On behalf of Battery Council International

Comparative LCA Motive power Lead Battery and LFP Batteries – North America

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On behalf of Sphera Solutions, Inc. and its subsidiaries

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List of Abbreviation

ADP	Abiotic Depletion Potential
AGM	Absorbent Glass Mat
AP	Acidification Potential
BCI	Battery Council International
BOM	Bill of Materials
CML	Centre of Environmental Science at Leiden
CN	China
EC/DMC	Ethylene carbonate / Dimethyl carbonate
EAF/SAF	Electric Arc Furnace / Submerged Arc Furnaces
EF	Environmental Footprint
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
EU-28	Europe 28 members
EFB	Enhanced Flooded Battery
FU	Functional Unit
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing) - LCA software
GHG	Greenhouse Gas
GLO	Global
GWP	Global Warming Potential
ILA	International Lead Association
ILCD	International Reference Life Cycle Data System
ICE	Internal Combustion Engine
ISO	International Organization for Standardization
ISS	Idle Stop Start
JP	Japan
LCI / LCIA	Life Cycle Inventory / Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LFP	Lithium Iron Phosphate
MPV	Multi-Purpose Vehicles

158	NA	North America
159	NMVOC	Non-Methane Volatile Organic Compound
160	NMC	Lithium Nickel Manganese Cobalt Oxide Batteries
161	PbB	Lead battery / Lead-based battery
162	PED	Primary Energy Demand
163	PEFCR	Product Environmental Footprint Category Rules
164	PP	Polypropylene
165	POCP	Photochemical Ozone Creation Potential
166	PVDF	Polyvinylidene fluoride
167	RNA	Region North America
168	SLI	Starting, Lighting, and Ignition
169	VRLA	Valve Regulated Lead Acid Battery
170	VOC	Volatile Organic Compound
171	WWT	Wastewater Treatment

Life cycle

A view of a product system as "consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, section 3.2)

Life Cycle Inventory (LCI)

"Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 14040:2006, section 3.3)

Life Cycle Impact Assessment (LCIA)

"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 14040:2006, section 3.4)

Life cycle interpretation

"Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 14040:2006, section 3.5)

Functional unit

"Quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20)

Allocation

"Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14040:2006, section 3.17)

Closed-loop and open-loop allocation of recycled material

"An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties."

"A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials."

(ISO 14044:2006, section 4.3.4.3.3)

Foreground system

"Those processes of the system that are specific to it … and/or directly affected by decisions analyzed in the study." (JRC 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background system

"Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good…." (JRC 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

"Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment" (ISO 14044:2006, section 3.45).

Executive Summary

Goal of the Study

The goal of the study is to assess the life cycle environmental profile of two different battery chemistries for the motive power batteries used in forklift, produced in North America. This study assesses the cradle-to-grave environmental impact of lead-based (PbB) battery compared to a Lithium-ion Phosphate (LFP) motive power battery within North America. The study is conducted according to ISO 14040/44, the international standards on life cycle assessment (LCA).

Application /audience

The results of the study are to be used by the Battery Council International (BCI) and the International Lead Association (ILA) to improve their understanding of the environmental impact of lead-based battery production from cradle-to-grave and promote continuous improvement in the environmental sustainability of lead batteries. The results generated from the study will help BCI to respond to demands from various stakeholders for reliable, quantified environmental data. Finally, the study enables BCI and the International Lead Association (ILA) to continue to participate in and contribute to a range of sustainability initiatives and the ongoing methodological discussions within LCA and related disciplines.

The intended audience for this study amongst others, includes BCI and its members, ILA and its members, legislators, customers, environmental practitioners, and non-governmental organizations.

Critical Review

A third-party critical review panel of the study according to ISO 14040, ISO 14044, and ISO/TS 14071 is carried out by Matthias Finkbeiner from Technical University Berlin, Tom Gloria from the Industrial Ecology Consultants and Arpad Horvath. [1]

Main findings

Overall, the study highlights that lead battery manufacturing has a lower environmental impact compared to LFP.

The motive power batteries assessed in this study are used in a conventional forklift with a lifetime of 10 years. Based on the assumptions defined for the study, the use stage dominates the overall life cycle for the two battery types (Pb and LFP). Lead batteries have a higher weight compared to the LFP batteries, and therefore a respective counterweight has been considered in the assessment. The baseline assumption for lead and LFP batteries is a 48 V, 500 Ah battery (24 kWh) discharged to 80% of nominal capacity (19.2 kWh). 5 days per week, 50 weeks/year = 250 cycles per year, with a respective battery lifetime of 6 years for lead and 10 years for LFP.

Key conclusions from the study over the complete life cycle from cradle-to-grave can be summarized as such: between the assessed batteries and for most impact categories, the differences in the results are small. Given the uncertainties associated with modelling assumptions, results are not qualified as being

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[1] The reviewers were not engaged or contracted as official representatives of their organization but acted as independent expert reviewers.

significant; for the reference flow of 10 years lifetime of the forklift. The lead battery presents a lower impact at the manufacturing stage (between 2-6 times lower depending on impact category[2]) although the battery lifetime of the Lead Battery is 40% lower. The energy consumption of the PbB in the use stage is by 11% higher. However, when the whole life cycle of both batteries is compared the differences are low (1% in PED and 5% GWP).

Figure 1-1 displays the overall GWP per battery technology. It can be appreciated that PbB has a lower impact (-6%) than LFP to the Global Warming potential in the two battery types under the assumptions taken in the baseline scenario of the study.

In the manufacturing stage for PbB, lead production and electricity use are most often the primary drivers of impacts. For LFP batteries, cell raw materials and electronics have the highest contribution to the manufacturing stage, while steel tray and counterweight have minor contributions to all impact categories analyzed. Under the baseline scenario shown in Table 4-5, the environmental impacts of manufacturing the LFP battery compared to manufacturing the lead-based battery are roughly greater by a factor of 3. At EoL, the collection rate is set to 99% for PbB and LFP within the analyzed applications (BCI, 2019)..[3] After disassembly, the substitution approach has been applied for PbB where these batteries are recycled and are used in the production of secondary lead on the input side of the production stage. LFP batteries are disassembled into separate components that are treated separately; cells are sent to incineration with energy recovery and all other materials such as battery casings, cabling and electronics are sent to material recovery with the application of credits accordingly.

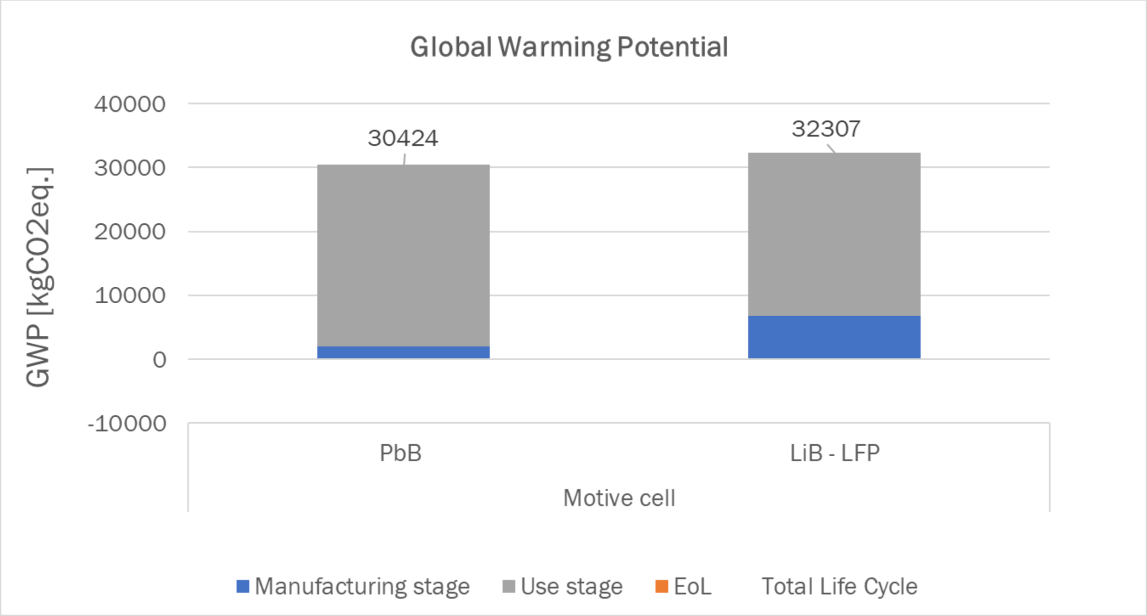

Figure 1-1: Overall Life Cycle GWP per battery technology

Conclusions and recommendations

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[2] GWP 3 times lower, PED 4 times lower

[3] According to a study conducted by the Battery Council International, the collection rate for motive power lead-acid batteries in the United States was approximately 99%. In this study, an additional EOL scenario has been considered.

The results of this study are only applicable to PbB and LFP batteries used for the described forklift applications in North America. Even in this case, the lack of primary data for LFP as well as assumptions regarding battery weights, composition, and performance, have to be considered when interpreting the representativeness of the results.

It may not be appropriate to extrapolate these results to other regions, especially if there are significant differences in lead-based battery recycling rates, energy grid mixes, etc. In addition, LFP is not representative of all lithium battery chemistries and the results for other types of Li-ion batteries could be significantly different.

This study shows that:

- Most impact categories showed small differences between both batteries assessed, with lead batteries performing better in the baseline scenario due to lower burdens in the manufacturing (2 to 6 times lower) depending on the impact category.
- The study highlights challenges in recycling of LFP battery and is limited by the economic viability for recovering materials like iron and phosphate.

It is recommended to:

- Study Lithium-ion battery types comprising cathode materials other than LFP.
- Study LFP with primary industry data rather than relying on secondary information from the available literature.
- To conduct a comparative risk assessment of the 2 batteries type regarding human health and/or ecological toxicity.

1. Goal of the Study

The goal of the study is to assess the life cycle environmental profile of two different battery chemistries for the motive power batteries used in forklift, produced in North America. The study has been conducted according to ISO 14040/44, the international standards on life cycle assessment (LCA). The results of the study are to be used by Battery Council International (BCI) and the International Lead Association (ILA), to improve their understanding of the environmental impact of lead-based battery production from cradle-to-grave and promote continuous improvement in the environmental sustainability of lead batteries. The data generated from the study will help BCI and ILA to respond to demands from various stakeholders for reliable, quantified environmental data. Finally, the study enables BCI and ILA to continue to participate in and contribute to a range of sustainability initiatives and the ongoing methodological discussions within LCA and related disciplines. The intended audience for this study includes BCI, the International Lead Association (ILA), lead and battery producers, legislators, customers, environmental practitioners, and non-governmental organizations.

A third-party critical review panel of the study according to ISO 14040, ISO 14044 and ISO/TS 14071 is carried out by Matthias Finkbeiner from Technical University Berlin, Tom Gloria and Arpad Horvath. [4]

This technical report will be publicly available and can be made accessible to interested parties upon request to the study commissioners BCI and ILA. The study commissioners may use the study report to prepare and provide information materials, for example, a technical summary of the report, a flyer addressing the major outcomes of the study and other materials.

The results of the study are intended to be used for comparative assessments intended to be disclosed to the public. It is acknowledged that the data provided might be used by others for further comparative assessments. Such comparisons should only be made on a product system basis and be carried out in accordance with the ISO 14040/44 standards, including an additional critical review by a panel (ISO 14040:2006 and ISO 14044:2006).

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[4] The reviewer acts and was contracted as an independent expert, not as a representative of his affiliated organization.

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1. Product Systems

Forklift trucks used for materials handing in factories, warehouses, and in distribution may be powered by internal combustion engines or electrically powered in which case the onboard power supply is a rechargeable battery.

There are two types of batteries used: lead-based batteries and lithium-based batteries. The preferred lithium-based batteries for this application are lithium iron phosphate types (LFP). These are a variant of Li-ion battery widely used for electric vehicles. As well as forklift trucks, there are many types of vehicles used for materials handling such as pallet trucks, walkie trucks, narrow aisle rucks, tow trucks and many types of speciality vehicles including sweeper trucks, access platforms, ice machines and other applications.

Motive Power batteries are used to provide electric power for traction for vehicles and other mobile applications.

Lead-based batteries (LbB) applied to motive power application:

- **Lead (Pb) 48 V, 500 Ah (24kWh)**

Lithium-Ion based batteries (LFP) applied to motive power application

- **Li-Ion (LFP) 48 V, 500 Ah (24kWh)**

The product system to be studied is a cradle to gate including a use stage and End of Life (EoL). Product Functions and Functional Unit

The rechargeable batteries considered in this study are designed to store energy for motive power purposes and to deliver energy to the application, a forklift, as required.

Rechargeable batteries for all applications must provide power measured in kW for the required time to deliver energy (kWh) for the intended application. The energy storage capacity is measured in kWh which is the nominal capacity of the battery and the total energy provided over the service life of the battery; it is also measured in kWh over the total of charge and discharge cycles. This may also be referred to as capacity turnover.

The energy consumption in actual use is the total energy delivered to the application load plus self-discharge, the overcharge current, and charging efficiency as a result of resistive heating losses. In the case of LFP batteries, although there is no current flowing through the cells, the battery management circuitry will consume a very small current which will be additive to the self-discharge.

The functional unit is: Rechargeable storage of energy to fulfill the service lifetime of a forklift (10 years).

The associated reference flow is the number of batteries needed to fulfill this (see Table 2-1).

Table 2-1: Industrial Battery Technical characteristics & Reference flow

	Battery type	Battery weight (kg)	Deionized water refill per year (l)	Recharging electricity per year (MWh)	Floating electricity per year (kWh)	Life span (years)	Total electricity (MWh)	No. batteries vehicle lifetime
Motive Power (battery)	PbB	700	50	5,3	None	6	53	1.67
	LFP	300	None	5,1	None	10	51	1

The baseline assumption for lead and LFP batteries is a 48 V, 500 Ah battery (24 kWh) discharged to 80% of nominal capacity (19.2 kWh). 5 days per week, 50 weeks/year = 250 cycles per year. Similarly, an average life of 10 years is a reasonable figure but there will be a spread of lives depending on intensity of use and maintenance conditions.[5]

The requirement for lead motive power batteries is a life of 1500 cycles[6] If 250 cycles per year (50 weeks operation) is assumed, then the life is six years. Life will be determined by the cumulative number of cycles rather than calendar life in normal operation. For LFP batteries, the cycle life should exceed 2500 cycles. For both types of battery, if the battery use is more or less intensive, then the calendar life will be reduced or extended. For example, in warehousing operations with 7 days, three-shift operation, two or more cycles per battery may be used with batteries being exchanged so that the forklift truck can operate continuously. This would result in 700 cycles per year for 50 weeks of operation and the limit of cycle life would be reached in just over two years.

For lead batteries, 90% charge efficiency is assumed and to return 19.2 kWh, 21.3 kWh is required which makes the annual input 5.3 MWh.[7]

This assumes that a state-of-the-art charger is used which will limit overcharge through the use of intelligent diagnostics, charging profiles and either electrical or mechanical methods to limit stratification of the electrolyte.

For LFP batteries, it has been assumed that the charge efficiency is 95% so 20.2 kWh is required to return 19.2 kWh which makes the annual input 5.1 MWh. LFP batteries are intrinsically more efficient than lead batteries because the electrolyte is not decomposed in normal use. The charging profile needs to be carefully controlled for efficiency and to ensure safe operation.

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[5] (May, FOCUS Consulting, 2022)

[6] (EN 60254-1:2005: Lead acid traction batteries - Part 1: General requirements and methods of tests, 2005).

[7] (May, Secondary Batteries – Lead-Acid Systems, 2009)

2.2. System Boundaries

The system boundary of the study addresses a cradle-to-grave scope. This includes raw material extraction and/or processing, inbound transport to the production facility, battery materials manufacturing, battery assembly the use of the battery and EoL treatment over the lifetime of the application. Figure 2-1 presents all life cycle stages.

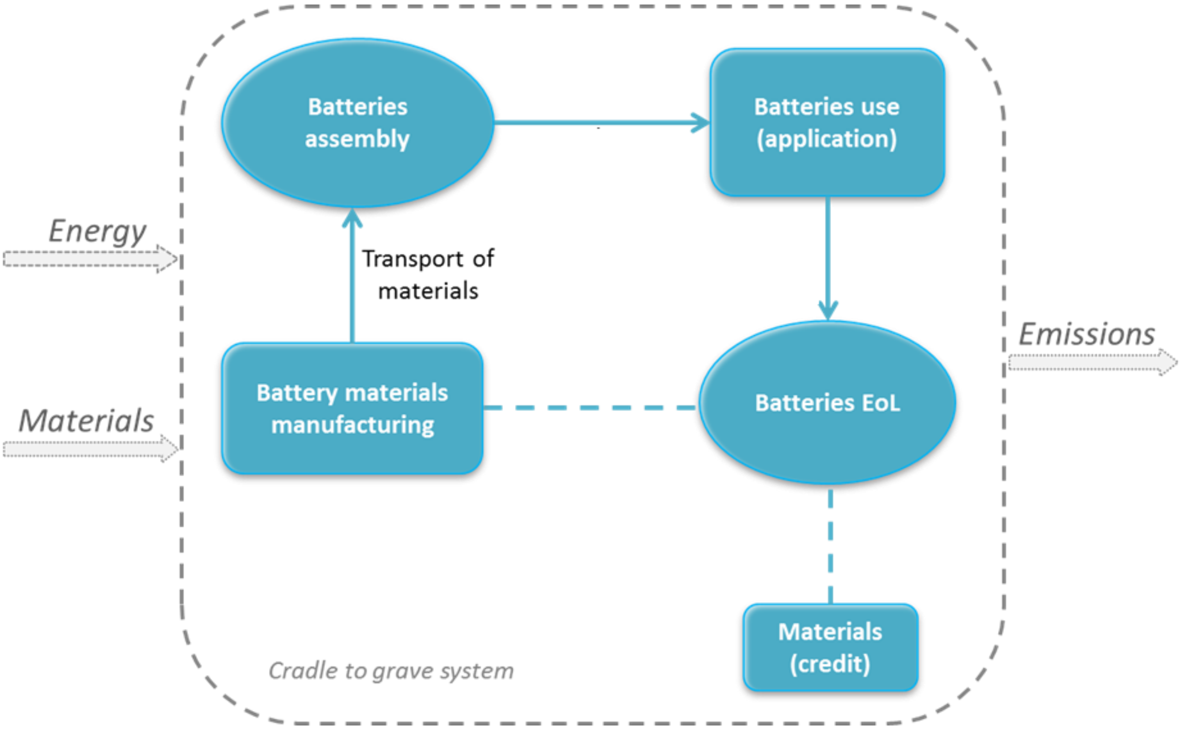


Figure 2-1: System boundary

Inclusions and exclusions to the system boundary are listed in Table 2-2. The scrap from battery manufacturing is recycled and is accounted for in this study.

