publications in different topics of the energy sector that used OpenLCA (Li, 2018 and Nelson, 2017). However, the key deciding factor was that OpenLCA was open-source, which means that anyone can use OpenLCA without paying for a license. Of course, a separate license would be needed if a database was used. Nonetheless, the OpenLCA was deemed to be more suitable for this project since this thesis utilizes different sources of data. OpenLCA was also used to conduct the life cycle impact assessment step and the sensitivity analysis. Therefore, most of the calculations were completed in the OpenLCA software.

3.6 Results interpretation: sensitivity and comparison with another study

Once again, LCA studies are iterative processes (ISO, 2006). This means that although there are results that will be presented in Chapter 4 of this report, it does not mean that this result will be static. The inputs and outputs will change with time, which means that the resulting environmental impact is also subject to change. As an analogy, the results of this thesis is similar to a ‘photograph’, which means it only describes the condition at one specific point in time. Therefore, another LCA must be done once again if it is necessary to determine the environmental impact again in the future. The whole process of analyzing the environmental impact results from an LCA is the focus of the results interpretation step. Note that in this thesis project, at the end of the results interpretation step, suggestions on measures for improving the overall environmental impact throughout the LIB life cycle will be added.

Now, to have a better picture of how the system would react to a change in the value of the input, a sensitivity analysis was done in this thesis project. In a sensitivity analysis, the input values of a process in the life cycle are changed. The change would affect the environmental impact results from the process, where this change should illustrate how ‘sensitive’ is the system (ISO, 2006). This begs the question, which process should be used for the sensitivity analysis? The most common recommendation is to choose the process with the *highest uncertainty* (Wei, et al. 2014). Therefore, for this thesis project, the sensitivity analysis should be done in a *foreground process*, because those processes used primary data which could mean a higher uncertainty. Further, the sensitivity analysis should focus on the process with the *highest contribution* to the overall environmental impact, also known as ‘hotspot’ processes. This is because knowing which aspects improve (or worsen) the hotspot process could help in proposing measures to reduce the overall environmental impact. Hence, conducting the sensitivity analysis is important, especially in a foreground process with a high contribution to the total environmental impact.

On the other hand, the results of this thesis project will be compared with two other publications: Peters et al. (2018) and the PEFCR for rechargeable batteries (2020). As repeatedly described in Chapter 2, it is difficult to compare the results of this study with others because of the different scope, functional units, LIB chemistries, battery usage scenario, and environmental impact categories. Nevertheless, a comparison with the study by Peters et al. (2018) and the PEFCR document will be done to give an illustration to the readers, while some short explanations would also be given to help understand the cause of the differing results. Of course, the scope will be up to the cradle-to-gate stage. To elaborate, Table 13 highlights the differences between the studies that will be compared.

Table 13, Differences between the thesis study, Peters (2018), and the PEFCR for Rechargeable Batteries (2020)

Study	Battery Chemistry	Scope	Usage Scenario	Functional Unit	Impact Assessment Method
This thesis	LFP, NMC, and NCA	Cradle-to-grave	Grid: Stand-by scenario	Per kWh energy delivered	Environmental Footprint 2.0
Peters (2018)	LFP, LTO, LMO, NMC, NCA	Cradle-to-gate	Excluded	Per kg battery weight; Per kWh battery capacity	ILCD
PEFCR for Rechargeable Batteries (2020)	LIB in general (based on NMC)	Cradle-to-grave	Electric vehicles	Per kWh energy delivered	Environmental Footprint 2.0

4 Results and Discussion

This section will display and discuss the obtained results from the thesis study. First, the environmental impact of LIBs from the whole cradle-to-grave analysis will be presented, along with a comparison against lead-acid batteries. The environmental impact categories that will be of focus can be seen again in Table 12. Then, a more granular look into the cradle-to-gate stage of the LIBs will be done, where the contribution of each manufacturing process will be shown. Finally, a sensitivity analysis will be conducted to observe how the cradle-to-grave environmental impacts react to change. Note that the results are described in terms of *per functional unit* as suggested by the Batteries PEFCR document (EC, 2020). Therefore, 1 kWh_D is used to state the impact results.

4.1 Comparison of lifecycle environmental impacts of lithium-ion batteries and lead-acid batteries

Table 14 summarizes the resulting environmental impact of different types of batteries. The five impact categories follow Table 12, as they are the five most relevant impact categories according to the PEFCR for rechargeable batteries. Since lead-acid batteries are the comparative baseline, their impacts are denoted as “100%”, while the impacts of the LIB chemistries are expressed as a percentage of the lead-acid batteries’ environmental impact. Now, in Table 14, the cells that are highlighted in green and red indicate the battery type with the least environmental impact and the most environmental impact, respectively. The simulation shows that lead-acid batteries perform worse than the LIBs in three different categories: climate change, fossil resource use, and minerals resource use. Meanwhile, the LIBs generate more impact in the acidification and human health – particulate categories.

In general, lead-acid batteries generate more impact due to their *lower energy density*, which means a higher number of lead-acid batteries are required than LIBs when supplying the same amount of energy. Then, between the LIBs, the LFP chemistry seems to perform worse in all impact categories except minerals and metals resource use. To break down the environmental impact of the batteries, by life cycle stage, the following sections will delve deeper into each environmental impact category, where the impact contribution trees will also be discussed.

Table 14, cradle-to-grave impact summary of lithium-ion batteries and lead-acid battery, levelized to the lead-acid battery (Functional unit: per kWh energy delivered)

Impact Category/Battery Type	LFP	NMC	NCA	Lead-Acid
Climate Change (kg CO ₂ -Eq.)	81%	59%	53%	2
Acidification (mol H ⁺ -Eq)	101%	35%	63%	0.02
Resource Use - Fossil (MJ)	75%	62%	55%	33
Resource Use – Minerals and Metals (kg Sb-Eq)	6%	11%	7%	8E-0.4
Human Health - Particulate (disease incidence)	135%	49%	50%	1E-0.7

Note: green and red cells indicate the battery type with the least environmental impact and the most environmental impact, respectively

4.1.1 Climate Change

From Section 4.1.1 to Section 4.1.5, the reference values of lead-acid batteries will refer to Table 14. Now, Figure 10 shows the cradle-to-grave climate change impact of the batteries, while Table 15 breaks down the contribution tree for each battery. The blacked-out portion of the bar chart in Figure 10 represents the whole cradle-to-gate process of the lead-acid batteries. Since the contribution tree for the lead-acid battery’s cradle-to-gate phase cannot be broken down, it will be represented as one aggregated portion. For this impact category, the LIBs had outperformed the lead-acid batteries. Specifically, the NCA battery chemistry has the lowest climate change potential compared to the others.

Between the LIBs, the use stage electricity contributes the most towards the climate change environmental impact. Recalling from Figure 9, electricity is modelled as the only input in the use phase of the battery life

cycle. Therefore, it can be said that the use phase is the largest contributor to climate change in the case of the LIBs. This is directly affected by the location chosen for the use phase since the *electricity mix* will follow the local conditions. Therefore, should the electricity mix have less emission factor, the use phase climate change impact should consequently decrease. From Table 6, the use stage location is the United States, so the environmental impact can be seen as a reflection towards the nation’s electricity mix.

In addition, although the lead-acid batteries perform worse, they obtain the most credits from the end-of-life phase. Meanwhile, the LFP batteries obtained a net burden instead of credit from the same stage. This is because compared to the NCA and NMC chemistries, the end-of-life treatment of the LFP batteries did not recover nickel, manganese, nor cobalt. The NCA batteries, however, had obtained a net credit due to the inclusion of nickel and cobalt recycling in the end-of-life stage.