Table 2-2: System boundaries

Included	Excluded
✓ Extraction and processing of materials ✓ All associated energy and fuels ✓ All associated emissions ✓ Transportation of raw and processed materials ✓ Use stage ✓ End-of-life	× Production of capital equipment and infrastructure × Overhead (heating, lighting, etc.) of manufacturing facilities × Human labor × Packaging × Production of forklift × Transport to customer ×

Packaging has been excluded from the study as it is expected to have a minimal contribution to the total impact. Production and maintenance of capital goods and overhead have also been excluded from the study. It is expected that these impacts will be negligible compared to the impacts associated with running the equipment over its operational lifetime. Finally, the production of the application in which the batteries are used falls outside the scope of this study.

2.2.1. Time Coverage

The results of this study are intended to represent the year 2021. They are relevant for 202323(the year in which the study is completed) and are expected to be relevant until such time as there is a significant change in the production mix, energy mix, or manufacturing technology.

2.2.2. Technology Coverage

This study assesses the cradle-to-grave impacts of lead-based battery production, the use of lead-based batteries in their specified capacity, and their eventual EoL based on the current North American technology mix. Primary site data have been gathered from BCI's members to ensure that the model used to assess the environmental impact of lead-based battery is technologically representative for each stage of the production process. For LFP batteries literature data has been used and represents batteries used in North American vehicles. Please see Table 3-2 and Table 3-1 for more information on the background data used.

2.2.3. Geographical Coverage

The results of this study are intended to represent lead battery produced in North America (production and assembly in NA) and LFP battery produced in Asian countries (mainly China for cell materials production and assembly of imported cells in NA). The upstream data on energy and fuels are based on region. For NA production, regional US data are used where national data are unavailable. These data are combined with primary data gathered from manufacturing sites to ensure that the data and models are representative of the relevant region. The use and EoL stages of the life cycle for the two battery types are assumed to be in NA.

2.3. Cut-off Criteria

No cut-off criteria have been defined for this study. As summarized in section 2.2, the system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The production and maintenance of capital goods, overhead, and human labour have been excluded from the study. It is expected that these impacts will be negligible compared to the impacts associated with running the equipment over its operational lifetime. The choice of proxy data is documented in chapter 3. The influence of these proxy data on the results of the assessment has been carefully analyzed and is discussed in chapter 3.

2.4. Allocation

2.4.1. Multi-input Allocation

Multi-input allocation follows the requirements of ISO 14044, section 4.3.4.2, with the allocation rule most suitable for the respective process step applied within the process. No foreground processes require multi-input allocation; however, multi-input allocation is applied for waste processes including energy recovery, landfill and wastewater treatment. The allocation rules applied to these processes are described in greater detail in the LCI section (chapter3).

2.4.2. Multi-output Allocation

Multi-output allocation generally follows the requirements of ISO 14044, section 4.3.4.2. When allocation becomes necessary during the data collection phase, the allocation rule most suitable for the respective process step has been applied and is documented along with the process in the LCI chapter.

Where there is more than one type of battery produced at a site, mass allocation was applied to the data provided by each company before creating the production-weighted average.

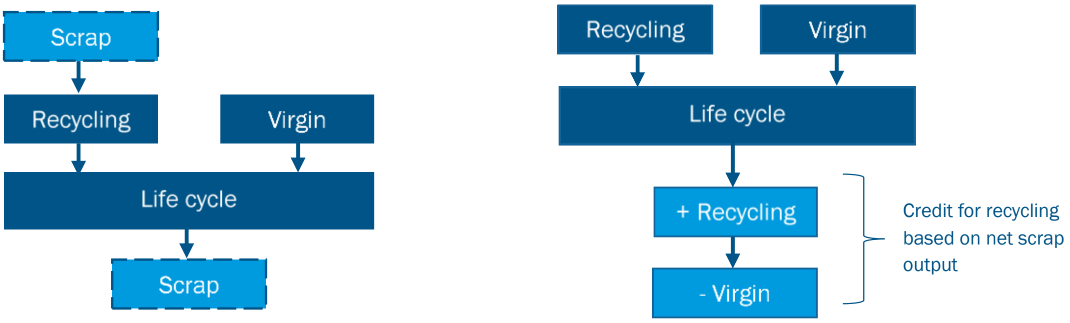
Allocation of background data (energy and materials) taken from the Sphera LCA for Experts (GaBi) 2022.1 database is documented online (Sphera Solutions Inc., 2022).

2.4.3. End-of-Life and Waste Allocation

End-of-Life allocation generally follows the requirements of ISO 14044, section 4.3.4.3. Such allocation approaches address the question of how to assign impacts from virgin production processes to material that is recycled and used in future product systems.

Two main approaches are commonly used in LCA studies to account for end-of-life recycling and recycled content.

- Substitution approach (also known as 0:100, closed-loop approximation, recyclability substitution or end of life approach) – this approach is based on the perspective that material that is recycled into secondary material at end of life will substitute for an equivalent amount of virgin material. Hence a credit is given to account for this material substitution. However, this also means that burdens equivalent to this credit should be assigned to scrap used as an input to the production process, with the overall result that the impact of recycled granulate is the same as the impact of virgin material. This approach rewards end of life recycling but does not reward the use of recycled content.
- Cut-off approach (also known as 100:0 or recycled content approach) – burdens or credits associated with material from previous or subsequent life cycles are not considered and are "cut-off". Therefore, scrap input to the production process is considered to be free of burdens but, equally, no credit is received for scrap available for recycling at end of life. This approach rewards the use of recycled content but does not reward end of life recycling.



(i) Cut-off approach (scrap inputs and outputs are not considered)

(ii) Substitution approach (credit given for net scrap arising)

Figure 2-2: Schematic representations of the cut-off and substitution approaches

The substitution approach has been chosen as the allocation approach for the EoL due to the recovery of several materials. The paragraphs below describe in more detail what has been accounted in the EoL stage.

Material recycling (substitution approach): the lead used in the manufacturing of the batteries can come from two main routes, secondary and primary. The secondary lead dataset has an open post-consumer battery input and secondary materials inputs. After collection of the current batteries at the EoL stage, a recycling process is applied. This remaining net scrap is then sent to material recycling. The original burden of the primary material input is allocated between the current and subsequent life cycle using the mass of recovered secondary lead to scale the substituted primary material. The battery recycling process also accounts for the recovery of plastics by assigning environmental credits. The batteries EoL allocation approach applied will be described in greater detail in the LCI section.

Energy recovery (substitution approach): In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. This method allows for the heat, electricity and emissions to be allocated between the various material inputs to a waste-to-energy plant. Credits are assigned for power and heat outputs using the regional grid mix and thermal energy from natural gas. The latter represents the cleanest fossil fuel and therefore results in a conservative estimate of the avoided burden.

Landfilling (substitution approach): In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilization rates (flaring vs. power production). Credit is assigned for power output using the regional grid mix.

Wastewater treatment (substitution approach): Wastewater streams are linked to industry-average inventories. These inventories allocate impacts to water on a mass basis. Users are able to select relevant inventories for the region or country in question. These inventories capture the impacts related to wastewater treatment for the country/region and take into account the proportion of dry sludge that is used as fertilizer, incinerated, landfilled or sent for composting. Credits are assigned for the sludge used as a fertilizer (where it replaces synthetic fertilizers), for electricity produced from the incineration of sludge and for electricity produced from landfill gas.

2.5. Selection of LCIA Methodology and Impact Categories

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-3 and Table 2-4.

TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) has been selected as it is currently the only impact assessment methodology framework that incorporates US average conditions to establish characterization factors ((Bare, 2012)) ((EPA, 2012)).

For impact categories where TRACI characterization factors are not available (e.g., land use transformation) or where they are not considered to be the most current or robust (e.g., global warming potential, human- and eco-toxicity), alternative methods have been used and are described in more detail below.

Global warming potential and non-renewable primary energy demand were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest. The global warming potential impact category has been assessed based on the latest IPCC (Intergovernmental Panel on Climate Change) characterization factors taken from the 5th Assessment Report (IPCC, 2013) for a 100-year timeframe (GWP100), as this is currently the most commonly used metric.

Eutrophication, acidification, and smog formation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burden associated with commonly regulated emissions such as NO_x, SO_2, VOC (volatile organic compound), and others. These methods are also based on the TRACI impact category methods.

Additionally, this project includes measures of toxicity and particulate matter/respiratory inorganics. These categories are all subject to significant uncertainties.

Human toxicity and ecotoxicity have been assessed using the USEtox™ characterization model. USEtox™ is currently the best-available approach to evaluate toxicity in LCA and is the consensus methodology of the UNEP-SETAC Life Cycle Initiative. The precision of the current USEtox™ characterization factors is within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity (Rosenbaum, 2008). This is a substantial improvement over previously available toxicity characterization models, but still significantly higher than for the other impact categories noted above. Given the limitations of the characterization models for each of these factors, results are not to be used to make comparative assertions.

The particulate matter/respiratory inorganics impact category measures the effect on human health of selected particulate matter/ inorganic emissions. The Human Health Impacts from Exposure to Particulate Matter[8] category used in TRACI 2.1 has been applied, which uses $PM_{2.5}$ as a reference substance.

Ozone depletion potential has not been included in this study. The *Montreal Protocol on Substances that Deplete the Ozone Layer* was implemented in 1989 with the aim of phasing out emissions of ozone depleting gases. The protocol has been ratified by *all* members of the United Nations – an unprecedented level of international cooperation. With a few exceptions, use of CFCs (chlorofluorocarbons), the most harmful chemicals has been eliminated, while complete phase out of less active HCFCs (hydrochlorofluorocarbons) will be achieved by 2030[9]. As a result, it is expected that the ozone layer will return to 1980 levels between 2050 and 2070. In addition, no ozone-depleting substances are emitted in the foreground system under study. For these reasons, ozone depletion potential has not been considered in this study.

Land use is not part of the scope of this study since the available data is not sufficient to generate robust results, also considering the challenges of the methodology. (UNEP, 2019)

Abiotic depletion of elemental resources assesses the availability of natural elements in minerals and ores. Abiotic depletion of elements may be calculated based on either ultimate resource, which is a measure of the total crustal abundance of an element or based on reserves which is a measure of what is economically feasible to extract. These two approaches lead to very different results, and neither is widely accepted by the metals industry (PE International, 2014). Further issues arise with the definition of available resources/reserves, leading to significantly different results for different methods as acknowledged in the ReCiPe methodology report (Goedkoop, 2008)). Although, there has been a consensus reported in (UNEP, 2019) regarding ADP.

Table 2-3: Impact category descriptions

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP100)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on	kg CO_2 equivalent	(IPCC, 2013)

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[8] Terminology in TRACI "human health particulate,"

[9] ((UNEP), 2016)

	ecosystem health, human health and material welfare.		
Eutrophication Potential	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg N equivalent	(Bare, 2012) (EPA, 2012)
Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	
Smog Formation Potential (SFP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg O_3 equivalent	
Human toxicity, Eco-toxicity (recommended only)	A measure of toxic emissions which are directly harmful to the health of humans and other species.	Comparative toxic units (CTUh, CTUe)	(Rosenbaum, et al., 2008)
Human Health Impacts from Exposure to Particulate Matter	A measure of the risk to human health associated with particulate matter and selected inorganic emissions	kg $PM_{2.5}$ equivalent	(Bare, 2012) (EPA, 2012)

Table 2-4: Other environmental indicators

Indicator	Description	Unit	Reference
Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g., petroleum, natural gas, etc.) and energy demand from renewable resources (e.g., hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g., power, heat, steam, etc.) are taken into account.	MJ (lower heating value)	(Guinée, 2002)
Water	A measure of the total blue water consumption (excluding hydropower)	kg	(thinkstep, 2019)

It shall be noted that the above impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

The study's scope was confined to the use of purely volumetric indicators for blue water consumption section4.8, and a more relevant impact-based water footprint was beyond its scope. Hence, the results of the analysis must be interpreted with care.

Due to their subjective and uncertain nature, no normalization, grouping or cross-category weighting has been applied. Instead, each impact is discussed in isolation, without reference to other impact categories, before final conclusions and recommendations are made.

2.6. Interpretation to Be Used

The results of the LCI and LCIA are interpreted according to the Goal and Scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results.
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations and recommendations.

2.7. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- It is assumed that measured primary data are of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data for PbB and secondary data for LFP based on the sector expertise and valuable publications.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties can approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.
- Representativeness expresses the degree to which the data match the geographical, temporal, and technological requirements defined in the study’s goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g., no industry-average data available for NA), best-available proxy data were employed. Detailed description in section 3.1to 3.5The baseline scenario chosen in this study is based on expert judgement of the BCI and its members as well as justified by literature data, as far as those were available, in section 0. Moreover, scenarios have been calculated to validate the baseline choice, section 5.

An evaluation of the data quality with regard to these requirements is provided in the LCI Chapter.

2.8. Type and format of the report

In accordance with the ISO requirements (ISO, 2006), this document aims to report the results and conclusions of the LCA completely, accurately and without bias to the intended audience. The results, data, methods, assumptions, and limitations are presented in a transparent manner and with sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study. It is intended that the results of the study will be made available to a wider audience through the BCI and ILA websites and it is the intention that the life cycle inventories will be made available to users of the Sphera LCA for Experts LCA software through the Sphera professional database.

2.9. Software and Database

The LCA model was created using the Sphera LCA for Experts Software system for life cycle engineering, developed by Sphera. The LCA for Experts (GaBi) 2022.1 LCI database provides the life cycle inventory data for most of the raw and process materials obtained from the background system.

2.10. Critical Review

In accordance with ISO 14044 section 6.3 and ISO/TS 14071, a critical review of this study is undertaken by Matthias Finkbeiner (panel chair) from Technical University Berlin, Germany, Tom Gloria from the Industrial Ecology Consultants and Arpad Horvath to ensure conformity with ISO 14040/44. [10] The critical review was performed concurrently (after G&S and after report) to the study. The analysis and the verification of software model and individual datasets are outside the scope of this review.

The Critical Review Statement will be found in Annex A. The Critical Review Report containing the comments and recommendations by the independent experts as well as the practitioner’s responses is available upon request from the study commissioner in accordance with ISO/TS 14071.

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[10] The reviewers were not engaged or contracted as an official representative of their organization but acted as independent expert reviewers.

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

The following paragraphs describe the data collected and used for all life cycle stages modelling, and the most relevant references are listed.

3.1.1. Lead Battery

Average primary data were collected in the context of the externally reviewed NAM LCA Lead batteries study (BCI, Sphera Solutions, 2022) commissioned by BCI and reviewed by Matthias Finkbeiner from Technical University Berlin, Germany to ensure conformity with ISO 14040/44[11].

In this study, 6 North American batteries companies[12] contributed with its company specific data to develop a representative environmental profile for the LbB. The study covers three industrial lead-based battery technologies (motive, renewable, and standby), with the contributing industry data representing more than 85% of the production volume for those technologies in North America.

3.1.2. LFP Battery

The data collection for LFP battery was undertaken by initially reviewing available literature for appropriate data-specifically:

- Ricardo (2020) Lead Battery Automotive Trends Review-Final Report RD19-001611-11 (Ricardo Strategic Consulting (RSC), 2020)
- A123 Ultra Phosphate Lithium-ion 12 V starter battery specifications downloaded from http://www.a123systems. com/automotive/products/systems/12v-starter-battery/ on 18/6/2020
- Previous ELV Annex II (2014) submissions on Lithium-ion starter batteries by Contribution of A123 Systems, Fraunhofer, LG Chem and Samsung SDI (A123 Systems LLC, 2020)
- Input from lead battery expert Geoffrey May, Focus consulting (May, FOCUS Consulting, 2022)
- Input from companies who produce Lithium-ion batteries within membership of EUROBAT and Consortium for Battery Innovation (EUROBAT, 2020)
- PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications (Recharge, 2018)

BCI's review of LFP data was by dialogue with senior technical staff in member companies.

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[11] The reviewer was not engaged or contracted as an official representative of his organization but acted as independent expert reviewer.

[12] (BCI, Sphera Solutions, 2022)

3.2. Production Stage

3.2.1. Lead Battery

Manufacturers' data were weighted based on production volumes to create average batteries, which were then scaled to the average battery weight defined in Table 3-1. It lists the inputs and outputs associated with the production of the Lead battery, including all processes and on-site wastewater treatment. All lead and lead alloy compounds are derived from primary and secondary production of lead. Water sent through on-site wastewater treatment was subsequently sent to municipal wastewater treatment.

The following emissions to air, if not reported by a company, were approximated using the average of all other reporting companies: sulfuric acid vapor, lead, antimony, arsenic, dust, and VOCs. All other emissions were either reported by companies or, as in the case of combustion emissions, included by using the relevant Sphera datasets. For emissions to water, arsenic, cadmium, copper, and lead were approximated using an average of other companies if not reported by a site.

Table 3-1: Gate-to-gate data for average Lead batteries

Type	Flow	Motive power Cell	Unit
Input	ABS, PC-ABS blend		kg
	Copper	0,525	kg
	EPDM	0,020725	kg
	Expander	0,3075	kg
	Glass (incl. fibers, mats)	2,95	kg
	Lead	282,5	kg
	Lead alloys	(126 primary)	kg
	Lime	184	kg
	PE, HDPE	0	kg
	PET	6,075	kg
	PP	0,02625	kg
	PVC	16,45	kg
	Sodium sulfate	2,44	kg
	Steel	0	kg
	Styrene acrylonitrile	73,5	kg
	SBR	0	kg
	Sulfuric acid	0,01405	kg
	Tribasic lead sulfate	116,5	kg
	Wood, paper	0,16125	kg
	Water (deionized)	0	kg
	Water, ground	14,25	kg
	Water (municipal)	357,5	kg
	Iron sulfate - WWT	178	kg
	Poly iron sulfate - WWT	0,0037	kg
	Sodium hydroxide - WWT	0,00275	kg
	Electricity	0,04625	MJ
	Thermal energy from natural gas	1852,5	MJ

Type	Flow	Motive power Cell	Unit
	Other thermal energy (propane, kerosene)	867,5	MJ
Output	Lead acid battery	700	kg
	Lead scrap	0,112	kg
	Hazardous waste	0,122	kg
	Waste for disposal	0,122	kg
	Waste for recovery	1,465	kg
	Wastewater to municipal treatment	0,064	kg
Emissions to air	Antimony	156,5	kg
	Arsenic	0,000305	kg
	Particulate matter (> PM10)	0,000323	kg
	Lead	0,0275	kg
	NMVOC	0,001548	kg
	Sulfur dioxide	0,002975	kg
	Sulfuric acid	0,00445	kg
	Water vapor	0,0185	kg
Emissions to water	Antimony	315	kg
	Arsenic	6,13E-05	kg
	Biological oxygen demand	4,1E-06	kg
	Cadmium	0,3025	kg
	Chemical oxygen demand	1,05E-05	kg
	Copper	0,000093	kg
	Iron	2,43E-05	kg
	Lead	0	kg
	Mercury	0,000111	kg
	Nickel	3,93E-09	kg
	Tin	3,93E-11	kg
	Zinc	7,6E-09	kg
	Water to river	7,6E-09	kg

3.2.2. LFP battery

It was not possible to obtain manufacturers' data for the 48 V motive LFP batteries currently on the market, therefore validated literature data by the BCI members have been used.

Table 3-2 lists the bill of material and production data for one LFP battery. The production data (electricity, emissions to air and auxiliary materials) have been calculated considering the values reported in the PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications (Recharge, 2018). As referenced in the same PEFCR an increase of 5% of the cell mass components amounts and 3% increase for passive components have been considered to include direct manufacturing wastes. The respective manufacturing wastes have been treated as described in the End-of-Life Section 3.4.1.

Table 3-2: Bill of Material LFP battery

Input parameter	Amount	Unit
ASSEMBLY DATA		
Energy		
Electricity CN[13] (cell electrodes production & forming)	16	GJ
Electricity NA[14] (battery assembly)	76	MJ
Emissions to air		
Dust to air	4	mg
SO_2 to air	1,0	mg
NOx to air	19	µg
Auxiliary materials		
Water deionized (anode + production)	85	kg
N-Methyl pyrrolidone (cathode)	33	kg
Waste treatment in manufacturing		
Total 5% of cell weight	11,9	kg
Plastic (battery case + other internal components)	0,5	kg
Internal clamps, Stainless steel	0,3	kg
Copper wire	0,4	kg
Electronics	0,1	kg
BATTERY COMPONENTS		
Total battery weight	300	kg
Anode		
Copper foil	25,6	kg
Graphite	25,6	kg
Cathode		
Al	16,1	kg
LFP	59,6	kg
Carbon black	2,8	kg
Binder (PVDF)	2,8	kg
Electrolyte		
EC/DMC	33,1	kg
$LiPF_6$	6,6	kg
Separator		
PP	26,5	kg
Cell case, foil pouch		
Al	28,4	kg
Battery case		
Polypropylene	18,9	kg

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[13] Electricity grid mix for China
[14] Electricity grid mix for US

Passive components		
Internal clamps, fastenings (stainless steel)	9,5	kg
Internal connectors and terminals (copper wire)	11,4	kg
Internal circuitry, PCB + components +internal wiring, some in metal cases (electronics)	4,7	kg
External accessories for LFP (not included in battery weight, calculated in Manufacturing results)		
Steel battery tray (outer)	30	kg
Counterweight (steel, cast iron or concrete)	400	kg

3.3. Use stage

The use stage has been modelled considering the available information from the motive power sector, nevertheless, the authors acknowledge other factors that might contribute to these savings, such as the users' behavior.

Table 2-2 define the characteristic lifetime and electricity consumptions for both batteries.

The baseline assumption for lead and LFP batteries is a 48 V, 500 Ah battery (24 kWh) discharged to 80% of nominal capacity (19.2 kWh). 5 days per week, 50 weeks/year = 250 cycles per year, as described in chapter. 0.

The requirement for lead motive power batteries is a life of 1500 cycles. If 250 cycles per year (50 weeks operation) is assumed, then the life is six years. Life will be determined by the cumulative number of cycles rather than calendar life in normal operation. For LFP batteries, the cycle life should exceed 2500 cycles. For both types of battery, if the battery use is more or less intensive, then the calendar life will be reduced or extended. For example, in warehousing operations with 7 days, three shift operation, two or more cycles per battery may be used with batteries being exchanged so that the forklift truck can operate continuously. This would result in 700 cycles per year for 50 weeks operation and the limit of cycle life would be reached in just over two years.

In lead batteries, during the final stages of charging, the electrolyte, which consists of sulfuric acid and water, undergoes electrolysis to produce hydrogen and oxygen. c This is replenished from time to time by adding water in a maintenance operation. There are also ohmic losses which result in heating during charging. This reduces the efficiency of lead batteries to ~90%. Therefore, for lead batteries, 90% charge efficiency is assumed and to return 19.2 kWh, 21.3 kWh is required which makes the annual input 5.3 MWh.

This assumes that a state-of-the-art charger is used which will limit overcharge through the use of intelligent diagnostics, charging profiles and either electrical or mechanical methods to limit stratification of the electrolyte.

For LFP batteries, it has been assumed that the charge efficiency is 95% so 20.2 kWh is required to return 19.2 kWh which makes the annual input 5.1 MWh. LFP batteries are intrinsically more efficient than lead batteries because the electrolyte is not decomposed in normal use, however, there are ohmic losses. The charging profile needs to be carefully controlled for efficiency and to ensure safe operation.

3.4. End of Life Stage

3.4.1. Lead-based batteries EoL

The substitution approach (closed loop recycling approach) was used to assess the impacts associated with the use of recycled lead from lead scrap in the batteries.

This approach connects the amount of scrap generated by the process to the amount of scrap demanded and compensates for any difference with additional lead production. Only the difference in lead leads to an impact or credit from secondary lead in the production stage. The burden of processing the secondary lead falls in the recycling stage.

On average, the lead used in the manufacturing of the batteries comes mainly from secondary Lead[15] . The secondary lead dataset has open material inputs from collected batteries. This allows, after collection of the current batteries, to loop back to the production stage replacing the net amount of EoL batteries as input to the secondary lead dataset (recycling) (see Figure 3-1 Secondary lead – closed loop). The differences between supplied and resulting EoL battery mass values are compensated by sending the remaining amount to recycling in the EoL stage and a credit is applied. Figure 3-1 depicts the approach applied.

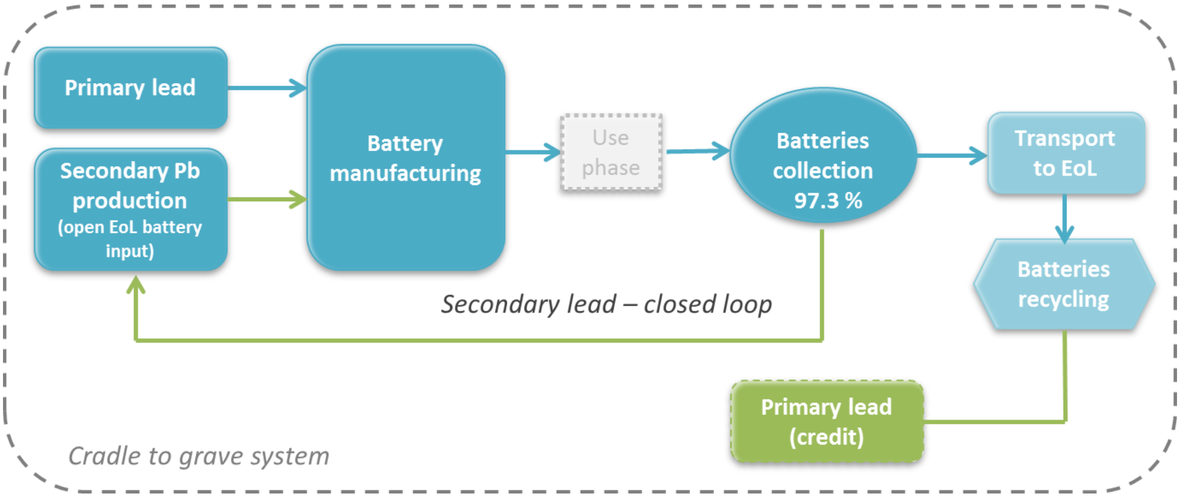

Figure 3-1: Lead batteries EoL – Material recycling (substitution approach) approx. 70% is secondary Lead.

3.4.2. LFP batteries EoL

In this study, the baseline was set with assuming pyrolysis for the LFP battery cells to recover energy from the incineration process. Material recovery was assumed for the BMS and battery housings and other components.

Today there are some commercial processes specifically designed for LFP cell recovery, but rather LFP cells are mixed into the metallurgical processes where NMC batteries are recovered. And in this context

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[15] (BCI, Sphera Solutions, 2022)

an overall recovery of 50% as required by the EU Battery Directive can be achieved for LFP in general. This includes the BMS, housing, etc.

The LFP battery cell is incinerated (with material and energy recovery as described in Table 3-3) and only the passive components, electronics, battery case are recycled. By doing so a recycling efficiency of around 15 % is achieved. The steel battery tray and counterweight are also recycled, but not included in the calculation of the recycling efficiency since these are considered as additional accessories for the correct function of the battery.

A scenario was carried out by modelling a future metallurgical process that can recover the lithium and other components from LFP cells whilst neglecting the iron phosphate. Recovering the lithium and the aluminum foils and copper in the cells increases the recovery rate to approximately 60 %, taking into consideration a collection rate of 99%, as described in chapter 5.3.4.

Table 3-3: End of Life – LFP battery

Cell / battery component	Amount	Unit	EoL Treatment	Credits
Battery LFP Cell				
ANODE			Hazardous waste incineration with energy recovery The dataset covers all relevant process steps for thermal treatment and corresponding processes, such as disposal of air pollution control residues or metal recycling. The system is partly terminated in order to consider credits (open outputs electricity and steam). Credits for recovered metals are already included.	Electricity / Thermal energy
Copper foil	26,7	kg		
Graphite	26,7	kg		
CATHODE				
Al	16,8	kg		
LFP	62,4	kg		
Carbon black	2,98	kg		
Binder (PVDF)	2,98	kg		
ELECTROLYTE				
EC/DMC	34,7	kg		
$LiPF_6$	6,9	kg		
SEPARATOR				
PP	27,7	kg		
Cell case, foil pouch				
Al	29,7	kg		
Battery case				
PP	19,8	kg	recycling plastic granulate	Polypropylene granulate
Passive components (electronics)				
Internal clamps, fastenings (stainless steel)	9,9	kg	recycling	Stainless steel
Internal connectors and terminals (copper wire)	11,8	kg	recycling	Copper
Internal circuitry, PCB + components +internal wiring, some in metal cases	1.50	kg	shredding & recovery (>50% landfill / incineration & recycling)	Electricity & thermal energy / Copper / Palladium / Silver / Gold
External accessories for LFP (not included in battery weight, calculated in EoL results)				
Steel battery tray (outer)	30	kg	metal recycling, plastic incineration	Copper / Electricity / Thermal energy

Counterweight (steel, cast iron or concrete)	400	kg	metal recycling	Steel billet

3.5. Background data

Documentation for all Sphera datasets can be found online (Sphera Solutions Inc., 2022).

3.5.1. Fuels and Energy for production

National or regional averages for fuel inputs and electricity grid mixes were obtained from the Sphera 2022.1 databases. Table 3-4 shows the most relevant LCI datasets used in modelling the product systems. Electricity consumption for LFP batteries was modelled using China country grid mix for the battery cell production and NA for the assembly of the battery components.

Table 3-4: Key energy datasets used in inventory analysis

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Electricity	US (average)	Electricity grid mix	Sphera	2018	-
	CN	Electricity grid mix	Sphera	2018	-
Thermal energy	US	Thermal energy from natural gas	Sphera	2018	-

3.5.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the Sphera 2022.1 database. Table 3-5 shows the most relevant LCI datasets used in modelling the product systems. Some datasets used are from other geographical regions and therefore referred to Geo. as proxy.

Table 3-5: Key material and process datasets used in inventory analysis for Lead Battery

Material / Process	Geo.	Dataset	Data Provider	Reference Year	Proxy?
ABS	US	Acrilonitrile-Butadiene-Styrene Granulate (ABS)	Sphera	2021	-
Expander	US	Barium sulphate (BaSO4)	Sphera	2021	-
Expander	US	Carbon black (furnace black; general purpose)	Sphera	2021	-
Expander	US	Cellulose	Sphera	2021	-
Copper parts	GLO	Copper (99.99%; cathode)	ICA	2018	-
Cardboard	US	Corrugated product	ts/AF&PA	2012	-
EPDM	US	Ethylen Propylene Dien Elastomer (EPDM)	Sphera	2021	-
Glass	EU-28	Float flat glass	Sphera	2021	Geo.
Glass mat	EU-28	Glass wool	Sphera	2021	Geo.
Paper	EU-28	Kraft paper (EN15804 A1-A3)	Sphera	2018	Geo.
Wood	EU-28	Log softwood mix	Sphera	2021	Geo.
Phosphoric acid	US	Phosphoric acid (highly pure)	Sphera	2021	-

PC	US	Polycarbonate Granulate (PC)	Sphera	2021	-
HDPE	US	Polyethylene High Density Granulate (HDPE/PE-HD)	Sphera	2021	-
LDPE	US	Polyethylene Low Density Granulate (LDPE/PE-LD)	Sphera	2021	-
PET	US	Polyethylene Terephthalate Fibers (PET)	Sphera	2021	-
PP	US	Polypropylene granulate (PP)	Sphera	2021	-
PVC	US	Polyvinyl chloride granulate (Suspension, S-PVC)	Sphera	2021	-
Lead, secondary	NAM	Secondary lead average production mix	ILA	2015	-
Sand	US	Silica sand (Excavation and processing)	Sphera	2021	-
Sodium sulfate	GLO	Sodium sulphate	Sphera	2021	-
Stainless steel	EU-28	Stainless steel cold rolled coil (304)	Eurofer	2014	Geo.-
Steel coil	RNA	Steel cold rolled coil (version released in 2011)	worldsteel	2011	-
SAN	EU-28	Styrene acrylonitrile (SAN), a-Methyl styrene acrylonitrile (AMSAN)	Plastics Europe	2013	-
Rubber	US	Styrene-butadiene rubber (S-SBR)	Sphera	2021	-
Sulfuric acid	US	Sulphuric acid (high purity)	Sphera	2021	-
Tin	GLO	Tin	Sphera	2021	-
TBLS	EU-28	Tribasic lead sulphate (stabilizer, estimation)	Sphera	2021	Geo.-
Deionized water	US	Water deionized	Sphera	2021	-
Ferrous/ferric sulfate (WWT)	US	Ferrous sulfate	Sphera	2021	Tech.
Hazardous waste treatment	US	Hazardous waste (statistic average) (no C, worst case scenario incl. landfill)	Sphera	2021	-
Ferric chloride (WWT)	US	Iron (III) chloride	Sphera	2021	-
Lime (WWT)	US	Lime (CaO; quicklime lumpy) (estimation)	Sphera	2021	-
Lubricants	US	Lubricants at refinery	Sphera	2021	-
Wastewater treatment	US	Municipal wastewater treatment (mix)	Sphera	2021	-
Injection molding	GLO	Plastic injection molding (parameterized)	Sphera	2021	-
Soda (WWT)	US	Sodium hydroxide (caustic soda) mix (100%)	Sphera	2021	-
Sheet stamping and bending	GLO	Steel sheet stamping and bending (5% loss)	Sphera	2021	-
Rubber vulcanization	GLO	Vulcanization of synthetic rubber (without additives)	Sphera	2021	-
Water	US	Tap water from groundwater	Sphera	2021	-

Table 3-6: Key material and process datasets used in inventory analysis for LFP Battery

Material / Process	Geo.	Dataset	Data Provider	Reference Year	Proxy?
Cell material	CN	Lithium hydroxide	Sphera	2021	-

	US	Phosphoric acid (75%)	Sphera	2021	Geo.
	EU-28	Iron (II) sulphate	Sphera	2021	Geo.
	CN	Polyvinylidene fluoride (emulsion polymerization) (PVDF) - open inputs energy	Sphera	2021	-
	CN	Carbon Black	Sphera	2021	-
	CN	Aluminum part	Sphera	2021	-
	GLO	Steel sheet part	Sphera	2021	-
	CN	Synthetic graphite via calcined petroleum coke	Sphera	2021	-
	GLO	Copper sheet part	Sphera	2021	-
	GLO	Dimethyl carbonate	Sphera	2021	-
	CN	Aluminum part	Sphera	2021	-
	GLO	Water (desalinated; deionized)	Sphera	2021	-
	JP	Lithium Hexafluorophosphate ($LiPF_6$)	Sphera	2021	-
Electronics	GLO	Cable 1-core signal 24AWG PE (4.5 g/m) D1.4	Sphera	2021	-
	GLO	Cable 3-core mains power 10A/13A 16AWG PVC (100 g/m) D8	Sphera	2021	-
	DE	Connector T-block (5-way, without Au, PA6.6 basis)	Sphera	2021	Geo.
	GLO	Connector PATA	Sphera	2021	-
	GLO	Average Printed Wiring Board with Power Electronics (DfX-compatible)	Sphera	2021	-
	GLO	Average Printed Wiring Board with Signal-Power Electronics (DfX-Compatible)	Sphera	2021	-
	EU-28	Tap water from groundwater	Sphera	2021	Geo.
	GLO	Transistor power THT/SMD SOT93/TO218 7 leads (4.80g) 15.5x12.9x4.7	Sphera	2021	-
	GLO	EMS Shielding	Sphera	2021	-
	EU-28	Gasoline mix (regular) at refinery	Sphera	2021	Geo.

Table 3-7: EoL background data for Lead Batteries

	NAM	Lead bearing scrap recovery	ILA	2015	-
	EU/NAM	Lead primary route production mix	ILA	2015	-

Table 3-8: EoL background data for LFP Batteries

EoL	EU-28	Copper scrap values (average scrap) - EoL recycling potential	Sphera	2021	Geo.
	GLO	Recycling of stainless-steel scrap	Sphera	2021	-
	EU-28	Recycling of polypropylene (PP) plastic	Sphera	2021	Geo.
	EU-28	Hazardous waste in waste incineration plant	Sphera	2021	Geo.
	EU-28	Polypropylene granulate (PP) mix	Sphera	2021	Geo.
	DE	Incineration of electronics scrap (Printed Wiring Boards, PWB)	Sphera	2021	Geo.

3.5.3. Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials, operating materials, and auxiliary materials to production facilities. Relevant datasets are shown in Table 3-9 and Table 3-10.

Table 3-9: Transportation and road fuel datasets

Mode / fuels	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Class 8b truck (basic enclosed)	US	Truck - Trailer, basic enclosed / 45,000 lb payload - 8b	Sphera	2021	-
Diesel	US	Diesel mix at filling station	Sphera	2018	-
Class EU 6 mix truck	GLO	Truck-trailer, Euro 6 mix, 34 - 40t gross weight / 27t payload capacity	Sphera	2021	-
Container ship	GLO	Container ship, 5,000 to 200,000 dwt payload capacity, ocean going	Sphera	2021	-
Diesel	CN	Diesel mix at refinery	Sphera	2018	-
Fuel oil	CN	Heavy fuel oil at refinery (1.0wt. % S)	Sphera	2018	-

Table 3-10: Use stage forklift datasets

Mode / fuels	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Electricity grid mix	US	Electricity grid mix	Sphera	2018	no

Water deionized (only Lead battery)	US	Water deionized	Sphera	2018	no

4. Life Cycle Impact Assessment

4.1. Overall Results Summary

Total results for the total life cycle of lead and LFP batteries are displayed in Table 4-1.