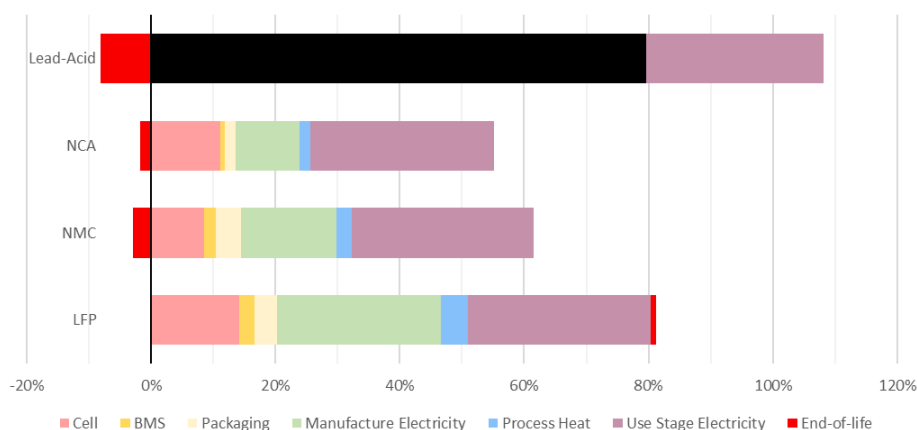


Figure 10, Cradle-to-grave climate change impact, in kg CO₂-eq. per kWh energy delivered

Table 15, Cradle-to-grave climate change impact contribution percentages

Activity	LFP	NMC	NCA	Lead-Acid
Battery cell manufacturing	14%	8%	11%	80%
BMS module manufacturing	2%	2%	1%	
Packaging manufacture	4%	4%	2%	
Manufacturing electricity input	26%	15%	10%	
Manufacturing heat input	4%	3%	2%	
Use stage electricity consumed	29%	29%	29%	28%
End-of-life treatment	1%	-3%	-2%	-8%
Total	81%	59%	53%	100%

4.1.2 Acidification, terrestrial and freshwater

Table 16 and Figure 11 illustrates the cradle-to-grave acidification potential of the batteries. This time, the LFP chemistry generates the most environmental impact, which is slightly higher than the lead-acid chemistry. At 56%, the manufacturing process of battery cells contributes the most to the acidification impact for the LFP batteries. A similar distribution can be seen for the NCA batteries. In its case, the battery cell manufacturing activity accounts for 70% of the total acidification impact.

On the other hand, similar to the climate change environmental impact, lead-acid batteries received the highest credit from the end-of-life stage, while the LFP batteries received a net burden. Also, notice that the potential acidification impact from process heat does not account to even 1% for the NCA and LFP batteries. It reaches 1%, however, for the NMC batteries. Of course, this is also because the NMC batteries have the lowest acidification impact potential between the four.

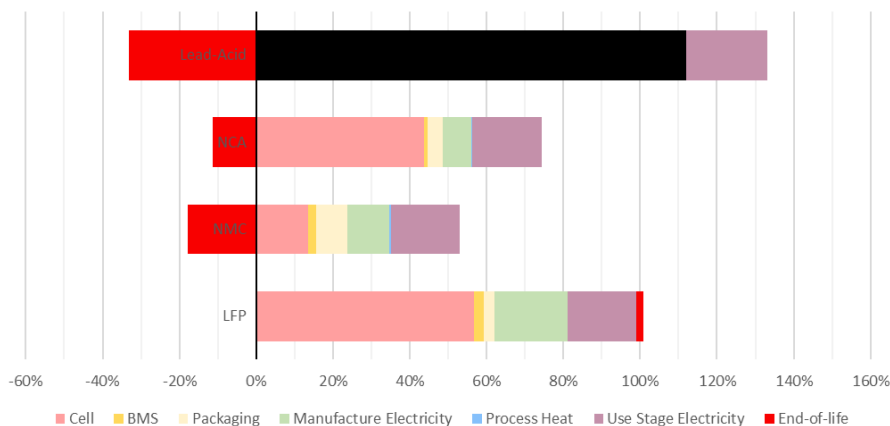


Figure 11, Cradle-to-grave acidification impact, in mol N-eq. per kWh energy delivered

Table 16, Cradle-to-grave acidification impact contribution percentages

Activity	LFP	NMC	NCA	Lead-Acid
Battery cell manufacturing	57%	14%	44%	112%
BMS module manufacturing	3%	2%	1%	
Packaging manufacture	3%	8%	4%	
Manufacturing electricity input	19%	11%	8%	
Manufacturing heat input	0%	0%	0%	
Use Stage Electricity	18%	18%	18%	21%
End-of-life	2%	-18%	-11%	-33%
Total	101%	35%	63%	100%

4.1.3 Resource use: energy carriers

Figure 12 and Table 17 depicts the cradle-to-grave energy carriers (or energy resources) use impact for the batteries. The lead-acid batteries can be concluded as the most energy-intensive out of the four, while the NCA can be considered to use the least energy throughout its life cycle. Apart from the lead-acid batteries, the use phase electricity usage of the three LIBs is the highest contributor to this environmental impact. Similar to the climate change environmental impact, this means that the energy carriers resource use impact is highly correlated to the United States' electricity mix. On the other hand, there are no credits from the end-of-life stage for the LIBs. This is because when using the PEFRCR's inventory, *no energy recovery* was assumed during the end-of-life stage, which results in zero credits related to the energy carriers use environmental impact. Nevertheless, this is because the default end-of-life scenario of the PEFRCR was used. In case of the availability of primary data, energy recovery should be included in the life cycle model, if it is present.

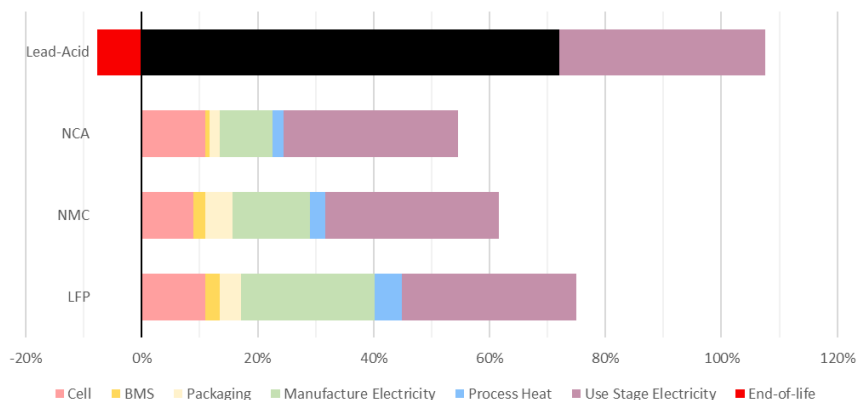


Figure 12, Cradle-to-grave energy carriers use impact, in MJ per kWh energy delivered

Table 17, Cradle-to-grave energy carriers use impact contribution percentages

Activity	LFP	NMC	NCA	Lead-Acid
Battery cell manufacturing	15%	15%	20%	72%
BMS module manufacturing	3%	3%	1%	
Packaging manufacture	5%	8%	3%	
Manufacturing electricity input	31%	22%	17%	
Manufacturing heat input	6%	4%	3%	
Use Stage Electricity	40%	49%	55%	36%
End-of-life	0%	0%	0%	-8%
Total	75%	62%	55%	100%

4.1.4 Resource use, mineral and metals

The overall cradle-to-grave minerals and metals resource use environmental impact can be seen in Table 18 and Figure 13. Lead-acid batteries have an overwhelmingly higher amount of this environmental impact compared to the LIBs, which is approximately ten times higher. Also, notice that almost all the contribution comes from the cradle-to-gate stage of the batteries, where it even reaches 100% for the lead-acid batteries. For the LIBs, the highest contribution comes from the manufacturing process of their cells. This is understandable because this process requires the most minerals and metals, such as copper, nickel, aluminium, iron, etc. An important point to note is that there are credits from the end-of-life stage for all batteries, albeit they are extremely small. Therefore, although some materials are recovered from the end-of-life treatment process, it pales in comparison with the actual impact.