Table 4-1: Total Life Cycle LCIA for Lead and LFP batteries per reference flow

Impact / Indicator	PbB	LFP	Dev. -%
GWP 100, excl biogenic CO2 [kg CO2 eq.]	30424	32307	-6%
Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	592196	606982	-2%
Acidification [kg SO2 eq.]	66	76	-16%
Eutrophication [kg N eq.]	3,8	5,4	-41%
Human Health Impacts from Exposure of Particulate Matter [kg PM2.5 eq.]	5,1	6,1	-21%
Photochemical Smog Formation [kg O3 eq.]	767	946	-23%
Blue water consumption [kg]	261644	255555	2%

4.2. Primary Energy Demand

Primary energy demand is the quantity of energy directly taken from the environment prior to undergoing any anthropogenic changes and can be renewable (e. g. solar, hydropower) or non-renewable (e. g. coal, natural gas).

How primary energy demand is calculated varies according to the type of energy source. For fossil and nuclear fuels, primary energy demand is calculated as the energy content of the raw material. Similarly, the primary energy demand of renewable fuels is based on the energy content of the biomass used. For renewable energy technologies that directly generate electricity such as wind power, hydropower, solar power and geothermal power, the primary energy calculation is based on the efficiency of the conversion of the specific energy source (e. g. a wind turbine converts about 40% of the kinetic energy of the wind into electricity, so 1 MJ electricity requires around 2.5 MJ primary energy from wind).

In Table 4-2 the PED for the lead and LFP batteries according to the defined application and FU for each life cycle stage is displayed. In Table 5-1 the share between non-renewable and renewable sources is displayed.

Table 4-2: Primary energy demand [MJ]

Life Cycle Stage	PbB	LFP
Manufacturing stage	26069	103369
Use stage	566358	507597
EoL	-232	-3985
Total Life Cycle	**592196**	606982

As in the rest of analyzed impact categories and indicators, the use stage dominates the overall results for the two batteries type. As described in section 3.3, the use stage refers to the electricity consumption of the battery taking into consideration the charging efficiency and performance of each battery type.

In Figure 4-1 the overall results for both batteries are displayed.

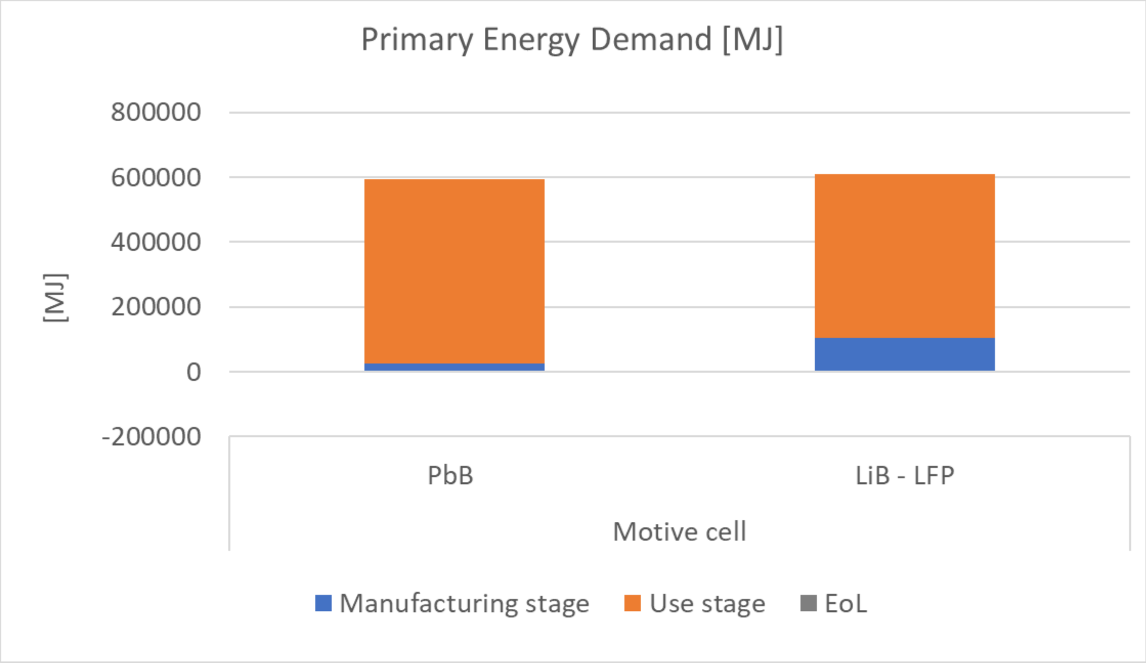

Figure 4-1: Overall Life Cycle PED

In Figure 4-2 the main contributors to the manufacturing stage are displayed.

Table 4-3: Relative contribution of non-renewable and renewable energy resources – LFP batteries

		End of Life	Manufacturing	Use stage
Primary energy from non renewable resources (net cal. value) [MJ]	81%	-1%	15%	81%
Crude oil (resource)	5%	0%	2%	5%
Hard coal (resource)	37%	0%	9%	37%
Lignite (resource)	3%	0%	0%	3%
Natural gas (resource)	34%	0%	4%	34%
Peat (resource)	0%	0%	0%	0%
Uranium (resource)	22%	0%	2%	22%
Primary energy from renewable resources (net cal. value) [MJ]	24%	0%	3%	24%
Biomass (MJ)	0%	0%	0%	0%
Primary energy from geothermic	4%	0%	0%	4%
Primary energy from hydro power	31%	0%	4%	31%
Primary energy from solar energy	35%	0%	5%	35%

Primary energy from waves	0%	0%	0%	0%
Primary energy from wind power	30%	0%	4%	30%

Table 4-4: Relative contribution of non-renewable and renewable energy resources – Lead batteries

		End of Life	Manufacturing	Use stage
Primary energy from non renewable resources (net cal. value) [MJ]	81%	-1%	15%	81%
Crude oil (resource)	5%	0%	2%	5%
Hard coal (resource)	37%	0%	9%	37%
Lignite (resource)	3%	0%	0%	3%
Natural gas (resource)	34%	0%	4%	34%
Peat (resource)	0%	0%	0%	0%
Uranium (resource)	22%	0%	2%	22%
Primary energy from renewable resources (net cal. value) [MJ]	24%	0%	3%	24%
Biomass (MJ)	0%	0%	0%	0%
Primary energy from geothermic	4%	0%	0%	4%
Primary energy from hydro power	31%	0%	4%	31%
Primary energy from solar energy	35%	0%	5%	35%
Primary energy from waves	0%	0%	0%	0%
Primary energy from wind power	30%	0%	4%	30%

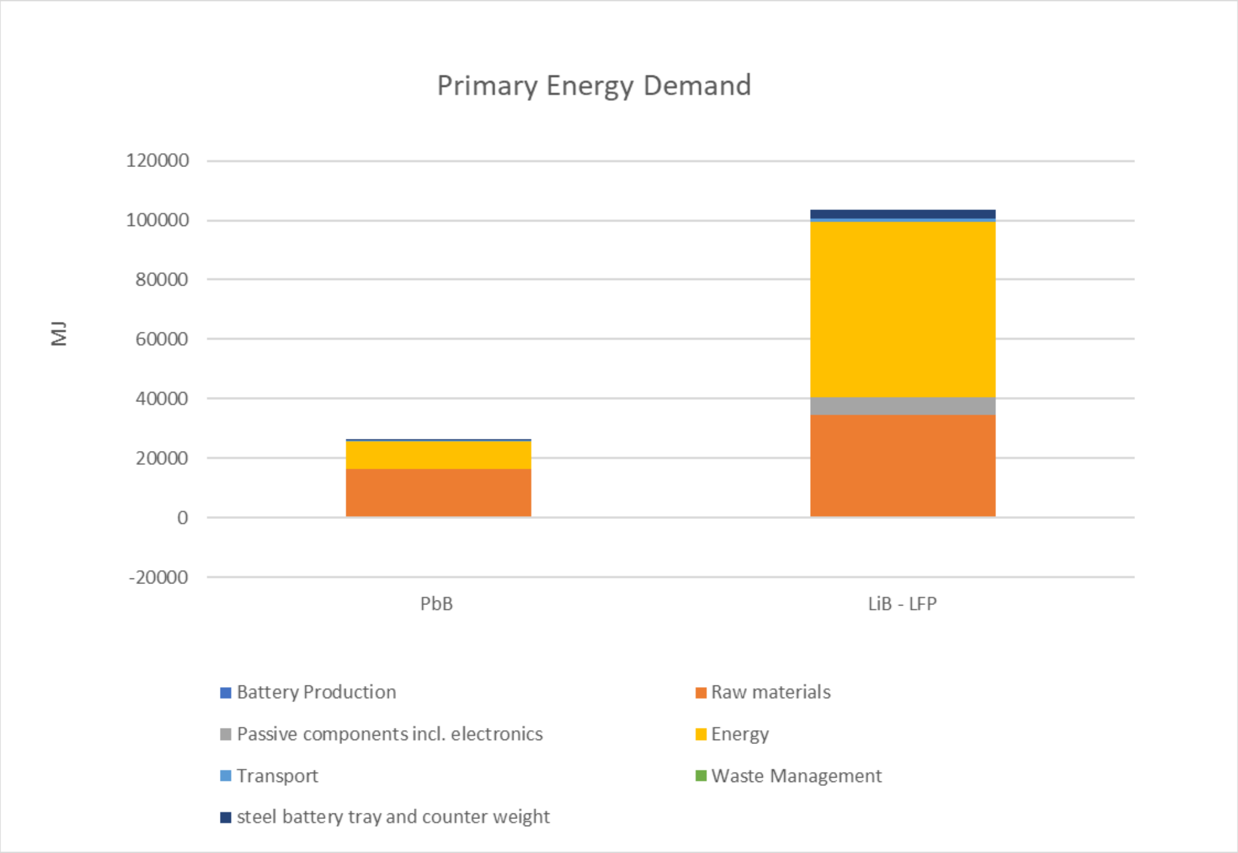

Figure 4-2: Main contributors to the PED (manufacturing stage)

For both battery types the manufacturing stage is dominated by the raw materials (approx. 62% for PbB and 33% for LFP) followed by electricity (approx. 36% and 57%, accordingly). raw materials.

4.3. Global Warming Potential

In Table 4-5 the GWP for the lead and LFP batteries according to motive power application per FU for each life cycle stage is displayed.

Table 4-5: Global Warming Potential [kg CO_2 eq.]

Life Cycle Stage	PbB	LFP
Manufacturing stage	2016	6832
Use stage	28443	25492
EoL	-36	-17
Total Life Cycle	**30424**	**32307**

As in the rest of analyzed impact categories and indicators, the use stage dominates the overall results. As described in section 3.3, the use stage the use stage refers to the electricity consumption of the battery taking into consideration the charging efficiency and performance of each battery type.

In Figure 4-3 the overall results per battery technology and application according to the functional unit is displayed.

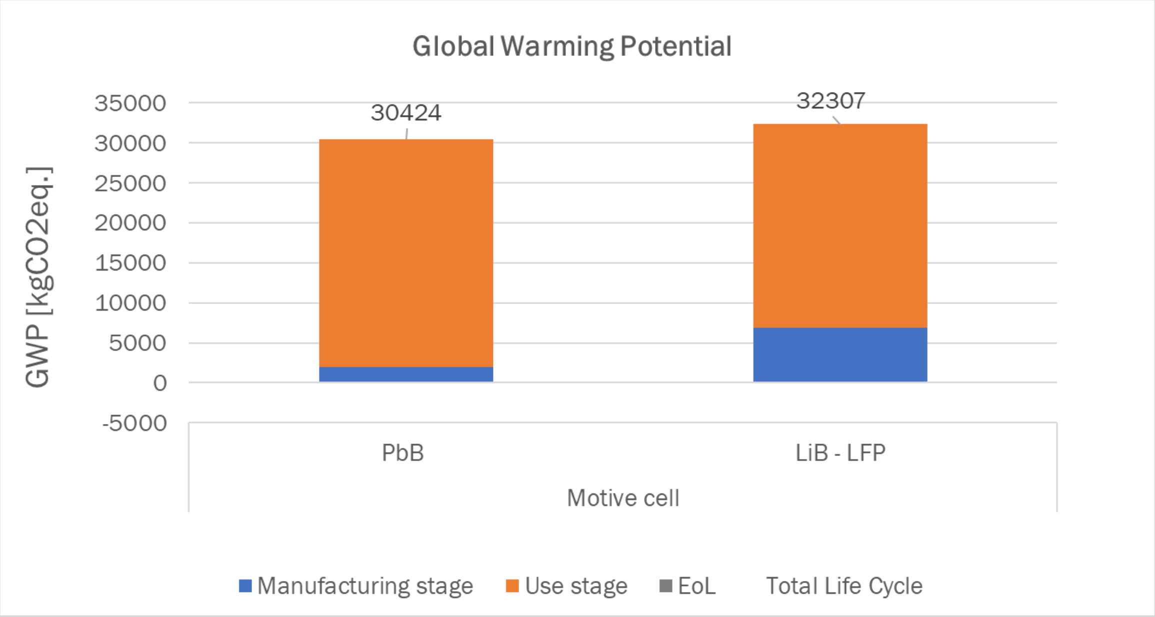

Figure 4-3: Overall Life Cycle GWP

In Figure 4-4 the main contributors to the manufacturing stage are displayed.

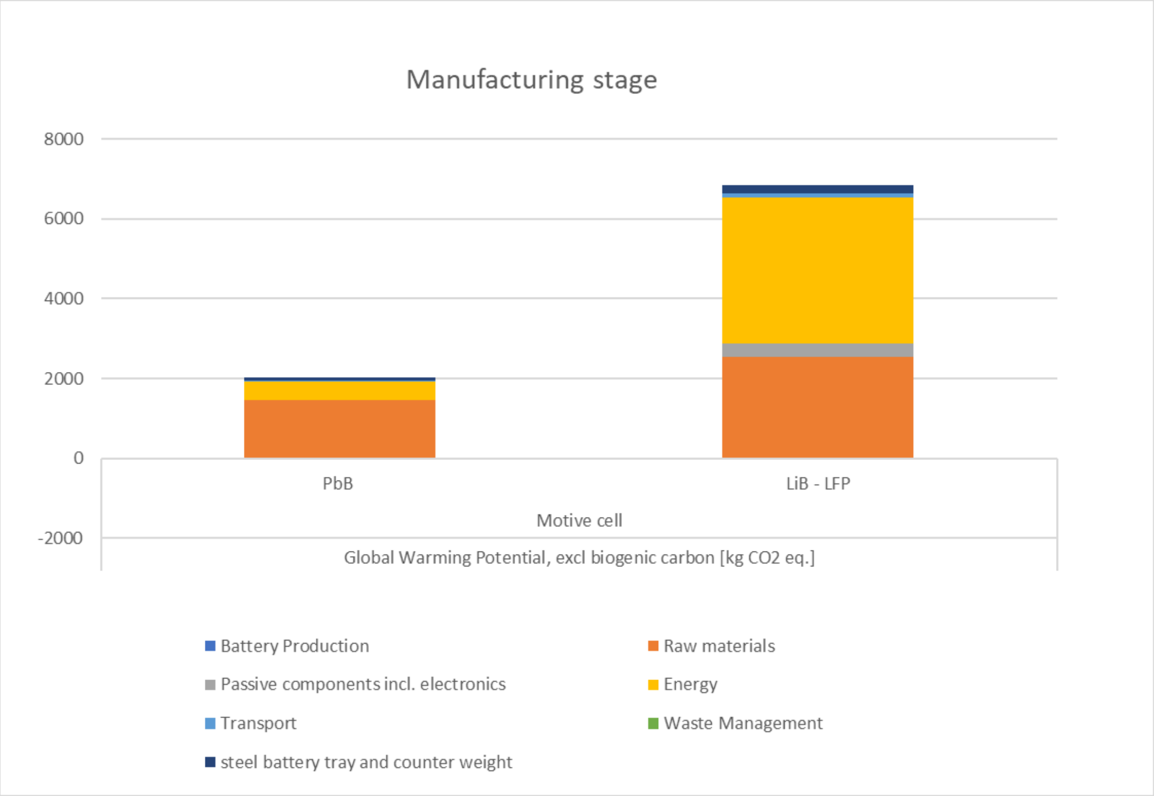

Figure 4-4: Main contributors to the GWP (manufacturing stage)

For PbB the manufacturing stage is dominated by the raw materials (approx. 72%) followed by electricity (approx. 23%). In the case of LFP, the electricity and raw materials dominate the manufacturing stage (approx. 54% and 37%, respectively) followed by the passive components including electronics (approx. 5%). Other components such as steel battery tray and counterweight (approx. 4% for PbB and 3% for LFP).

4.4. Acidification Potential

In Table 4-6 the AP for the lead and LFP batteries according to the different technologies for each life cycle stage is displayed.

Table 4-6: Acidification Potential [kg SO_2 eq.]

Life Cycle Stage	PbB	LFP
Manufacturing stage	10	27
Use stage	55	49
EoL	0,08	-0,02
Total Life Cycle	**66**	**76**

. As described in section 3.3, the use stage refers to the electricity consumption taking into consideration charging efficiency and battery performance.

In Figure 4-5 the overall results for both batteries are displayed.

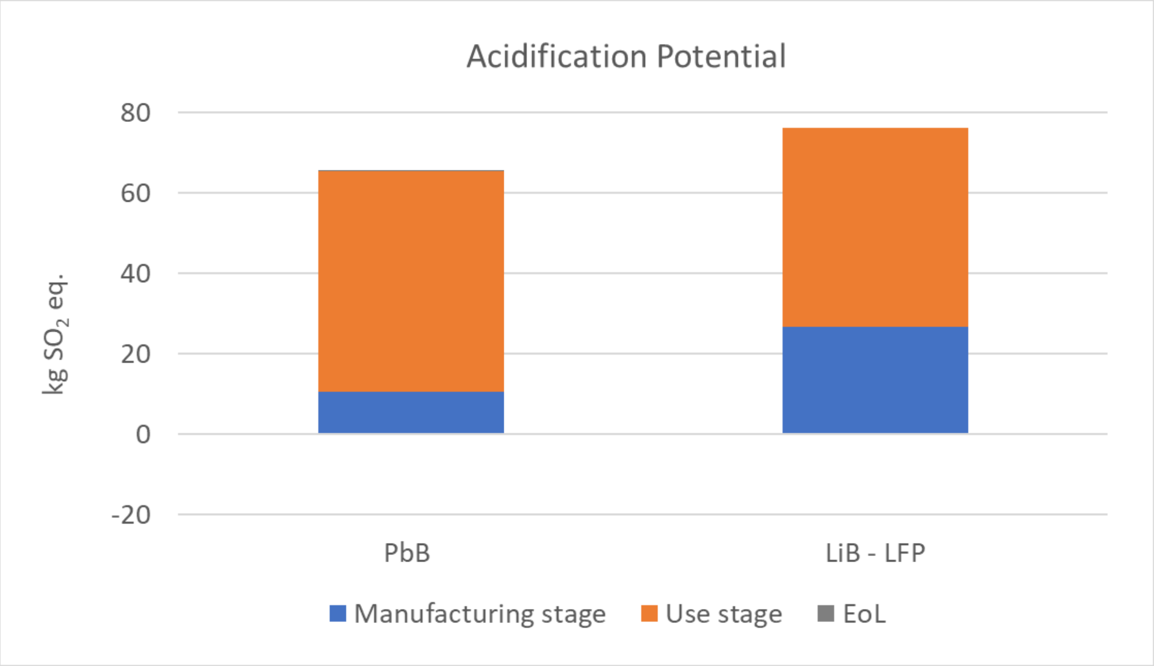

Figure 4-5: Overall Life Cycle AP

In Figure 4-6 the main contributors to the manufacturing stage are displayed.

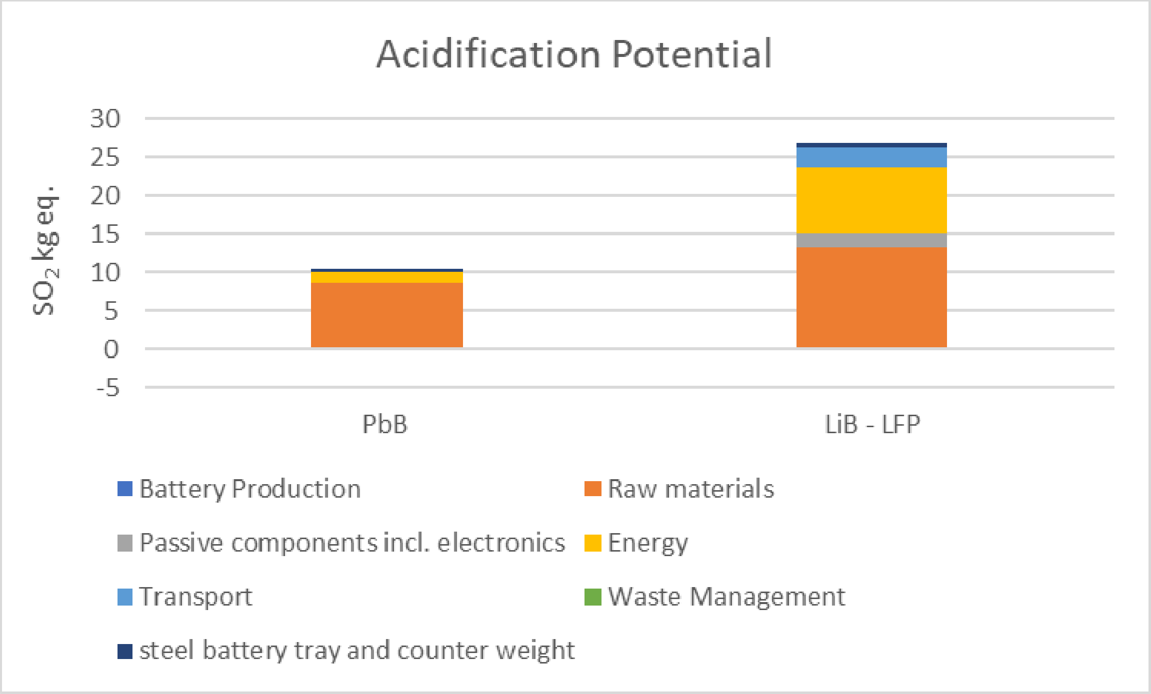

Figure 4-6: Main contributors to the AP (manufacturing stage)

For all battery types the manufacturing stage is dominated by the raw materials (approx. 83% - PbB and 49% - LFP) followed by electricity (approx. 13% for PbB and 32% LFP). Other components such as steel battery trays and counterweights have a lower contribution to the manufacturing stage results.

4.5. Eutrophication Potential

In Table 4-7 the EP for the lead and LFP batteries according to the different technologies and FU for each life cycle stage is displayed.

Table 4-7: Eutrophication Potential (EP) [kg N eq.]

Life Cycle Stage	PbB	LFP
Manufacturing stage	0,4	2,3
Use stage	3,5	3,1
EoL	0,0009	-0,02
Total Life Cycle	**3,8**	**5,4**

As in almost all of analyzed impact categories and indicators, the use stage dominates the overall results. As described in section 3.3, the use stage refers to electricity consumption taking into consideration charging efficiency and battery performance.

In Figure 4-7 the overall results for both battery types per reference flow are displayed.

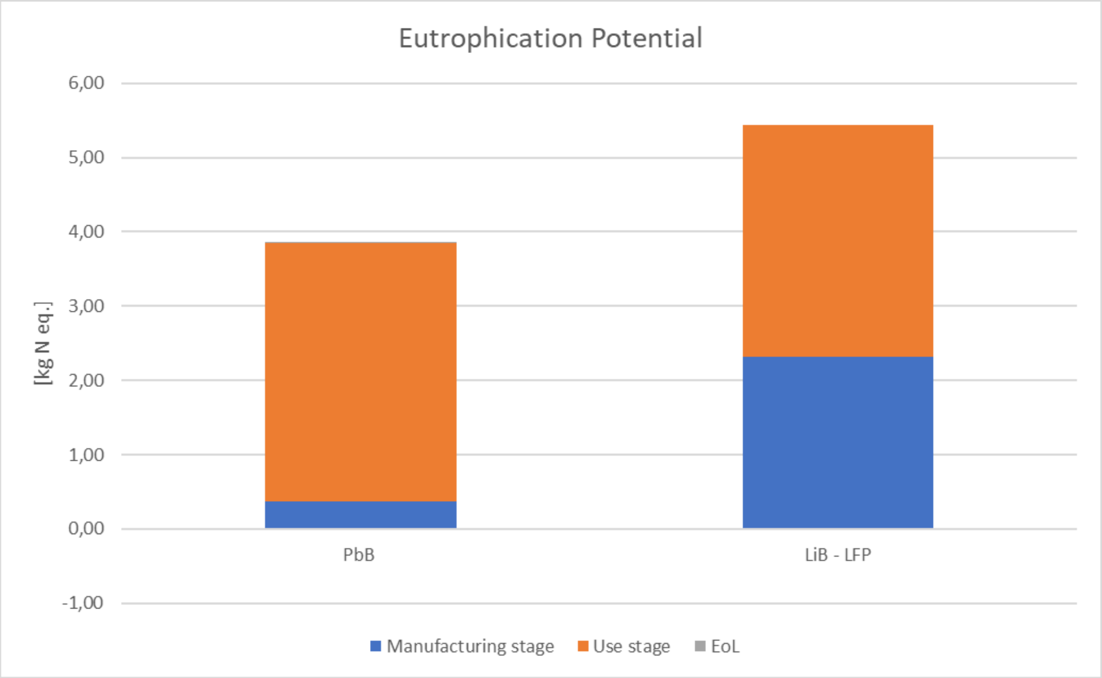

Figure 4-7: Overall Life Cycle EP

In Figure 4-8 the main contributors to the manufacturing stage are displayed.

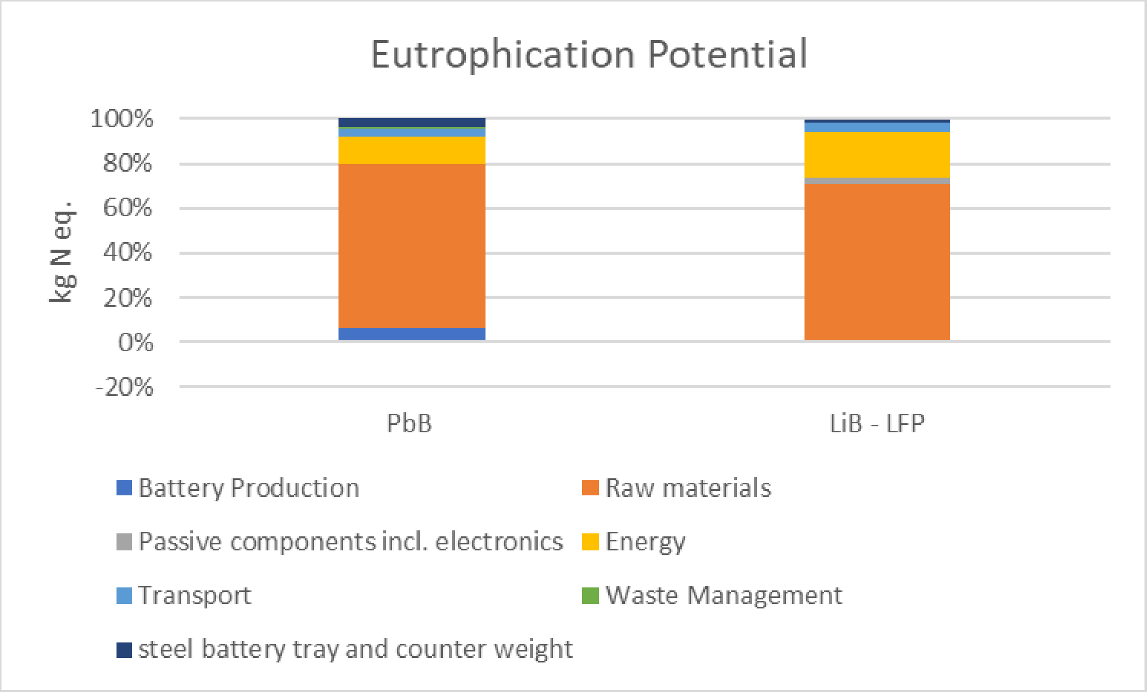

Figure 4-8: Main contributors to the EP (manufacturing stage)

For PbB the manufacturing stage is dominated by the raw materials (approx. 74%) followed by electricity (approx. 12%). In the case of LFP, the raw materials (approx. 70%) dominates the manufacturing stage followed by the electricity (approx. 21%) and the passive components including electronics (approx. 3%). Other components such steel battery tray and counterweights have a lower contribution to the manufacturing stage results.

4.6. Human Health Impacts from Exposure to Particulate Matter

The particulate matter/respiratory inorganics impact category measures the effect on human health of selected particulate matter/ inorganic emissions. The ‘human health particulate air’ category used in TRACI 2.1 has been applied, which uses $PM_{2.5}$ as a reference substance.

In Table 4-8 the Human Health Particulate Air for the lead and LFP batteries according to the different technologies and FU for each life cycle stage is displayed.

Table 4-8: Human Health Impacts from Exposure to Particulate Matters [kg $PM_{2.5}$ eq.]

Life Cycle Stage	PbB	LFP
Manufacturing stage	1,45	2,94
Use stage	3,63	3,26
EoL	-0,031	-0,11
Total Life Cycle	**5,05**	**6,09**

The use stage dominates the overall results for both battery types. As described in section 3.3, the use stage refers to the electricity consumption considering charging efficiency and battery performance.

In Figure 4-9 the overall results for both battery types per reference flow are displayed.

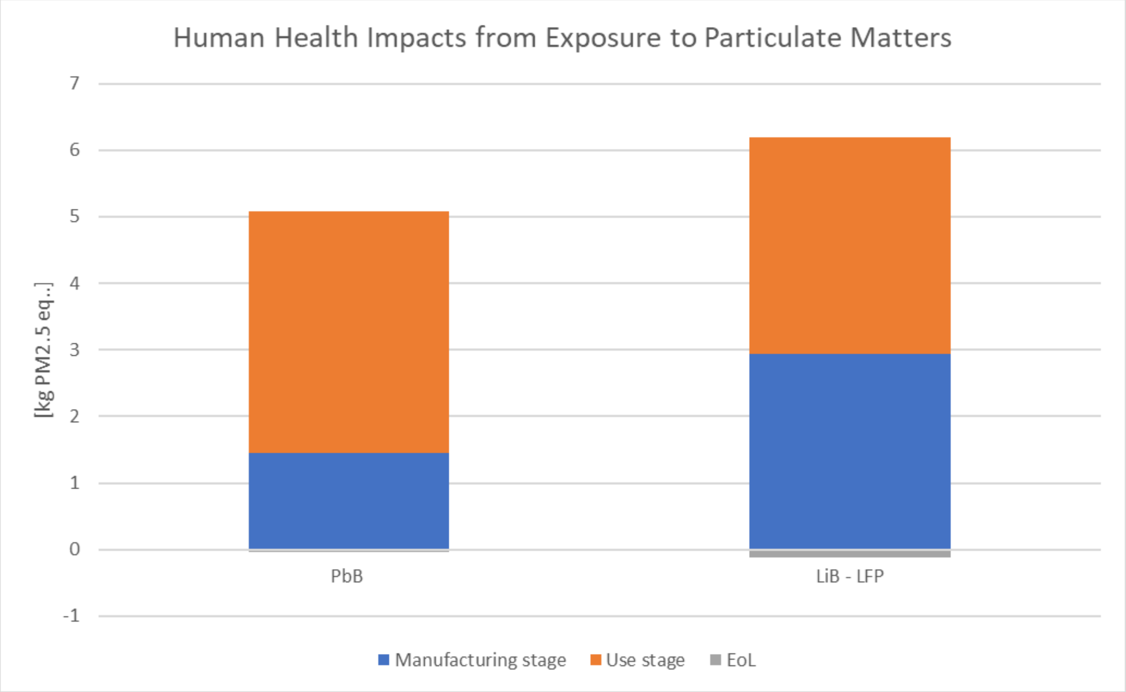

Figure 4-9: Overall Life Cycle Human Health Impacts from Exposure to Particulate Matters

In Figure 4-10 the main contributors to the manufacturing stage are displayed.

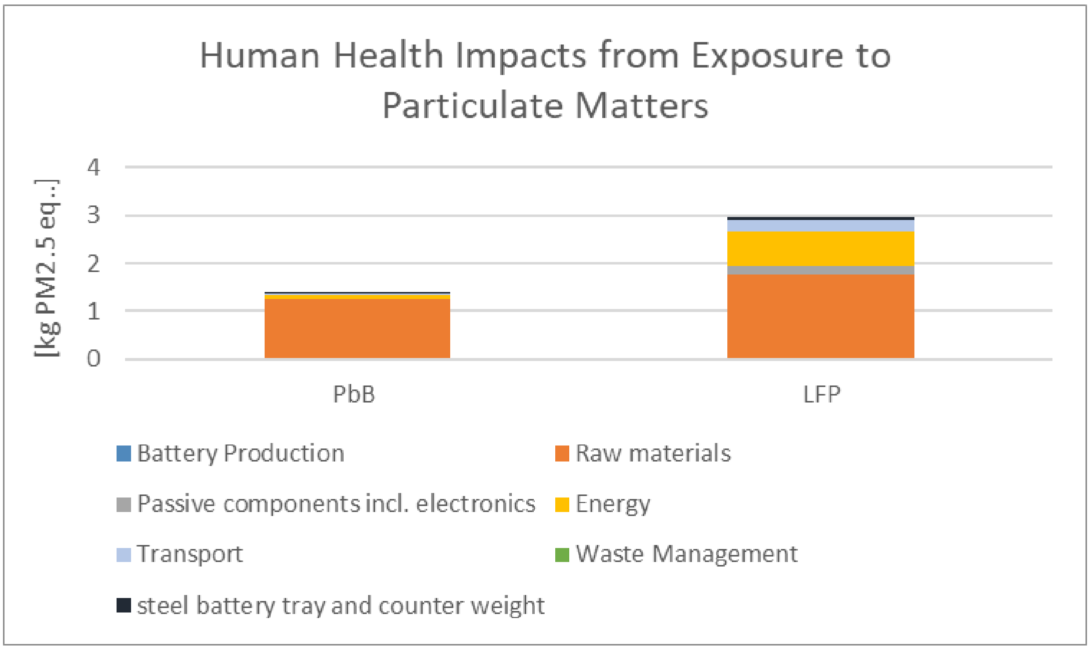

Figure 4-10: Main contributors to the Human Health Impacts from Exposure to Particulate Matters (manufacturing stage)

For PbB the manufacturing stage is dominated by the raw materials (approx. 90%) followed by electricity (approx. 7%). In the case of LFP, the raw materials (approx. 60%) dominate the manufacturing stage followed by the electricity (approx. 25%) and the passive components including electronics (approx. 5%). Other components such steel battery tray and counterweights have a lower contribution to the manufacturing stage results.

4.7. Photochemical Smog Formation

A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.

In Table 4-8 the Photochemical Smog Formation for the lead and LFP batteries according to the different technologies and FU for each life cycle stage is displayed.

Table 4-9: Photochemical Smog Formation (POCP) [kg O_3]

Life Cycle Stage	PbB	LFP
Manufacturing stage	90	341
Use stage	675	605
EoL	1,9	0,7
Total Life Cycle	**767**	**946**

In Figure 4-9 the overall results for both batteries are displayed.

The use stage dominates the overall results for both battery types. As described in section 3.3, the use stage refers to the electricity consumption considering charging efficiency and battery performance.

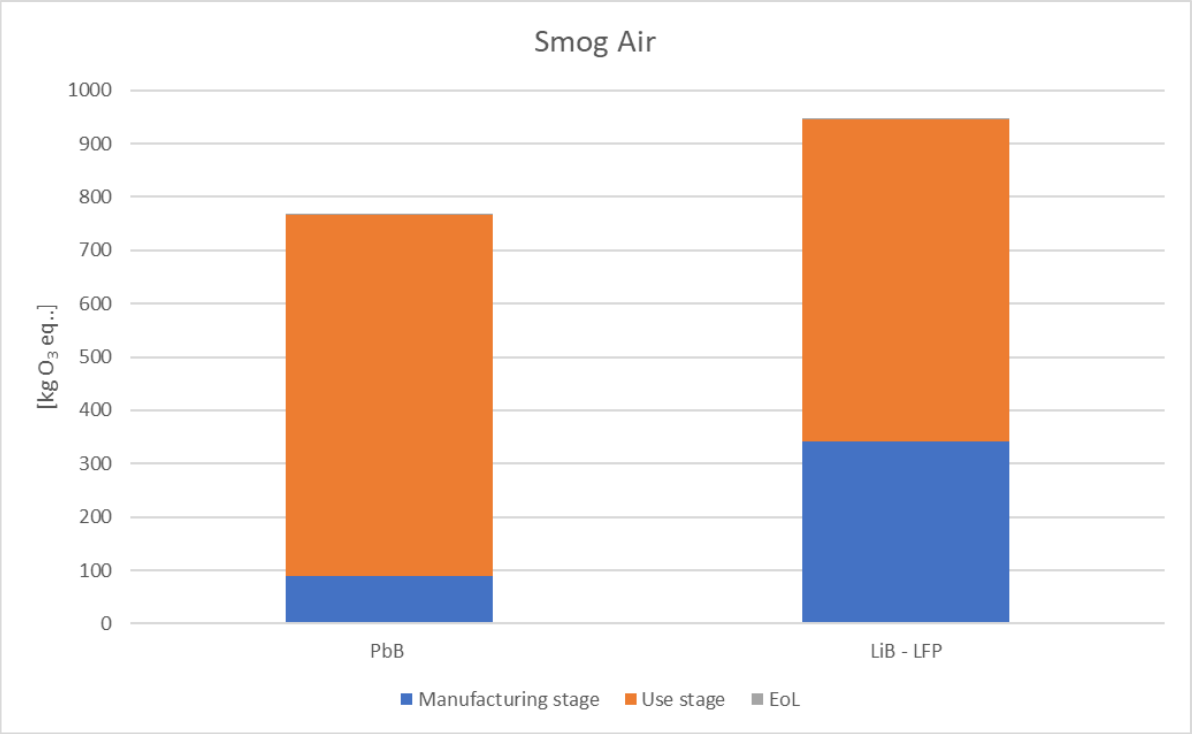

Figure 4-11: Overall Life Cycle Photochemical Smog Formation

In Figure 4-12 the main contributors to the manufacturing stage are displayed.