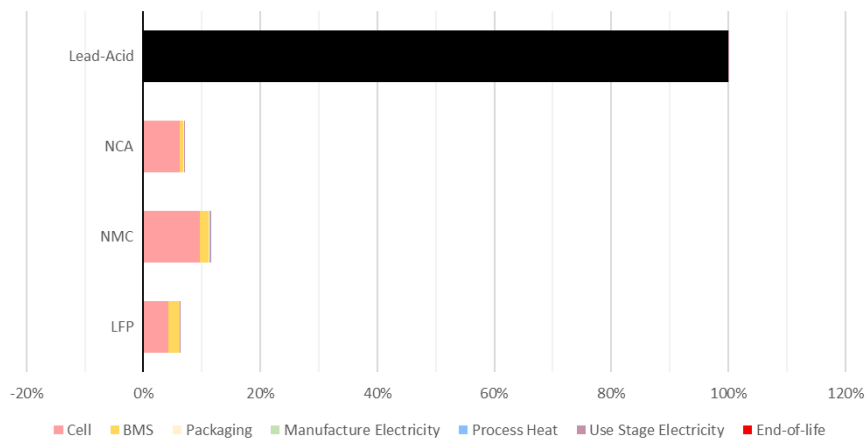


Figure 13, Cradle-to-grave minerals and metals use impact, in kg SB-eq. per kWh energy delivered

Table 18, Cradle-to-grave minerals and metals use impact contribution percentages

Activity	LFP	NMC	NCA	Lead-Acid
Battery cell manufacturing	11%	9%	11%	100%
BMS module manufacturing	3%	2%	1%	
Packaging manufacture	4%	5%	2%	
Manufacturing electricity input	23%	13%	9%	
Manufacturing heat input	5%	3%	2%	
Use Stage Electricity	30%	30%	30%	0%
End-of-life	0%	0%	0%	0%
Total	75%	62%	55%	100%

4.1.5 Respiratory inorganics

From Figure 14 and Table 19, the respiratory inorganics environmental impact from the four batteries can be obtained. First, LFP is the worst performer in this environmental impact, which is 1.35 times than the baseline lead-acid battery. On the contrary, the NMC and NCA battery chemistries have the least impact, only accounting for 0.49 times compared to the lead-acid chemistry. The contribution trees for the NCA and NMC chemistries are also similar, where most of their contribution comes from the manufacturing of the battery cells and the manufacturing electricity usage.

Now, notice that the contribution from manufacturing electricity is higher compared to the use phase electricity. This highlights that the electricity mix of the cradle-to-gate phase, which is in China, might generate more respiratory inorganics compared to the United States. Also, observe that the impact from the manufacturing process of LFP battery cells is higher compared to the other LIB chemistries. The cause of this will be discussed further when looking into the cradle-to-gate environmental impact of the batteries.

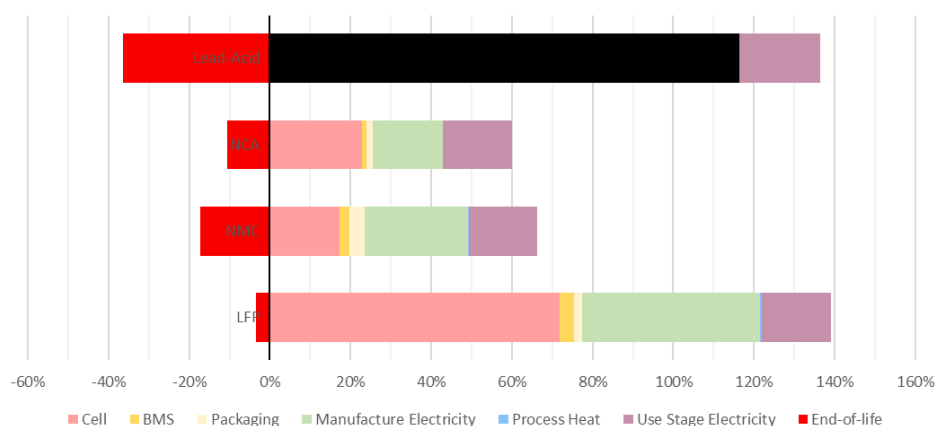


Figure 14, Cradle-to-grave respiratory inorganics impact, in disease incidence per kWh energy delivered

Table 19, Cradle-to-grave respiratory inorganics impact contribution percentages

Activity	LFP	NMC	NCA	Lead-Acid
Battery cell manufacturing	72%	17%	23%	116%
BMS module manufacturing	3%	3%	1%	
Packaging manufacture	2%	4%	1%	
Manufacturing electricity input	44%	26%	17%	
Manufacturing heat input	0%	0%	0%	
Use Stage Electricity	17%	17%	17%	20%
End-of-life	-3%	-17%	-11%	-36%
Total	136%	49%	49%	100%

4.2 Cradle-to-gate impact contribution analysis by process

This section of the report offers a deeper look into the environmental impacts generated due to the manufacturing process of batteries. The overall amount of the cradle-to-grave impact has been presented in Section 4. Therefore, this section will only show how each manufacturing activity and input contributes towards a *total cradle-to-gate impact*. Note that since the inventory of the lead-acid battery did not provide a thorough detail as for the LIB, they will only be described as one process throughout the cradle-to-gate stage. In the next figures, the lead-acid battery’s cradle-to-gate impact will be highlighted in black. The

main purpose of this section is to show how the three LIB chemistry differs from another and to determine the specific hotspots within the cradle-to-gate phase. To this end, the analysis in the following sections is also separated for each environmental impact category, so that the differences between each battery chemistry can be seen clearly. Finally, since the use phase is excluded, the functional unit of the cradle-to-gate LCA cannot be per kWh energy delivered. Instead, they will be in *per kWh battery capacity*. Table 20 summarizes cradle-to-gate impact comparison between the LIB and lead-acid batteries.

Table 20, *Cradle-to-gate environmental impact comparison of lithium-ion and lead-acid batteries (Functional unit: per kWh of battery capacity)*

Impact Category/Battery Type	LFP	NMC	NCA	Lead-Acid
<i>Climate Change (kg CO₂-Eq.)</i>	134%	114%	97%	125
<i>Acidification (mol H⁺-Eq)</i>	134%	77%	123%	1.4
<i>Resource Use - Fossil (MJ)</i>	118%	111%	84%	1730
<i>Resource Use - Minerals (kg Sb-Eq)</i>	12%	30%	18%	0.06
<i>Human Health - Particulate (disease incidence)</i>	198%	107%	92%	8.60E-06

In general, the LFP batteries are the worst performer from only a cradle-to-gate perspective. This is mainly caused by the resource-intensive processes of manufacturing an LFP cathode. However, the NMC batteries perform better than the LFP batteries, while the NCA batteries beat even the lead-acid batteries in four of the five impact categories. Some other factors that affect the impacts are the variation of battery lifetime and energy density as shown in Table 10. To understand better, the following sections will show how each life cycle stage affect the total cradle-to-gate environmental impact of the batteries. Similar to Section 4.1, the environmental impact categories used will follow Table 12.