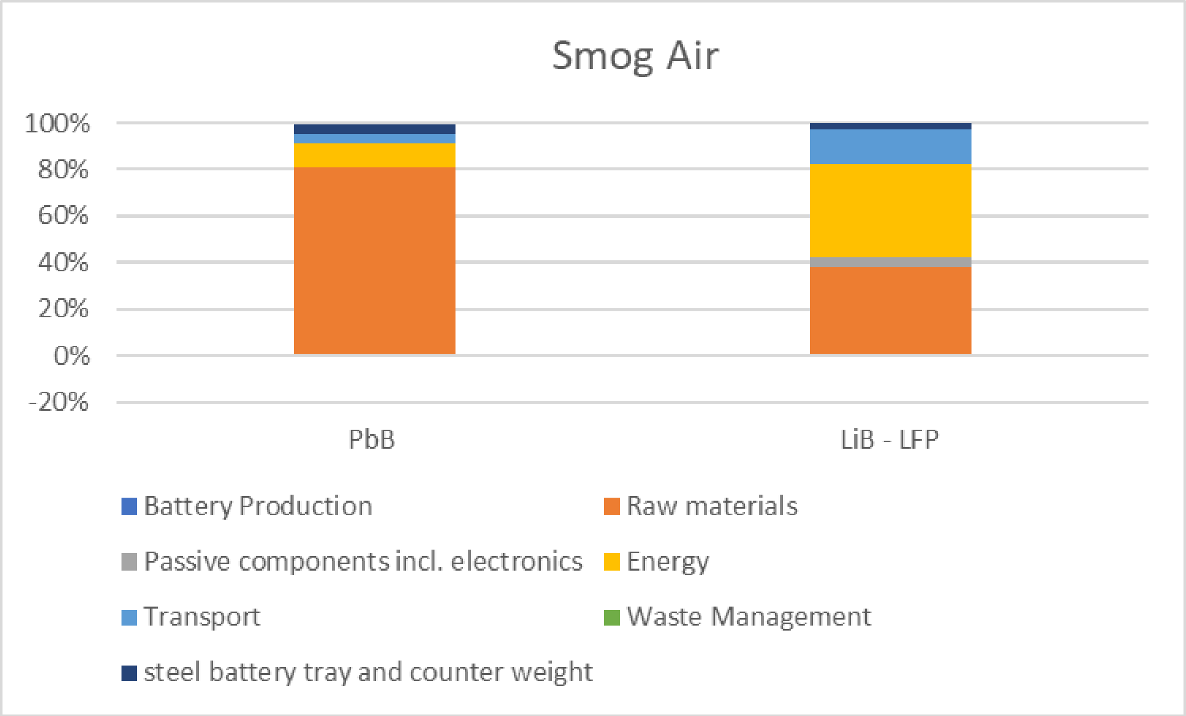

Figure 4-12: Main contributors to the Photochemical Smog Formation (manufacturing stage)

For PbB the manufacturing stage is dominated by the raw materials (approx. 82%) followed by electricity (approx. 10%). In the case of LFP, the raw materials (approx. 38%), the electricity (approx. 40%) and the passive components including electronics (approx. 5%) are the mayor contributors to the manufacturing stage. Other components such steel battery tray and counterweights have a lower contribution to the manufacturing stage results.

4.8. Blue water consumption

In Table 4-10 the Blue water consumption for the lead and LFP batteries is displayed.

Table 4-10: Blue water consumption [kg]

Life Cycle Stage	PbB	LFP
Manufacturing stage	28965	45435
Use stage	236927	211894
EoL	-4248	-1774
Total Life Cycle	**19**	**21**

The use stage dominates the overall results for both battery types. As described in section 3.3, the use stage refers to the electricity consumption considering charging efficiency and battery performance.

In Figure 4-13 the overall results are displayed.

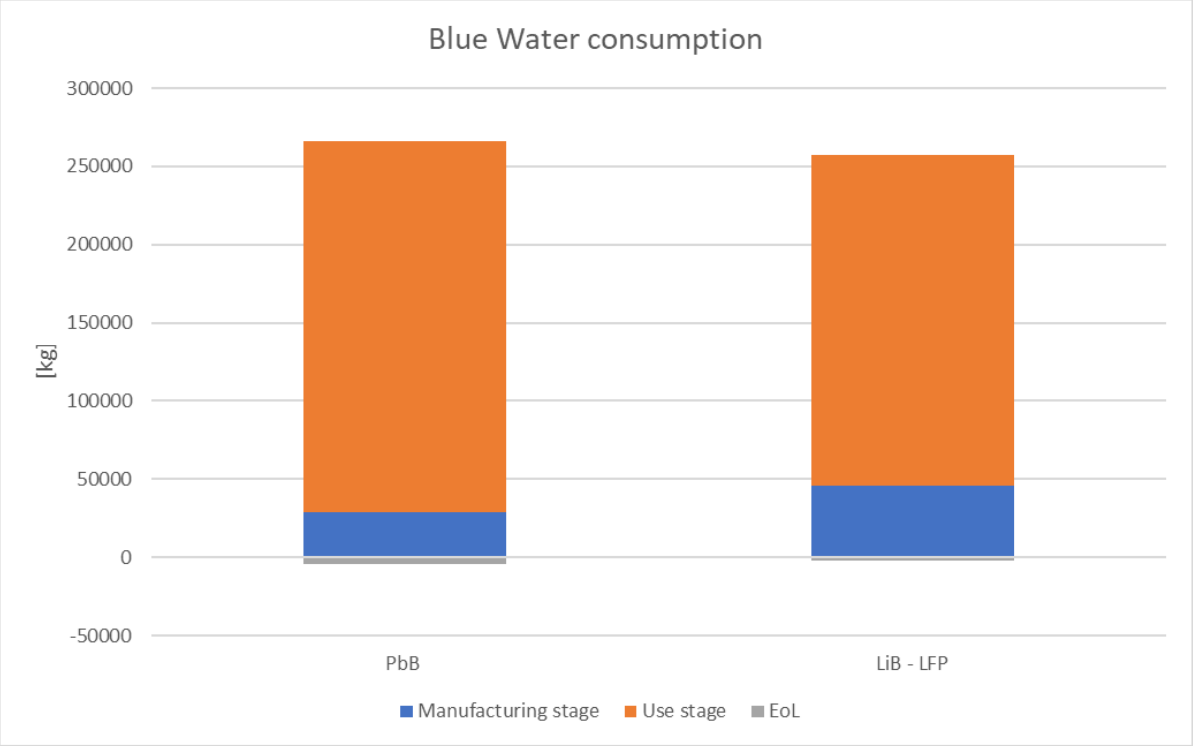

Figure 4-13: Overall Life Cycle Blue water consumption

In Figure 4-14 the main contributors to the manufacturing stage are displayed.

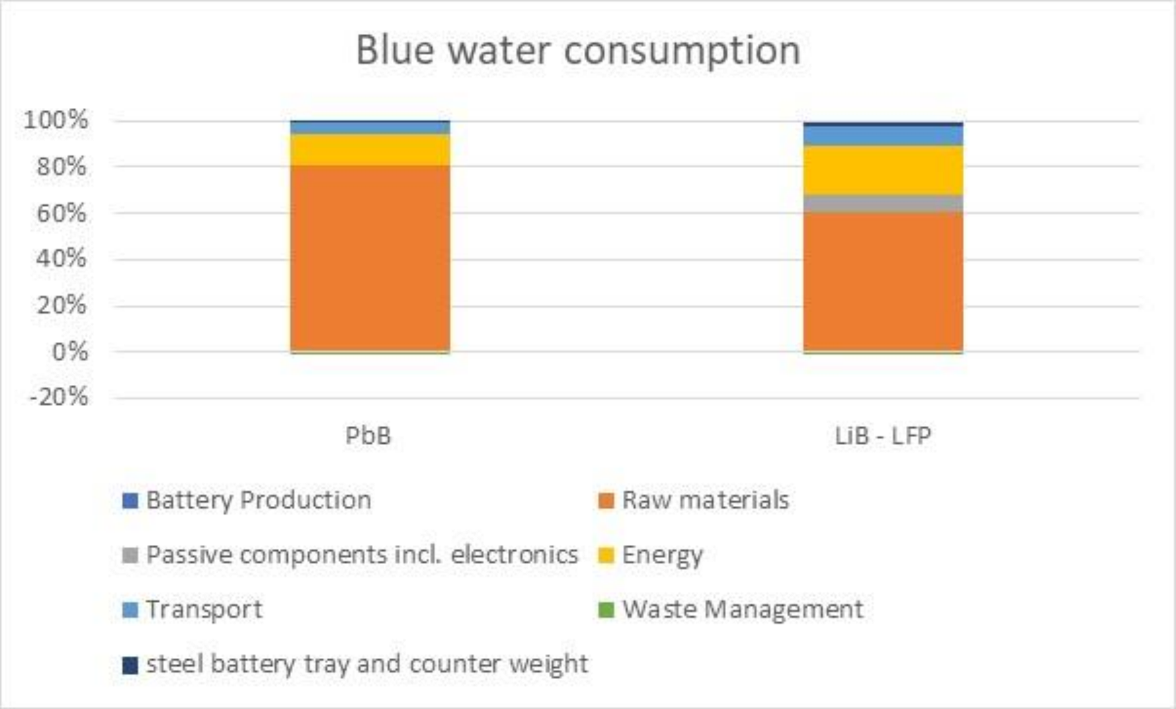

Figure 4-14: Main contributors to the Blue water consumption (manufacturing stage)

For PbB the manufacturing stage is dominated by the raw materials (approx. 81%) followed by electricity (approx. 14%). In the case of LFP, the raw materials (approx. 60%), the electricity (approx. 20%) and the passive components including electronics (approx. 8%) are the mayor contributors to the manufacturing stage. Other components such steel battery tray and counterweights have a lower contribution to the manufacturing stage results.

5. Interpretation

5.1. Identification of Relevant Findings

Based on the assumptions defined for the study, the use stage dominates the overall life cycle for the 2 battery types – PbB and LFP.

In the manufacturing stage, for PbB, lead production and electricity use are most often the primary drivers of impacts. Raw materials like sulfuric acid and plastic parts can also have a noticeable contribution. For LFP batteries, electricity, cell raw materials and passive components with electronics have a higher contribution to the manufacturing stage.

In the EoL, the collection rate is 99% for all battery types and applications (based on an analysis of collection rates seen for automotive lead batteries in the EU). After disassembly, the substitution approach has been applied for PbB where these batteries are recycled in the production of secondary lead on the input side of the production stage. For LFP batteries parts have been disassembled and treated separately having the cells sent to incineration with energy recovery and all other materials; battery case, cabling and electronics send to material recovery with the application of credits accordingly.

Table 5-1 presents a summary of the largest drivers of results. Further details can be found in the sections above.

Table 5-1: Summary of results main contributors for both battery types

Impact category	Main LC contributing to overall results	Main contributor to manufacturing results	Main input/output contributing to overall results
PED	PbB Use stage: 95% LFP Use stage: 85%	PbB Raw materials without electronics 62% / Electricity 36% LFP Raw materials without electronics 33% / Electricity 57% / Passive components with electronics 6%	PbB Non-renewable energy resources 80% LFP Non-renewable energy resources 81%
GWP	PbB Use stage: 92% Manufacturing: 8% LFP Use stage: 80% Manufacturing: 21%	PbB Raw materials without electronics 73% / Electricity 23% LFP Electricity 54% / Raw materials without electronics 37% / Passive components with electronics 5%	PbB Carbon dioxide emission to air 93% LFP Carbon dioxide emission to air 93%
Smog Air	PbB Use stage: 86% Manufacturing: 14% LFP Use stage: 65%	PbB Raw materials without electronics 82% / Electricity 10% LFP	PbB Nitrogen oxides 98% LFP Nitrogen oxides 98%

	Manufacturing: 37%	Electricity 40% / Raw materials without electronics 38% / Passive components with electronics 5%	
AP	PbB Use stage: 81% Manufacturing: 18% LFP Use stage: 66% Manufacturing: 18%	PbB Raw materials without electronics 84% / Electricity 13% LFP Electricity 32% / Raw materials without electronics 49% / Passive components with electronics 7%	PbB Sulfur dioxide 59%, Nitrogen oxides 32% LFP Sulfur dioxide 56%, Nitrogen oxides 35%
EP	PbB Use stage: 89% Manufacturing: 11% LFP Use stage: 58% Manufacturing: 43%	PbB Raw materials without electronics 74% / Electricity 12% LFP Electricity 21% / Raw materials without electronics 70% / Passive components with electronics 3%	PbB Nitrogen oxides 35%, Emission to fresh water 63% LFP Nitrogen oxides 30%, Emissions to freshwater 68%
Human Health Impacts from Exposure to Particular air	PbB Manufacturing: 32% Use stage: 68% LFP Manufacturing: 48% Use stage: 54%	PbB Raw materials without electronics 90% LFP Electricity 25% / Raw materials without electronics 60% / Passive components with electronics 5%	PbB sulfur dioxide 46%, Dust (PM 2,5) 38% LFP Sulfur dioxide 42%, Dust (PM 2,5) 38%

5.2. Assumptions and Limitations

The main limitation between the data used for both battery types have to do with the data origin, lead-based battery data are an industry average while LFP is literature based but validated by several experts from the battery and automotive sector. (see section 2.1).

To cover the data gap of waste generation during manufacturing LFP batteries, the waste treatment assuming a weight increase of 5% of all cell components mass amounts and 3% for passive components and electronics has been included in the model and results. This approach has been taken from the PEFCR of rechargeable batteries[16]. The same reference has been taken to include the manufacturing electricity, water, auxiliary materials, and emissions.

At the EoL stage a collection rate of 99% has been applied for LFP and lead-based batteries. While all old lead batteries on the market are taken back and recycled by manufacturers, there is a small amount which has been assumed to be untreated, accounting for any batteries not received after being used (due to the ‘hoarding effect.).).

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[16] Page 72: https://ec. europa. eu/environment/eussd/smgp/pdf/PEFCR_Batteries. pdf

Uncertainties associated with the assumptions on the recyclability of LFP battery, battery and forklift lifetime and material of the counterweight have been assessed via the sensitivity analysis in the sections below.

The study is limited to the North America market.

In the context of this study, the toxicity of Lead in batteries has not been covered. It is suggested to evaluate this topic in a specific study to evaluate the impact to health and environment.

5.3. Sensitivity Analysis Results

Sensitivity analyses were performed to test the variation of the results towards changes in parameter values that are based on assumptions or otherwise uncertain. Global warming potential has been selected for the analysis of these results.

5.3.1. Material for counterweight

A sensitivity analysis comparing the different possible materials for the counterweight, such as concrete and cast iron against the baseline material steel for the counterweight has been analyzed. As shown in Figure 4-4, 3% of the total impact in the manufacturing stage is due to the counterweight (1,7 %) and steel battery tray (1,3 %).

Table 5-2: Sensitivity counterweight material

	Manufacturing stage GWP [kgCO2 eq.]	**Deviation [%]**
EAF steel billet	6829	baseline
Concrete bricks	6753	-1%
cast iron	7345	8%

The selection of the material of the counterweight for the LFP battery can have an impact on the manufacturing stage results as described in Table 5-2 although in the overall life cycle results is negligible.

5.3.2. Recycling versus reuse of counterweight in the EoL

In the baseline scenario, it was assumed that the counterweight was recycled in the EoL, although it could be reused.

In the case the counterweight is reused, the EoL stage decreases by factor 3, i.e., the credit is higher.

Table 5-3: Recycling versus reuse of counterweight

	Global Warming Potential [kg CO_2 eq.]		
	PbB	LFP (baseline)	LiB-LFP (reuse)
EOL battery (including electronics)	16	-3	-3
Recycling steel tray	-49	-49	-49

	Global Warming Potential [kg CO_2 eq.]		
Recycling counter (steel)		35	0
total	-33	-17	-52

5.3.3. Forklift lifetime increase

The functional unit considers the quantity of batteries to fulfill the forklift lifetime. As described in chapter 0, the baseline scenario considers 10 years lifetime for the forklift, although references also indicate that the lifetime of the forklift depends on the operational behavior. Therefore, a scenario increasing the lifetime of the forklift to 15 years has been calculated. The table below shows the number of batteries needed to fulfill this lifetime for lead based and LFP batteries.

Table 5-4: Battery reference flows per Functional Unit (forklift lifetime increase)

Battery type		Battery weight (kg)	Life span battery (years)	No. of batteries forklift lifetime (10 yr.)	No. of batteries forklift lifetime (15 yr.)
Motive Power (battery)	PbA	700	6	1,67	2,5
	LFP	300	10	1	1,5

Table 5-5: Global Warming Potential [kg CO_2 eq.] – forklift lifetime sensitivity

	PbB	LFP	Div- %
lifetime 10 yr.	30424	31998	-5%
lifetime 15 yr.	45378	47912	-6%

The results in Table 5-5 show that even though the lifetime of the forklift increases, the total life cycle of the Lead Batteries is slightly lower. This is due to the low impact in the manufacturing of the Lead Batteries that compensate the higher energy consumption at the use stage.

5.3.4. EoL approach scenario

As described in section 2.4.3, there are two main EoL approaches commonly used in LCA studies to account for end-of-life recycling and recycled content. In Table 5-6 the baseline substitution approach, (also known as 0:100, closed-loop approximation, recyclability substitution or end of life approach) is compared with the cut-off approach (also known as 100:0 or recycled content approach).

Table 5-6: Global Warming Potential [kg CO_2 eq.] – EoL approach

Total GWP (CO_2 eq.) results per FU - EoL approach scenario

		EoL Baseline (with recovery)	EoL scenario (Cut-off)	Variation %
	PbB	30424	30460	<0
	LFP	31998	32330	<1

The results in Table 5-6 show that for the batteries in the forklift application the variation between the two EoL approaches is very low. The recovery of materials is a very important step in the EoL of product, it avoids the use of more raw materials and increases the efficiency in the use of material and energy resources avoiding disposal in landfills. The defined EoL approach baseline considers the most representative of current reality available for the batteries studied.

5.4. LFP End of Life Scenario Analysis

Unlike sensitivity analyses, scenario analyses compare results between discrete sets of parameter settings or model choices. A scenario has been tested to address the potential recovery of materials from the LFP cells, currently the base scenario considers its incineration with energy recovery as no commercial material recovery is available.

As a second scenario for optimizing the recycling of LFP cells Sphera worked together with Prof. Dr Markus Reuter from Helmholtz Institute in Freiberg, a metallurgist, and built up a simulation model in the HSC Sim 10 tool I[17]. The software enables metallurgists or plant designers to simulate all metallurgical processes and infrastructures. It is a thermodynamic model used to identify mass streams as well as energy consumption and losses.

The general potential recycling anticipated with existing process technology is a physical and pyrometallurgical process. In the flow chart Figure 5-1 and Figure 5-2, we have had a second option to recover $LiFePO_4$ which was not considered in the baseline scenario but can be added at a later stage. The focus in this scenario is to recover the lithium in form of lithium carbonate. The Figure 5-1 shows the idealized physical crushing (under inert atmosphere) to remove the casing and then the application of pyrolysis that removes the moisture and decomposes the electrolyte (which is rather different for different battery designs and thus difficult to recycle). As a comparison, the calcined carbon rich material is split 50:50 into a pyrometallurgical route (which uses the carbon as reductant as well uses the CO in the off gas to fuel the kiln) and then processes the slag and treatment of the calcined material in the hydrometallurgical process.

The lithium rich slag will then go into the spodumene process as an example of a processing possibility. The lithium slag has a lithium content of around 6% and is treated via crushing, calcination, sulfuric acid digestion, leaching, and filtering after precipitation to produce the Li_2CO_3. This route was chosen as an example however, in a normal recycling process, there exist various impurities in products that contaminate the final products and residues; this adds an additional purification cost to make the products and residues usable in batteries once again.

The produced waste streams are assumed to be landfilled because it was not possible to prove the economic viability of treating the waste streams to recover minor substances. The mapping of all materials and compounds provides a clear overview of the direction and distribution of these materials, facilitating

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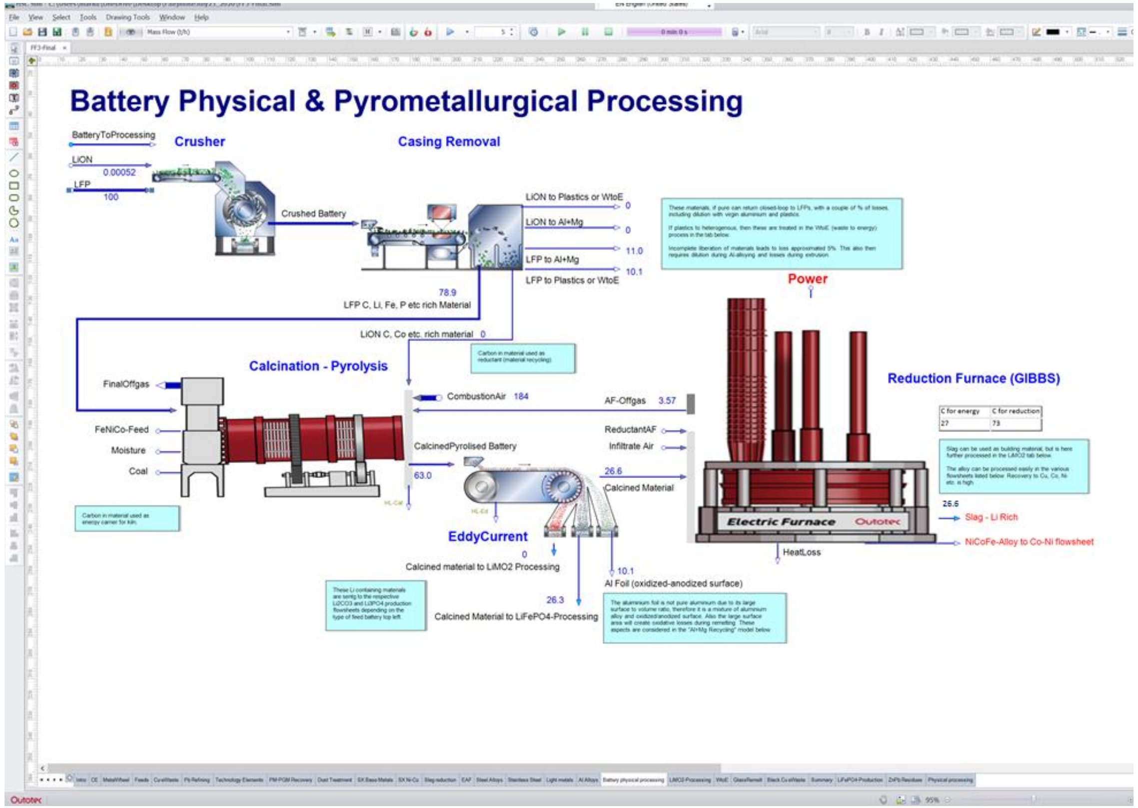
[17] https://www.metso.com/portfolio/hsc-chemistry/

an assessment of the potential for further processing of the complex mixtures, both from a technological and economic standpoint. A detailed simulation and engineering level study is required to determine the limitations and possibilities.

To summarize, a very large simulation model for any module from consumer electronics (220 reactors, 60 elements and all their compounds, 1000 materials, 1000 streams) is an indication of the true recyclability of products and in this case, batteries.



These materials, if pure can return closed-loop to LFPs, with a couple of % of losses, including dilution with virgin aluminium and plastics.

If plastics to heterogenous, then these are treated in the WtoE (waste to energy) process in the tab below.

Incomplete liberation of materials leads to loss approximated 5%. This also then requires dilution during Al-alloying and losses during extrusion.

Carbon in material used as reductant (material recycling)

Carbon in material used as energy carrier for kiln.

C for energy	C for reduction
27	73

Slag can be used as building material, but is here further processed in the LiMO2 tab below.

The alloy can be processed easily in the various flowsheets listed below. Recovery to Cu, Co, Ni etc. is high.

These Li containing materials are senitg to thei respective Li2CO3 and Li3PO4 production flowsheets depending on the type of feed battery top left.

The aluminium foil is not pure aluminium due to its large surface to volume ratio, therefore it is a mixture of aluminium alloy and oxidized/anodized surface. Also the large surface area will create oxidative losses during remelting. These aspects are considered in the "Al+Mg Recycling" model below.

Figure 5-1: LFP Battery Physical and Pyrometallurgical Processing[18]

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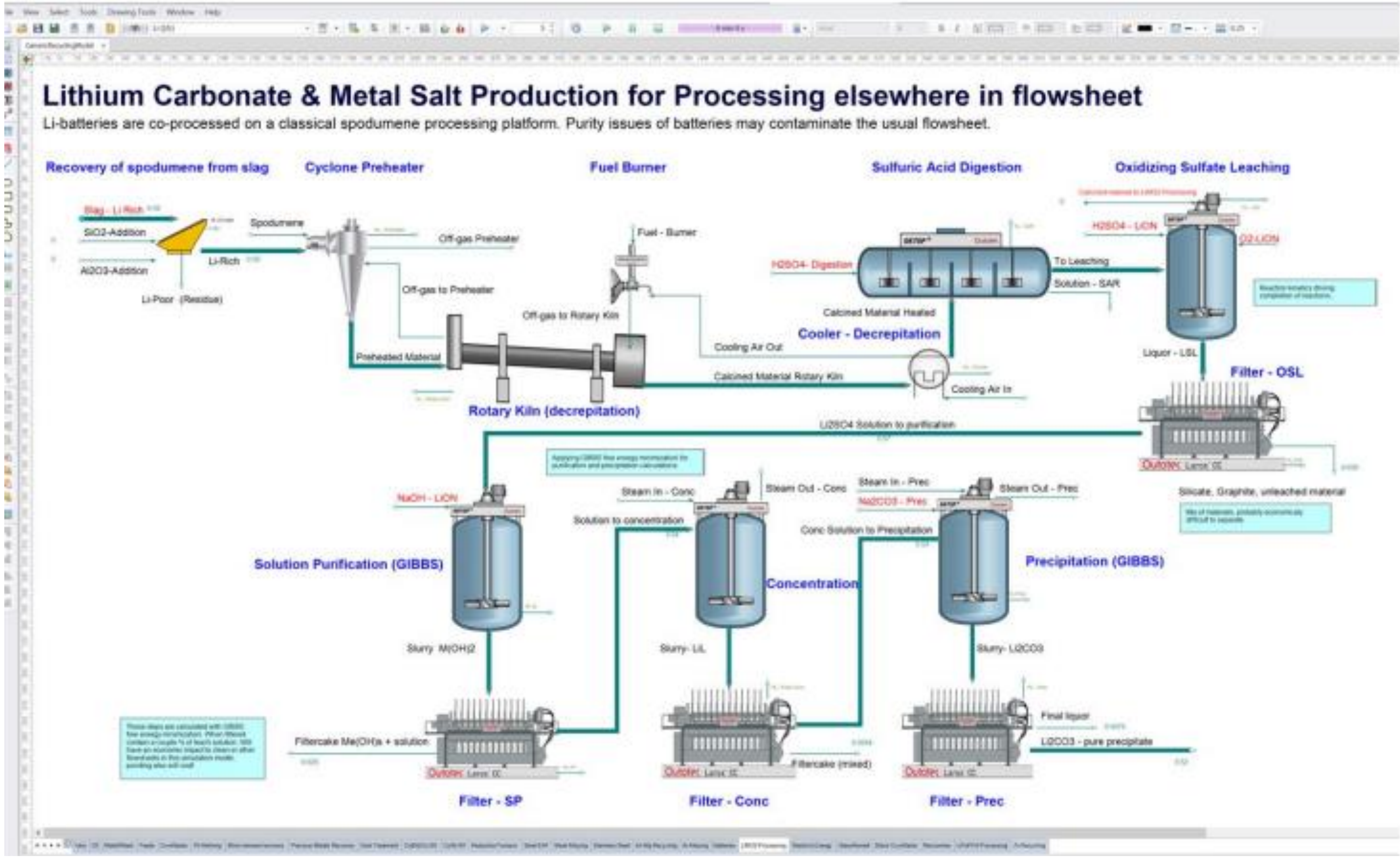
[18] https://www.metso.com/portfolio/hsc-chemistry/



Lithium Carbonate & Metal Salt Production for Processing elsewhere in flowsheet

Li-batteries are co-processed on a classical spodumene processing platform. Purity issues of batteries may contaminate the usual flowsheet.

Figure 5-2: Lithium Carbonate and Metal Salt Production[19]

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[19] https://www.metso.com/portfolio/hsc-chemistry//

Table 5-7: End of Life Cycle – LFP Battery Recovery Scenario Components Treatment

Cell / battery component	Amount	Unit	EoL Treatment	Credits
ANODE				
Copper foil	28,35	kg	copper scrap remelted	copper 99,99%
Graphite	28,35	kg	used as energy source in calcination process (see Figure 5-1).	none
CATHODE				
Al	17,85	kg	The foil is 50% oxidized and the remaining is remelted with the Al casing	credited with the most common casting alloy $AlSi_9Cu_3$
LFP	66,15	kg	Lithium carbonate is recovered, and the waste goes to landfill	Li_2CO_3 from Brine in Chile, as it has the biggest market share
Carbon black	3,15	kg	used as energy source in calcination process (see Figure 5-1).	None
Binder (PVDF)	3,15	kg		
ELECTROLYTE				
EC/DMC	36,75	kg	waste to landfill	None
$LiPF_6$	7,35	kg	waste to landfill	
SEPARATOR				
PP	29,4	kg	used in reduction furnace and lands in slag which will be treated in Spodumene process	None
CELL CASE, FOIL POUCH				
Al foil	31,5	kg	recovery via remelting to cast alloy	credited with the most common casting alloy $AlSi_9Cu_3$
BATTERY CASE				
PP	21	kg	recycling plastic granulate	virgin PP granulate

In the Table 5-8, the baseline scenario, which uses mainly incineration, is not as advantageous for CO_2 equivalent as the material recovery of this scenario. As described above, the main credits are given for the material recovery and the remaining waste from the hydrometallurgical filter processes (which is the smaller part) as well as slag. Only inert landfilling is considered. The recycling rate increases from 15% (baseline scenario) to 63%.

Table 5-8: End of Life Cycle – LFP Battery Recovery Scenario Results

Impact/ Indicator	EoL baseline	EoL scenario	Variation (factor)
GWP [kg CO2 eq.]	-17	-429	25
PED [MJ]	-3985	-7534	2
Acidification [kg SO2 eq.]	-0,024	-4,1	171

Impact/ Indicator	EoL baseline	EoL scenario	Variation (factor)
Eutrophication [kg N eq.]	-0,015	-0,71	47
Human Health Impacts from Exposure to Particulate Matter, [kg PM2.5 eq.]	-0,107	-0,24	2
Photochemical Smog Formation [kg O3 eq.]	0,697	-24	-34
Blue water consumption [kg]	-1774	-2573	1

The results show that the considered system boundaries are advantageous in performing material recovery, but the main mass stream is going into waste due to complexity and low value of processing back into battery grade materials. Aluminum foils are highly oxidized, i.e., there is low metal content and is hardly recoverable. Copper is best recovered as an alloy via the hydrometallurgical route because it must be leached and then recovered after purification of the electrolyte via energy intensive electrowinning. The pyrometallurgical route would make electrorefining possible, which is much more energy efficient. This study did not expand to prove the economic viability of treating the waste to get materials like iron (Fe) or phosphate out of the waste stream. This is a limitation as well as a totally separate study with a higher effort than covering the recycling of lithium carbonate.

As shown in Table 5-8, the EoL scenario shows an important impact on the EoL results, decreasing the results in the EoL stage by factors between 2 and 171. These results are due to the higher recycling rate (63%) in the EoL scenario compared to the baseline EoL scenarios (15%) and the cell treated as hazardous waste.

As shown in Table 5-9, the total life cycle results of both scenarios compared to the Lead battery, show lower differences. The Lead battery continues to have a lower impact (2%-24%) depending on the indicator.

Table 5-9: Life Cycle results baseline scenarios versus EoL scenario

Impact / Indicator	PbB	LFP	Dev. -%	PbB	LFP with cell recycling	Dev. -%
GWP [kg CO2 eq.]	30424	32307	-6%	30424	31895	-5%
PED [MJ]	592196	606982	-2%	592196	603433	-2%
Acidification [kg SO2 eq.]	66	76	-16%	66	72	-9%
Eutrophication [kg N eq.]	3,8	5,4	-41%	3,8	5	-24%
Human Health Impacts from Exposure of Particulate Matter [kg PM2.5 eq.]	5,1	6,1	-21%	5,1	6	-17%
Photochemical Smog Formation [kg O3 eq.]	767	946	-23%	767	922	-20%
Blue water consumption [kg]	261644	255555	2%	261644	254757	3%

5.5. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied), and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the Sphera 2022.1 database were used. The LCI datasets from the Sphera 2022.1 database are widely distributed and used with the Sphera LCA for Experts Software. The datasets have been used in LCA models worldwide in industrial and scientific applications internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.5.1. Precision and Completeness

- ✓ **Precision:** As most of the relevant foreground data are measured, calculated and literature based on primary information sources of the owner of the technology, precision is considered to be very good for lead-based batteries. In the case of LFP battery, foreground data are literature based and complemented with expert judgement of the sector such as (May, FOCUS Consulting, 2022) and (BCI, 2020), therefore the precision is considered to be representative. All background data are sourced from Sphera databases with the documented precision (Sphera Solutions Inc., 2022).

- ✓ **Completeness:** Each foreground process was checked for mass and energy balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is good for lead-based batteries and good for the LFP battery. All background data are sourced from Sphera databases with the documented completeness (Sphera Solutions Inc., 2022).

5.5.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail for PbB. In the case of LFP battery, theoretical published data[20] has been used since there was no primary data available, but the data were reviewed and ensured by Dr. Geoffrey May and BCI, therefore the consistency of the results can be seen as good. All background data were sourced from the Sphera databases.

- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modelling approaches.

5.5.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the year 2017. Most secondary data come from the Sphera 2022.1 databases and are representative of the years 2015 - 2021. As the study intended to compare

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[20] (Recharge, 2018)

the product systems for the reference year 2021, temporal representativeness is considered to be very good.

- ✓ **Geographical:** All primary and secondary data were collected as far as possible to specific to the countries or regions under study, as described in chapter 3.5. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be very good for PbB and good for LFP batteries.
- ✓ **Technological:** The majority of primary and secondary data were modelled as far as possible to be specific to the technologies or technology mixes under study, as described in chapter 3.5. Where technology-specific data was unavailable, proxy data were used. Technological representativeness is considered to be very good for PbB and good for LFP batteries.

5.6. Model Completeness and Consistency

5.6.1. Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed regarding the goal and scope of this study.

5.6.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimized by exclusively using LCI data from the Sphera 2022.1 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.7. Conclusions, Limitations, and Recommendations

5.7.1. Conclusions

This study represents a comparative LCA for motive battery applications. Two 48 V, 500 Ah motive power battery chemistries have been analyzed, lead-based batteries and LFP for use in a forklift. The lead-based batteries are produced in North America and the LFP cells are produced in China with a final battery assembly in North America. It is assumed that all batteries are used in forklifts placed on the market in North America and batteries at end-of-life are treated in North America recycling facilities.

The lead battery data used is representative as it is industry data representing 85% of the production volume for those technologies in NORTH AMERICA. As for LFP batteries, no primary data were available so some inconsistencies in the data quality are inevitable. However, efforts have been made to ensure that the BoM of

LiB-LFP batteries are as representative as possible. They are based on established references and the best available data validated by battery experts[21] and motive power and battery related stakeholders[22].

To account for the complete life cycle, the use and EoL phases of the batteries were modelled in the study. For the use stage it has been assumed that batteries are discharged to 80% of nominal capacity (19,2 kWh), 5 days per week, 50 weeks per year (meaning 260 cycles per year). Although modern chargers protect batteries from overcharging, and so, enabling a charging efficiency in Lead batteries of 90%, for the baseline of this study an 85% of charging efficiency has been assumed. This means that the annual energy consumption of the Lead batteries is 5,9 MWh. Notwithstanding, charging efficiency for LFP batteries has been assumed to be 95%, and so an annual energy consumption of 5,3 MWh. Therefore, the annual energy consumption of the Lead batteries against LFP batteries is 11% higher in this study.

For the EoL lead and LFP batteries, an EoL collection rate of 99 % was used. For LFP batteries, two EoL scenarios were considered: the first includes the incineration of the cell (with energy generation) and recycling for electronics and passive components and the second where a recycling scenario involves recovery of the lithium in form of lithium carbonate as well as other cell materials recovery such as Aluminum and Copper an PP. Besides that, the recycling rate of the LFP battery increases from 15% to approx. 60%, in the additional scenario, the Lead battery continues to have lower impact taking into consideration the whole Life Cycle (2% - 24%).