4.2.1 Climate Change: Cradle-to-gate

Table 21 and Figure 15 shows the contribution of each activity within the cradle-to-gate phase towards the total climate change environmental impact. Similar to the cradle-to-grave impact, electricity consumption plays a major role in the cradle-to-gate climate change impact. However, the electricity input this time is on the manufacturing level instead of the use phase. Although the components of the battery pack itself were manufactured in China and Hungary, it is not possible to pinpoint the impact from each country because the cradle-to-gate electricity input is aggregated at the battery pack manufacturing level, as mentioned in Section 3.3.1. Therefore, the climate change impact related to electricity consumption is directly affected by the Chinese electricity mix.

In addition, the second-highest contribution towards this impact comes from the cathode manufacturing processes. This is caused by the extraction and processing required of the raw materials that make up the cathodes. For LFP cathodes, the most impactful material in the cathode is ferrite, while it is nickel and cobalt for the NCA cathodes. Consequently, the highest contributing materials in the NMC cathode are nickel, manganese, and cobalt. However, NCA cathodes have a higher concentration of nickel, which results in a higher contribution towards the cradle-to-gate climate change impact.

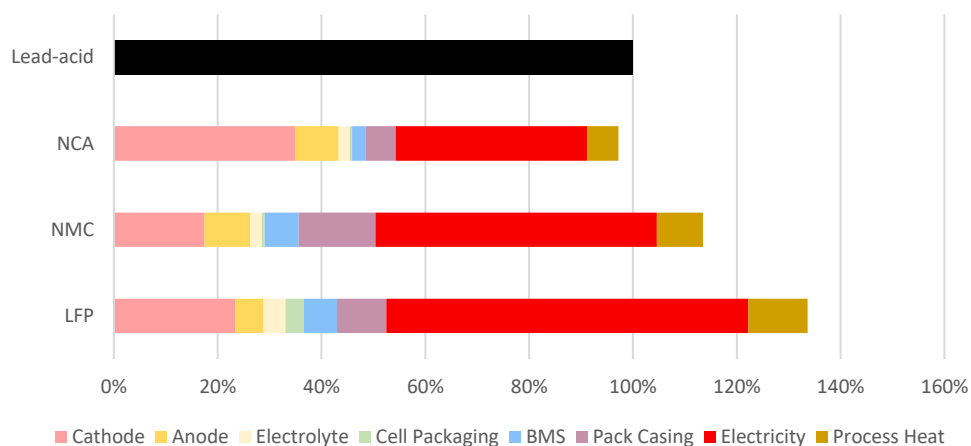


Figure 15, Cradle-to-gate climate change impact breakdown, in kg CO₂-eq. per kWh battery capacity

Table 21, Cradle-to-gate climate change impact contribution percentages

Manufacture of	LFP	NMC	NCA	Lead-acid
Cathode	23%	17%	35%	100%
Anode	5%	9%	8%	
Electrolyte	4%	2%	2%	
Cell Packaging	4%	1%	0%	
BMS	6%	7%	3%	
Pack Casing	10%	15%	6%	
Electricity	70%	54%	37%	
Process Heat	11%	9%	6%	
Total	134%	114%	97%	100%

4.2.2 Acidification, terrestrial and freshwater: Cradle-to-gate

Figure 16 and Table 22 depict the breakdown of the cradle-to-gate acidification environmental impact of the four batteries. For the NCA and LFP battery chemistries, the highest contribution comes from the manufacturing process of their cathodes. Meanwhile, it is the electricity consumption that scores the highest for the NMC chemistry. Further, the anode manufacturing process of the NMC batteries seems to contribute more than the cathode. Therefore, a closer look into the cathodes of each LIB chemistry should be done to obtain a clearer picture.

For the NCA, the high contribution coming from the cathode manufacturing process comes from the necessity to extract and process nickel as a natural resource. On the other hand, for the LFP cathode manufacturing process, the impact comes as a direct emission from the process of synthesizing the LFP cathode itself, instead of the material procurement. In the case of the NMC cathodes, processing nickel also contributes the most towards the overall acidification potential environmental impact. However once again, since the concentration is not as high as in an NCA cathode, the impact is consequently lower. To add, most of the impact contribution from the anode manufacturing process of the LIBs comes from the processing of copper to use as the cells' current collectors.

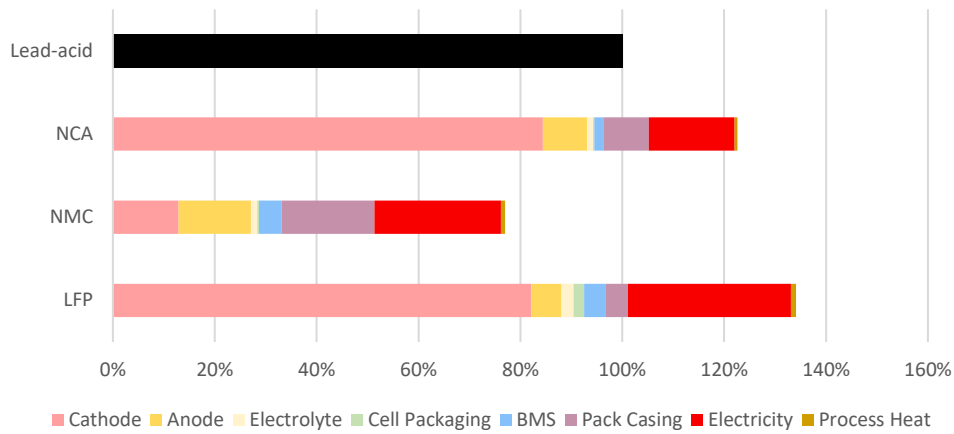


Figure 16, Cradle-to-gate acidification impact breakdown, in mol N-eq. per kWh battery capacity

Table 22, Cradle-to-gate acidification impact contribution percentages

Manufacture of	LFP	NMC	NCA	Lead-acid
Cathode	82%	13%	84%	100%
Anode	6%	14%	9%	
Electrolyte	2%	1%	1%	
Cell Packaging	2%	0%	0%	
BMS	4%	4%	2%	
Pack Casing	4%	18%	9%	
Electricity	32%	25%	17%	
Process Heat	1%	1%	1%	
Total	134%	77%	123%	

4.2.3 Resource use, energy carriers: Cradle-to-gate

Table 23 and Figure 17 illustrates the contribution of the cradle-to-gate processes towards the energy carriers resource use environmental impact. Similar to climate change impact, electricity consumption seems to be the highest contributor to this impact. Once again, this impact reflects the electricity mix of China, so the use of energy carriers might decrease if the Chinese electricity grid utilizes more renewable energy.

Another interesting point in this comparison is that the production of NCA cathodes seems to generate a higher impact compared to the NMC and LFP cathodes. Although the procurement and processing of raw nickel have the highest contribution in the manufacturing process of NCA cathodes, as usual, cobalt also seems to play a role in this environmental impact. Consequently, cobalt is the largest contributor for the NMC cathodes, although the overall is less than NCA cathodes due to the nickel difference. Finally, for the LFP cathodes, most of the impact comes from ferrite.

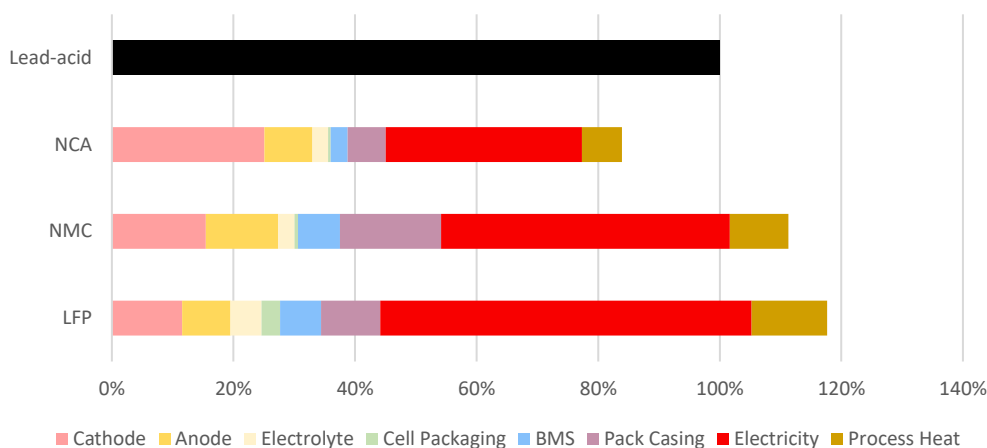


Figure 17, Cradle-to-gate energy carriers use impact breakdown, in MJ per kWh battery capacity

Table 23, Cradle-to-gate energy carriers use impact contribution percentages

Manufacture of	LFP	NMC	NCA	Lead-acid
Cathode	12%	15%	25%	100%
Anode	8%	12%	8%	
Electrolyte	5%	3%	3%	
Cell Packaging	3%	1%	0%	
BMS	7%	7%	3%	
Pack Casing	10%	17%	6%	
Electricity	61%	47%	32%	
Process Heat	12%	10%	7%	
Total	118%	111%	84%	100%

4.2.4 Resource use, mineral and metals: Cradle-to-gate

Figure 18 and Table 24 highlights the contribution of each cradle-to-gate process towards the minerals and metals resource use environmental impact of the batteries. Two interesting points separate this impact from the others. First, is the fact that manufacturing electricity plays a minimum role in this environment. Second, is that the contribution of anode manufacture is the largest, reaching up to 78% per cent of the total cradle-to-gate impact for NCA batteries. In the other impact categories, the manufacturing process of cathodes has a higher contributor compared to the anode, contrary to this impact category.

For the anode manufacturing process of the three LIB chemistries, the highest contribution seems to be coming from the same source: the anode current collectors. In the three batteries, their anodes use copper as the main material, so they require the extraction and the transformation of this raw material in the manufacturing process. Then, it turns out the procurement of copper is the highest contributor for the minerals and metals use environmental impact due to anode manufacturing. In fact, for the NCA battery chemistry, copper accounts for about 65% of the whole cradle-to-gate impact for this impact category, not only within the anode manufacturing process. Therefore, the key takeaway is that copper will contribute to the majority of minerals and metals resource uses environmental impact in the case of LIBs.

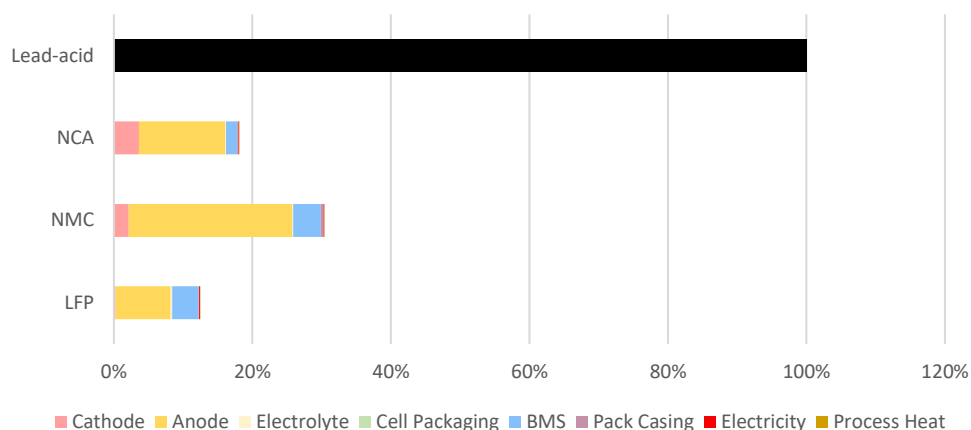


Figure 18, Cradle-to-gate minerals and metals use impact breakdown, in kg SB-eq. per kWh battery capacity

Table 24, Cradle-to-gate minerals and metals use impact contribution percentages

Manufacture of	LFP	NMC	NCA	Lead-acid
Cathode	0%	2%	4%	100%
Anode	8%	24%	12%	
Electrolyte	0%	0%	0%	
Cell Packaging	0%	0%	0%	
BMS	4%	4%	2%	
Pack Casing	0%	0%	0%	
Electricity	0%	0%	0%	
Process Heat	0%	0%	0%	
Total	12%	30%	18%	100%

4.2.5 Respiratory inorganics: Cradle-to-gate

The process contribution towards the cradle-to-gate respirator inorganics environmental impact for LIBs can be seen in Figure 19 and Table 25. For the NCA and NMC batteries, electricity consumption is the highest contributor to the overall impact. For the LFP batteries, however, the manufacture of their cathodes generates the most impact. Notice that for the NMC and NCA batteries, cathode manufacturing is also the second-highest contributor for their respective impacts. Since the electricity consumption cannot be zoomed in further, the manufacturing process of the cathodes will instead be broken down further.

In the case of the LFP cathode manufacturing process, the impact mostly comes from the direct emission of the process itself. Since the process generates carbon dioxide, it increases the contribution towards the impact of the respiratory organic. On the other hand, the contribution of the NCA cathode manufacturing process comes from a familiar source, nickel. Of course, the NMC cathodes also have the bulk of their contribution due to nickel, albeit at a lower concentration than NCA. Therefore, it is important to note that nickel is a high contributor towards several impact categories.

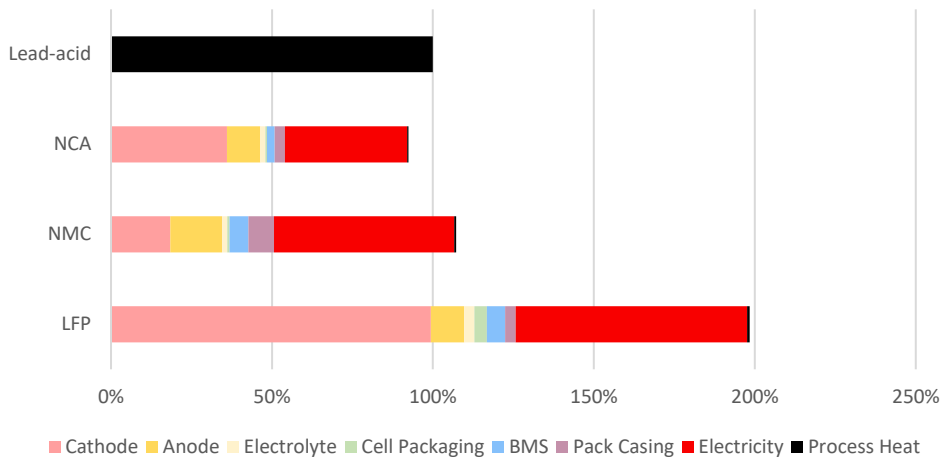


Figure 19, Cradle-to-gate respiratory inorganics impact breakdown, in disease incidence per kWh battery capacity

Table 25, Cradle-to-gate respiratory inorganics impact contribution percentages

Manufacture of	LFP	NMC	NCA	Lead-acid
Cathode	99%	18%	36%	100%
Anode	10%	16%	10%	
Electrolyte	3%	2%	2%	
Cell Packaging	4%	1%	1%	
BMS	6%	6%	2%	
Pack Casing	3%	8%	3%	
Electricity	72%	56%	38%	
Process Heat	1%	1%	0%	
Total	198%	107%	92%	100%

4.3 Results interpretation

4.3.1 Cradle-to-grave sensitivity analysis of lithium-ion batteries

The sensitivity analysis was carried out with the purpose of how processes with a high contribution in the total environmental impact react to a change of the input. From Section 4.1 and Section 4.2, these processes were determined to be the *electricity consumption in the use phase*, electricity consumption in the cradle-to-gate stage, and battery cell manufacturing in the cradle-to-gate stage. However, referring to Figure 8, use phase electricity consumption was the only process that is in the *foreground* of this study. Hence, the sensitivity analysis will describe how the cradle-to-grave environmental impact related to the life cycle of LIBs react to a change in the input electricity. Note that the LFP battery chemistry will be used as the subject of this sensitivity analysis. This should be representative enough since the environmental impact related to electricity consumption in the use stage for the three LIB chemistries only have a minimum difference.