Key conclusions from the study over the complete life cycle from cradle-to-grave can be summarized as such: between all batteries assessed and for most impact categories, the differences in the results are small. Given the uncertainties associated with modelling assumptions, results are not significantly different; for the reference flow of 10 years lifetime of the forklift. The energy consumption of the PbB in the use stage is by 11% higher. However, when the whole life cycle of both batteries is compared the differences are insignificant (1% in PED and 5% GWP).

Results show a negligible effect by increasing the lifetime of the forklift from 10 years to 15 years.

The sensitivity analysis regarding the impact of the material of the counterweight in the case of the LFP show that cast iron could increase the results on the manufacturing stage by 8% while concrete could reduce by 1% in comparison to the baseline material steel billet[23].

In the following paragraphs, the results are discussed for the individual life cycle stages.

In the manufacturing stage, the main / dominant contributor are the raw materials with around 73% of the GWP for the lead batteries and Electricity with approx. 54% followed by the raw materials with approx. 37% for the LFP batteries. Furthermore, a significant contributor to the LFP manufacturing impact is the manufacturing of the Battery Management System (BMS) that is required to ensure functional safety.

Under the baseline scenario described in 2.1, the environmental impact of LFP battery manufacturing is about 3 times higher than the impact of manufacturing equivalent lead batteries.

An advantage of lead batteries is that 68% of the raw material present in the battery is recycled lead-thus reducing the environmental impact; however, LFP batteries only utilize primary materials including lithium carbonate and phosphorus as well as electronics using precious metals (which are recovered).

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[21] (May, FOCUS Consulting, 2022)
[22] (BCI, 2020)
[23] Counterweight contributes to 1,7 % of the total manufacturing stage in the GWP.

The use phase was addressed in this life cycle assessment by considering the differences in battery charging efficiency. Due to the added counterweight (400 kg) in the case of the LFP, weight has no influence on the results.

The EoL phase has a smaller influence on the total life cycle results (contribution of -1%--14% per impact category) than the manufacturing and use phases). Adding the potential future recycling scenario that involves recovery of the lithium in form of lithium carbonate does not significantly alter this result despite additional life cycle benefits for LFP.

Overall, the study highlights that lead battery manufacturing has a lower environmental impact compared to LiB - LFP.

5.7.2. Limitations and Recommendations

The results of this study are only applicable to lead and LFP batteries used in NORTH AMERICA for the specific motive power applications described. Even for this use case, the lack of primary data for LFP and the assumptions taken on battery weights, compositions and performance must be reflected in interpreting the representativity of the results.

It may not be appropriate to extrapolate these results to other regions, especially if there are significant differences in lead battery recycling rates, energy grid mixes, etc. In addition, LFP is not representative of all lithium battery chemistries and the results for other types of Li-ion batteries could be significantly different.

A combined scenario where all sensitivity analysis parameters are analyzed together might provide a better insight on the uncertainty around LFP batteries parameters.

In the baseline scenario, a recycling rate of approximately 30% has been applied. .In the future it may be possible to recover more of the LFP battery materials and as such, the study includes an LFP end-of-life scenario analysis that is described in section 5.4 that uses simulations and thermodynamic modelling to predict what is theoretically technically possible (not taking into considerations of economics).

This study shows that:

- Most impact categories showed small differences between both batteries assessed, with lead batteries performing better in the baseline scenario due to lower burdens in the manufacturing (2 to 6 times lower) depending on the impact category.
- The study highlights challenges in recycling lithium-ion battery waste and is limited by the lack of economic viability analysis for recovering materials like iron and phosphate.

It is recommended to:

- Study Lithium-ion battery types comprising cathode materials other than LFP.
- Study LiB – LFP with primary industry data rather than relying on secondary information from the available literature.

Assess a comparative human health risk assessment of the mining, manufacturing, and EOL of the two battery technologies as this is a limitation of the LCA methodology.

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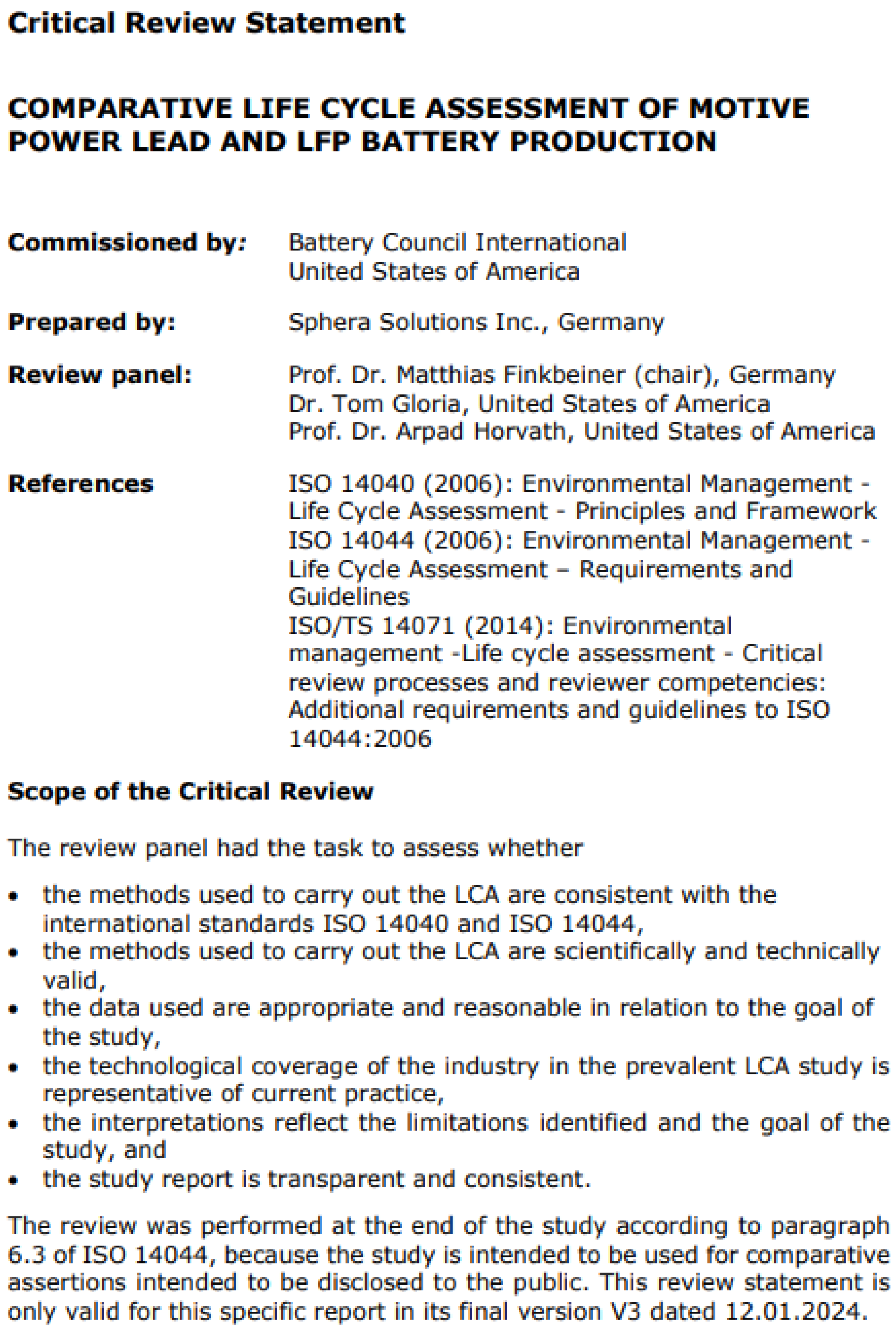
Annex A: Review Statement



Critical Review Statement

COMPARATIVE LIFE CYCLE ASSESSMENT OF MOTIVE POWER LEAD AND LFP BATTERY PRODUCTION

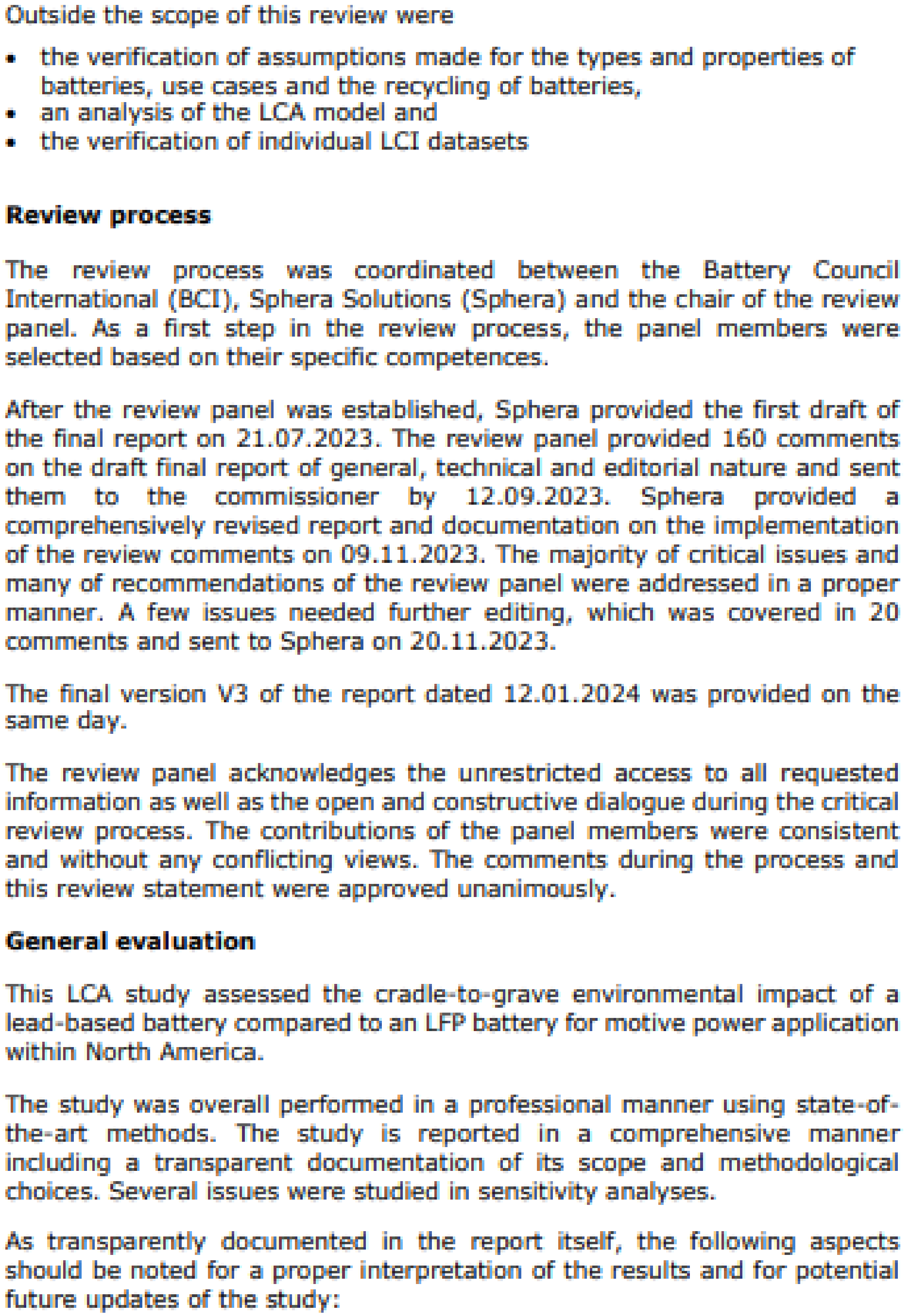
Commissioned by:	Battery Council International United States of America
Prepared by:	Sphera Solutions Inc., Germany
Review panel:	Prof. Dr. Matthias Finkbeiner (chair), Germany Dr. Tom Gloria, United States of America Prof. Dr. Arpad Horvath, United States of America
References	ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework ISO 14044 (2006): Environmental Management - Life Cycle Assessment – Requirements and Guidelines ISO/TS 14071 (2014): Environmental management -Life cycle assessment - Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

Scope of the Critical Review

The review panel had the task to assess whether

- the methods used to carry out the LCA are consistent with the international standards ISO 14040 and ISO 14044,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the technological coverage of the industry in the prevalent LCA study is representative of current practice,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

The review was performed at the end of the study according to paragraph 6.3 of ISO 14044, because the study is intended to be used for comparative assertions intended to be disclosed to the public. This review statement is only valid for this specific report in its final version V3 dated 12.01.2024.



Outside the scope of this review were

- the verification of assumptions made for the types and properties of batteries, use cases and the recycling of batteries,
- an analysis of the LCA model and
- the verification of individual LCI datasets

Review process

The review process was coordinated between the Battery Council International (BCI), Sphera Solutions (Sphera) and the chair of the review panel. As a first step in the review process, the panel members were selected based on their specific competences.

After the review panel was established, Sphera provided the first draft of the final report on 21.07.2023. The review panel provided 160 comments on the draft final report of general, technical and editorial nature and sent them to the commissioner by 12.09.2023. Sphera provided a comprehensively revised report and documentation on the implementation of the review comments on 09.11.2023. The majority of critical issues and many of recommendations of the review panel were addressed in a proper manner. A few issues needed further editing, which was covered in 20 comments and sent to Sphera on 20.11.2023.

The final version V3 of the report dated 12.01.2024 was provided on the same day.

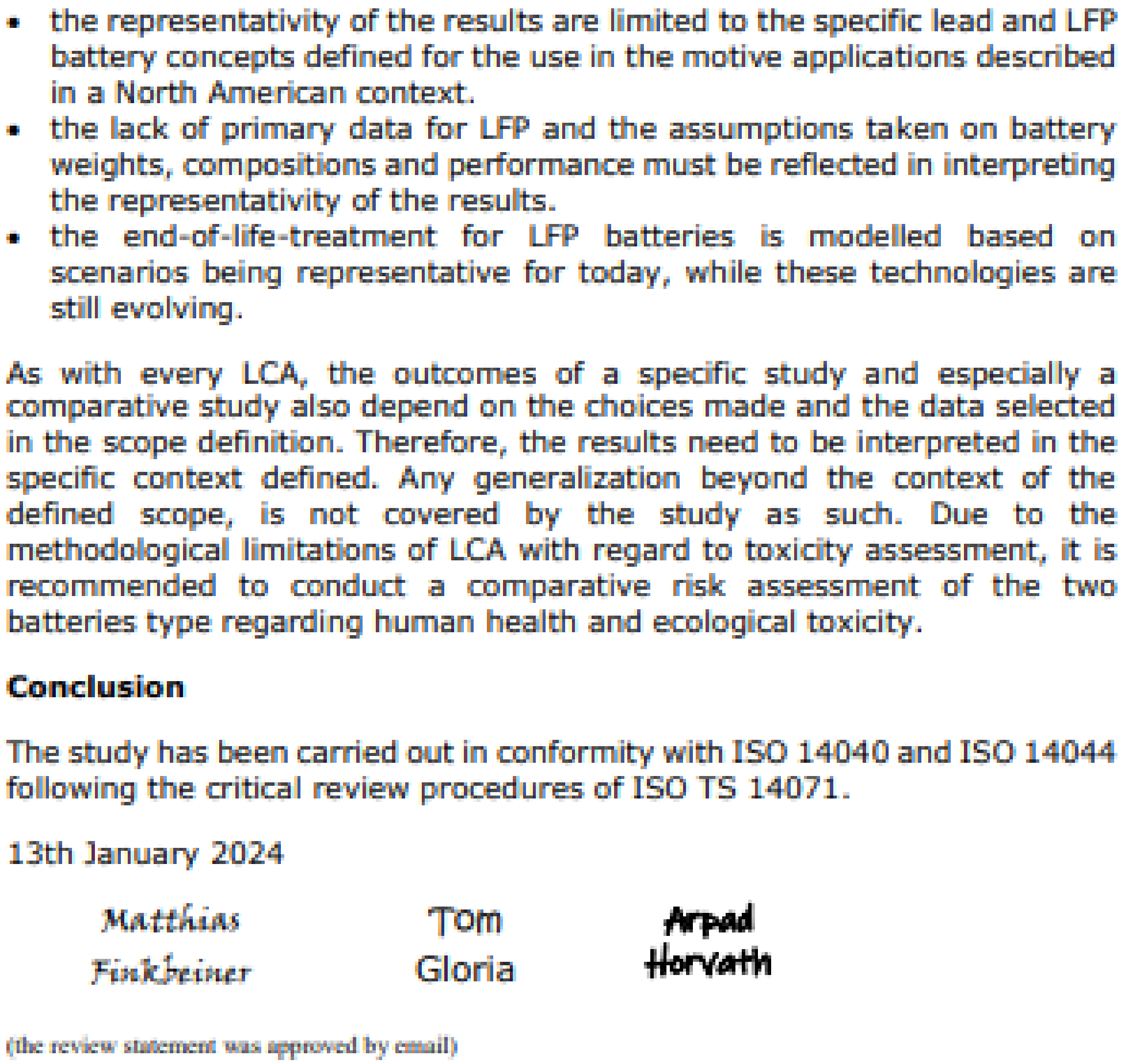
The review panel acknowledges the unrestricted access to all requested information as well as the open and constructive dialogue during the critical review process. The contributions of the panel members were consistent and without any conflicting views. The comments during the process and this review statement were approved unanimously.

General evaluation

This LCA study assessed the cradle-to-grave environmental impact of a lead-based battery compared to an LFP battery for motive power application within North America.

The study was overall performed in a professional manner using state-of-the-art methods. The study is reported in a comprehensive manner including a transparent documentation of its scope and methodological choices. Several issues were studied in sensitivity analyses.

As transparently documented in the report itself, the following aspects should be noted for a proper interpretation of the results and for potential future updates of the study:



- the representativity of the results are limited to the specific lead and LFP battery concepts defined for the use in the motive applications described in a North American context.
- the lack of primary data for LFP and the assumptions taken on battery weights, compositions and performance must be reflected in interpreting the representativity of the results.
- the end-of-life-treatment for LFP batteries is modelled based on scenarios being representative for today, while these technologies are still evolving.

As with every LCA, the outcomes of a specific study and especially a comparative study also depend on the choices made and the data selected in the scope definition. Therefore, the results need to be interpreted in the specific context defined. Any generalization beyond the context of the defined scope, is not covered by the study as such. Due to the methodological limitations of LCA with regard to toxicity assessment, it is recommended to conduct a comparative risk assessment of the two batteries type regarding human health and ecological toxicity.

Conclusion

The study has been carried out in conformity with ISO 14040 and ISO 14044 following the critical review procedures of ISO TS 14071.

13th January 2024

Matthias Finkbeiner
Tom Gloria
Arpad Horvath

(the review statement was approved by email)