The specific aspect that will be changed related to the use phase electricity consumption is the ‘percentage of renewable energy in the electricity mix’. Theoretically, increasing the contribution of renewables in an electricity mix would mean that electric energy can be obtained in a more environmental-friendly manner. Nevertheless, it should be interesting to see how it affects the five chosen impact categories in this study. Unfortunately, the percentages of an electricity mix cannot be changed directly when using the EcoInvent 3.71 database. Therefore, ‘proxy countries’ were used to emulate the different renewable energy percentages as shown in Table 26. Recall that the baseline scenario for the use stage electricity was the United States’

electricity mix, as it is the location of the battery usage. Hence, all values from using the alternative proxy country electricity mixes will refer to it in terms of percentages.

In Table 26, three percentages columns describe the electricity mix for the proxy countries: Renewables, Fossil Fuels, and Other, non-renewables. In short, renewables include solar, wind, hydro, and biomass for electricity generation. Fossil fuels cover the usage of different types of coal and natural gases. Finally, other, non-renewables is mostly made up of nuclear power. Since it is preferable to use only renewables and fossil fuels as the two variables in the electricity mix, the chosen proxy countries were decided to be the ones with minimum ‘other, non-renewable’ sources percentage, which is below 10%. Observe that the percentage of renewables used has an interval of 20% difference between each proxy country, with exception of the United States (30%) since it is the baseline scenario.

Table 26, Electricity mixes used in the sensitivity analysis, and the corresponding proxy country from EcoInvent 3.71

Renewables	Fossil Fuels	Other, non-rene.	Proxy Country
30%	63%	7%	United States
20%	78%	2%	China
40%	60%	0%	Ghana
60%	32%	8%	Austria
80%	20%	0%	South Korea

Now, Figure 20 and Table 27 presents the result from enacting the sensitivity analysis. Starting from the climate change impact, a proportional decrease can be seen as renewable energy contributes more to the electricity mix. This is expected since renewable energy generates no carbon dioxide when producing electricity, the climate change impact would consequently decrease. Also, the energy carriers resource use also follows the same decreasing pattern as seen in the climate change impact. This is intuitive because with less percentage of fossil fuel contribution in the mix, less energy carriers would be needed to generate electricity.

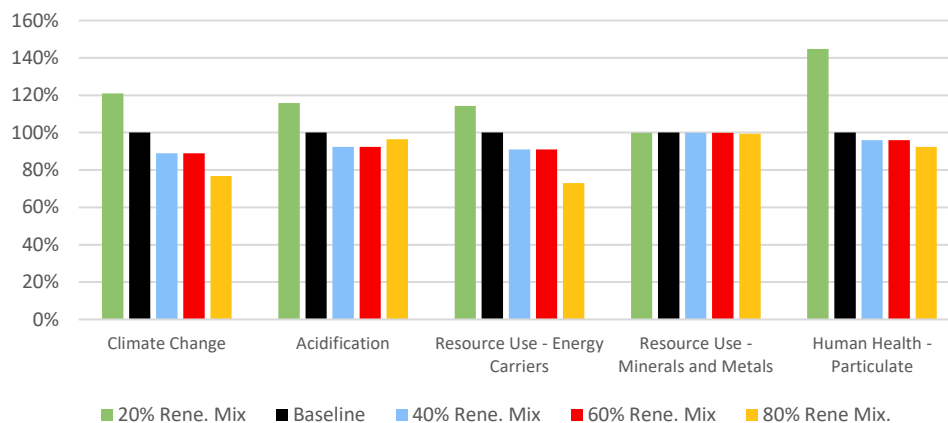


Figure 20, Graphical representation of the change in cradle-to-grave environmental impact due to changing the electricity mixes

Regarding the acidification impact, an increase seems to happen at the 80% renewable mix input. This is because the percentage of coal in the fossil fuel portion, and hydropower in the renewable energy portion, are higher compared to proxy countries used for the cases of 60% and 40% renewable mix. On the other hand, only minimum change can be seen in the minerals and metals resource use impact. This is in line with the results discussed in Section 4.1.4, where the use phase electricity consumption only has a minimal impact on this category. Finally, for the particulate inorganics impact category, the only observed extreme

difference was for the 20% renewable mix case. This is due to the very high utilization of coal in the proxy country of China, which is 7.6 times higher than the coal usage of the baseline scenario. Also, the impact from the 80% renewable energy mix case increases slightly, because once again, it has a higher contribution of coal compared to the 60% and 40% renewable mix cases. All-in-all, the general result is that with the increase of renewable contribution in the electricity mix, the resulting cradle-to-grave environmental impacts should decrease.

Table 27, Resulting environmental impacts from changing the electricity mix, described as a percentage against the baseline scenario (United States electricity mix)

Proxy Country	Environmental Impact	Impact Category
China	121%	Climate Change (kg CO ₂ -Eq.)
United States	100%	
Ghana	89%	
Austria	83%	
South Korea	77%	
China	116%	Acidification (mol H ⁺ -Eq)
United States	100%	
Ghana	92%	
Austria	89%	
South Korea	96%	
China	114%	Resource Use - Fossil (MJ)
United States	100%	
Ghana	91%	
Austria	84%	
South Korea	73%	
China	100%	Resource Use - Minerals (kg Sb-Eq)
United States	100%	
Ghana	100%	
Austria	100%	
South Korea	99%	
China	145%	Human Health - Particulate Inorganics (disease incidence)
United States	100%	
Ghana	96%	
Austria	90%	
South Korea	92%	

4.3.2 Results comparison with other studies

As mentioned throughout the document, comparing the full results of this study with other publications is difficult. For the use phase, choosing a usage scenario for the LIBs would greatly impact the obtained results since the scenario is related to the functional unit of the study: energy delivered. This means that the use phase of this thesis should not be compared to LIBs that are operating differently, such as for voltage regulation, energy arbitrage, and peak shaving. Further, for the end-of-life stage of LIBs, it was difficult to obtain thorough and accurate data for LIB recycling. This is because the recycling of LIBs is still in its pilot phase. Therefore, it was only feasible to compare the cradle-to-gate stage of this study's LIBs.

The cradle-to-gate results from this study will be compared to Peters and Weil (2018). This is because this thesis project had used the literature as the primary source of cradle-to-gate inventory data. However, various modifications were made to match the actual conditions, as described in section 3.2.1. So, it would

be interesting to compare this thesis and the literature to see how they differ. Even then, the literature only had two impact categories that are the same as Table 12, which are climate change and acidification potential. Hence, only those two categories will be compared. Now, Table 28 shows the cradle-to-gate impact comparison between the literature and the obtained results. Note that in this case, the functional unit is in *per kWh of battery capacity* and that the obtained results are described in terms of percentages of the literature values.

Except for the 65% difference between the literature and obtained results for the acidification potential of NCA battery packs, the other values do not differ much from each other. Nevertheless, several aspects were determined to be the differentiating factor between the results. The first factor is the location of the processes, which affects which electricity mix was used for the cradle-to-gate stage. The second factor is the energy density of the batteries. Finally, the material composition of the battery packs themselves is different. Because primary data is available for the battery packs, it was used for the study's LIBs. This results in different ratios of battery pack casing, battery cells, and BMS modules in the battery packs.

Table 28, Cradle-to-gate impact comparison between Peter and Weil (2018) and this Study (Functional unit: per kWh battery capacity)

Impact Category/Battery Type		Climate Change (kg CO ₂ -Eq.)	Acidification (mol H ⁺ -Eq)
LFP	Literature	169	2.33
	Obtained	100%	82%
NMC	Literature	104	1.04
	Obtained	139%	106%
NCA	Literature	115	5.1
	Obtained	99%	35%

In addition, a comparison between this study and the PEFCR for rechargeable batteries document (EC, 2020) can be seen in Table 29. However, the results are vastly different, especially for the acidification and resource use of minerals categories. This is due to three factors. First, the dataset used in the PEFCR document considers the European Union as the location of the LIB's whole life cycle. This resulted in a much lower environmental impact compared to this study, as the processes in this study took place in different locations. Second, the LIB used in the PEFCR document had different performance parameters than this thesis. Finally, the most important factor is that the batteries in the PEFCR document had a completely different use stage: electric vehicle utilization. This results in a different functional unit, which in turn yields varying input and output. Note that this would not change even if the comparison was done with another study concerning LIB LCA for grid storage, as long as the utilization scenario of the LIB is still different (see Section 2.2). Nevertheless, this comparison should help highlight the importance of having the same use scenario when comparing different LCAs on LIBs.

Table 29, Cradle-to-grave impact comparison between the PEFCR document (2020) and this Study (Functional unit: per kWh energy delivered)

Impact Category/Battery Type	LFP	NMC	NCA	PEFCR (NMC LIB)
<i>Climate Change (kg CO₂-Eq.)</i>	353%	257%	233%	<i>0.54</i>
<i>Acidification (mol H⁺-Eq)</i>	1860%	652%	1111%	<i>9.00E-04</i>
<i>Resource Use - Fossil (MJ)</i>	274%	225%	198%	<i>9</i>
<i>Resource Use - Minerals (kg Sb-Eq)</i>	775%	1397%	863%	<i>7.00E-06</i>
<i>Human Health - Particulate (disease incidence)</i>	542%	198%	199%	<i>2.50E-08</i>

4.3.3 Suggested measures to improve the overall environmental impact

Since the LCA is an iterative process, measures for improvement should be suggested at the end of a results interpretation step to help reduce the overall environmental impact of a system. For this thesis project's

case, the first suggestion should be based on the results of the sensitivity analysis (Section 4.3.1). It was determined that with increasing renewable energy contribution in the electricity mix, most of the environmental impact categories would decline. Of course, this will not affect the minerals resource use category significantly, since that category is related to the cradle-to-gate stage. To increase the renewables contribution, the easiest way would be to provide the necessary electricity for charging the battery independently. For example, if solar panels are attached to the batteries, the use phase electricity will virtually be zero if the cradle-to-grave environmental impact of the solar panels is not considered. In short, using more renewable electricity is an achievable measure for reducing the whole life cycle environmental impact of the LIB.

The second recommendation is related to the recycling process of the LIB. Compared to the lead-acid batteries, the credits arising from the end-of-life stage of LIB is much lower in categories such as acidification potential and respiratory inorganics. This is understandable since the recycling of LIB is still in its early stages, but the growth in this sector will reduce the environmental burden of implementing the LIB in grid storage as demonstrated by the lead-acid batteries. Further, providing accurate and publicly available data regarding the recycling of LIB should be of priority, so that other practitioners of LCA on LIB can publish better results. This would mean more comparative studies, which would then increase the overall quality of cradle-to-grave LCA of LIB. In essence, improving the recycling of LIB and disclosing the recycling data should help reduce the overall environmental impact of LIB in general.

Finally, although it is located in the background, there is an important suggestion regarding the cradle-to-gate stage of this thesis project. It is to move the whole upstream process of LIB manufacturing into countries with cleaner production of energy. As demonstrated in Section 4.3.2, one of the reasons for this study's higher environmental impact is the scattered manufacturing locations. This is because it is difficult to control the whole supply chain of a LIB, which means that suppliers from different locations are often necessary. Nevertheless, controlling the complete cradle-to-gate processes would create advantages for a LIB manufacturer, where one of them is directly related to the environmental impact of the LIB.

5 Conclusion

This study has discussed the overall process of conducting an LCA for LIBs, starting from determining the objective and continues to compiling previous publications, applying the LCA framework according to the ISO standard, describing the methodology used in the study, and presenting and interpreting the resulting environmental impact obtained from modelling the life cycle. This thesis has answered three research questions.

For the first question, the lead-acid battery had the following approximate environmental impact values (in per kWh energy delivered): 2 kg CO_{2-eq.} for climate change, 33 MJ for fossil resource use, 0.02 mol H⁺-eq. for acidification, 10⁻⁷ disease incidence for particulate emission, and 8x10⁻⁴ for minerals resource use. In the case of the LIB, for the climate change and fossil resource use impact categories, the best performer was the nickel cobalt aluminium (NCA) lithium-ion battery. It had 46% and 45% less impact than lead-acid for the respective categories. On the other hand, the nickel manganese cobalt (NMC) was the best for the acidification and particulate emission impact categories. It was 65% and 51% better than lead-acid for the categories. Finally, for the minerals and metals resource use category, the lithium iron phosphate battery (LFP) was the best performer, which is 94% less than lead-acid. So in general, *the LIBs were determined to be superior compared to the lead-acid batteries* in terms of the chosen cradle-to-grave environmental impact categories. However, this was not the case for the LFP battery, where it performed 1.35 times and 1.01 times worse compared to lead-acid batteries for the particulate inorganics and the acidification impact categories, respectively.

Second, the most critical processes in the LIBs' life cycle were determined to be the use stage electricity consumption, manufacturing electricity consumption, and cathode production. The generated impact related to electricity is directly affected by the chosen location, as they are dependent on the electricity mixes. On the other hand, the largest contributor to the impact generated by cathode production is the extraction and processing of raw materials, specifically nickel, cobalt, manganese, ferrite, and copper. Nonetheless, for the third question, the use phase was the only stage that is in the foreground of this study and has a high impact on the overall environmental impact. Therefore, the sensitivity analysis was conducted only for changes in the electricity input of the life cycle use stage. For the result, the general finding was that the environmental impact would *decrease* in conjunction with the increase of the renewable energy utilization in the electricity mix. Note that this was not the case for the resource use – minerals and metals impact category, as the use phase electricity was determined to have a minimum contribution for this category.

Finally, three improvement measures were proposed to improve the overall environmental impact results. In the foreground, there are two suggestions, which are to increase the contribution of *renewable energy sources* in the use phase electricity mix and to develop the *recycling* process of LIB. These suggestions were based on the results of the sensitivity analysis and by comparing them to the lead-acid battery's situation (mature recycling technology). Meanwhile, the proposed improvement in the background of this project is to *control* the whole cradle-to-gate processes in one area.

In the end, there are various rooms for improvements when a similar study is to be conducted. The first one would be to use primary data whenever possible. This is because if primary data is to be used, the resulting impacts would consequently become more accurate. Additionally, specific inventories should be used for the end-of-life stage of the LIBs. A clearer picture from the stage can be obtained if the recovered and disposed of materials can be pinpointed for each chemistry. Finally, sensitivity analysis should be carried out to more sections of the LIBs life cycle. Of course, this is only possible for the processes in the foreground of the study. Hence, the usage of primary data whenever available should be the priority when conducting an LCA study, especially for life cycles with complex processes.

Bibliography

- Amarakoon, Shanika, Jay Smith, and Brian Segal. 2013. *Application of Life Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles*. United States Environmental Protection Agency.
- Asian Development Bank. 2018. *Handbook on Battery Energy Storage System*. Manila: ADB.
- Battke, Benedikt, Tobias Schmidt, David Grosspietsch, and Volker Hoffmann. 2013. "A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications." *Renewable and Sustainable Energy Reviews* 240-250.
- Bauer, Christian. 2010. *Ökobilanz von Lithium-Ionen Batterien*. Villigen, Switzerland: Paul Scherrer Institut.
- Baumann, M., J.F. Peters, M. Weil, and A. Grunwald. 2017. "CO2 Footprint and Life-Cycle Costs of Electrochemical Energy Storage for Stationary Grid Applications." *Energy Technology* 1071-1083.
- BloombergNEF. 2020. *Electric Vehicle Outlook*. Accessed 03 05, 2021. <https://about.bnef.com/electric-vehicle-outlook/>.
- British Standards Institute Staff. 2006. *ISO 14040 Environmental management - Life cycle assessment - Principles and framework*. BSI.
- EC. 2020. *PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications*. European Commission.
- Ellingsen, Linda Ager-Wick, Guillaume Majeau-Bettez, and Bhawna Singh. 2013. *Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack*. Yale University.
- European Parliament. 2006. *Directive 2006/66/EC on batteries and accumulators*. Official Journal of the European Union.
- Frischknecht, Rolf. 1998. *Life cycle inventory analysis for decision-making*. The International Journal of Life Cycle Assessment.
- Hiremath, Mitavachan, Karen Derendorf, and Thomas Vogt. 2015. "Comparative Life Cycle Assessment of Battery Storage Systems for." *Environmental Science and Technology* 4825-4833.
- Hiremath, Mitavachan, Karen Derendorf, and Thomas Vogt. 2011. *Comparative Lifecycle Assessment of Battery Storage Systems for Stationary Applications*. Oldenburg: University of Oldenburg.
- Hischier, Roland, and Bo Weidema. 2010. *Implementation of Life Cycle Impact Assessment Methods*. Swiss Centre for Life Cycle Inventories.
- International Energy Agency. 2020. *Renewables 2020*. IEA. November. Accessed 03 02, 2021. <https://www.iea.org/reports/renewables-2020>.
- Li, Huan, and Kai Feng. 2018. "Life Cycle Assessment of the Environmental Impacts and Energy Efficiency of an Integration of Sludge Anaerobic Digestion and Pyrolysis." *Journal of Cleaner Production vol. 195* 476-485.
- Liang, Yuhuan, Jing Su, Beidou Xi, Yajuan Yu, and Yajuan Yu. 2017. "Life cycle assessment of lithium-ion batteries for greenhouse gas emissions." *Resources, Conservation, and Recycling vol. 117* 285-293.
- Lima, Ligia da Silva, Mattjis Quartier, Astrid Buchmayr, David Sanjuan-Delmas, Hannes Laget, Dominique Corbisier, Jan Mertens, and Jo Dewulf. 2021. "Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems." *Sustainable Energy Technologies and Assessments vol. 46*.
- Majeau-Bettez, Guillaume, Anders Strmman, and Troy Hawkins. 2011. "Life Cycle Environmental Assessment of Lithium-Ion and Nickel MetalHydride Batteries for Plug-In Hybrid and Battery Electric Vehicles." *Environmental Science and Technology*.

- Manfredi, Simone, Karen Allacker, Kirana Chomkhamsri, Nathan Pelletier, and Danielle Maia de Souza. 2012. *Product Environmental Footprint (PEF) Guide Institute for Environment and Sustainability (IES) Product Environmental Footprint Guide*. Ispra: European Commission.
- Melin, Hans Eric. 2019. *State of the art in reuse and recycling of lithium-ion batteries-a research review State-of-the-art in reuse and recycling of lithium-ion batteries*. London: Circular Energy Storage.
- Nelson, Granda Marulanda. 2017. "Sustainability Analysis for New Technologies of Biofuels and Additive Manufacturing." *Doctoral Dissertations - The University of Tennessee*.
- Notter, Dominic A, Marcel Gauch, Rolf Widmer, Patrick Wäger, Anna Stamp, Rainer Zah, and Hans-Jörg Althaus. 2010. "Contribution of Li-ion batteries to the environmental impact of electric vehicles."
- Pellow, Matthew, Hanjiro Ambrose, Dustin Mulvaney, Rick Betita, and Stephanie Shaw. 2020. "Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues." *Sustainable Materials and Technologies vol. 23*.
- Peters, Jens, and Marcel Weil. 2018. "Providing a common base for life cycle assessments of Li-Ion batteries." *Journal of Cleaner Production* 704-713.
- PRé Sustainability. 2020. *LCA software for fact-based sustainability*. Accessed July 6, 2021. <https://simapro.com/>.
- Ralon, Pablo, Michael Taylor, and Andrei Ilas. 2017. *Electricity Storage and Renewables: Costs and Markets to 2030*. IRENA.
- Roser, Max. 2020. *Why did renewables become so cheap so fast? And what can we do to use this global opportunity for green growth?* Our World in Data. December. Accessed 03 04, 2021. <https://ourworldindata.org/cheap-renewables-growth#:~:text=In%20most%20places%20in%20the,declines%20by%20the%20same%20fraction>.
- Ryan, Nicole, Yashen Lin, Noah Mitchell-Ward, and Johanna Mathieu. 2018. "Use-Phase Drives Lithium-Ion Battery Life Cycle Environmental Impacts When Used for Frequency Regulation." *Environmental Science and Technology* 10163-10174.
- SeaRates.com. 2021. *Distance and Time Calculator of Freight*. Accessed 05 02, 2021. <https://www.searates.com/services/distances-time/>.
- Spanos, Constantine, Damon Turney, and Vasilis Fthenakis. 2015. "Life-cycle analysis of flow-assisted nickel zinc-, manganese dioxide-, and valve-regulated lead-acid batteries designed for demand-charge reduction." *Renewable and Sustainable Energy Reviews vol. 43* 478-494.
- Tan, Kang Miao, Thanikanti Sudhakar Babu, Vigna Ramachandramurthy, Padmanathan Kasinathan, Sunil Solanki, and Shangari Raveendran. 2021. "Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration." *Journal of Energy Storage*.
- Tivander, Johan. 2019. "Environmental concerns of metals in Li-ion batteries Implications for recycling." Gothenburg.
- Wei, Wei, Pyrene Larrey-Lassalle, Thierry Faure, and Nicolas Dumoulin. 2014. "How to Conduct a Proper Sensitivity Analysis in Life Cycle Assessment: Taking into Account Correlations within LCI Data and Interactions within the LCA Calculation Model." *Environmental Science and Technology* 377-385.
- Zackrisson, Mats, Lars Avellán, and Jessica Orlenius. 2010. "Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles-Critical issues." *Journal of Cleaner Production* 1519-1529.