On behalf of BCI and ILA

Comparative LCA of Lead and LFP Batteries for Automotive Applications

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On behalf of Sphera Solutions Inc. and its subsidiaries

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List of Acronyms and Abbreviations

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
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
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
LCI / LCIA	Life Cycle Inventory / Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LiB	Lithium-ion Battery
LFP	Lithium Iron Phosphate
MPV	Multi-Purpose Vehicles
NMVOC	Non-Methane Volatile Organic Compound
PbB	Lead battery / Lead-based battery
PED	Primary Energy Demand
PEFCR	Product Environmental Footprint Category Rules

PP	Polypropylene
POCP	Photochemical Ozone Creation Potential
PVDF	Polyvinylidene fluoride
RNA	Region North America
SLI	Starting, Lighting, and Ignition
VRLA	Valve Regulated Lead Acid Battery
VOC	Volatile Organic Compound

Glossary

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 3.1 7)

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 analysed 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 the 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).

Proxy data

Data used to study a situation, phenomenon or condition for which no direct information - such as instrumental measurements - is available. ” (ISO 14044:2006, section 4.2).

Executive Summary

Goal of the Study

The goal of the study is to assess the comparative life cycle environmental profile of two different batteries used in the automotive sector. This study assesses the cradle-to-grave environmental impact of lead-based (PbB) automotive battery compared to a Lithium-ion Phosphate (LFP) automotive 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 LiB - LFP. This benefit is maintained in the baseline scenario during the full life cycle for conventional ICE battery applications – despite the higher weight and associated use phase burdens of lead battery.

The batteries assessed in this study are used in internal combustion engines (ICE), start-stop and micro-hybrid vehicles. Based on the assumptions defined for the study, the use stage dominates the overall life cycle for all battery types (Pb and LFP) particularly for start-stop and micro-hybrid due to the fuel saving properties of these vehicles. Lead batteries have a higher weight compared to the LFP batteries, which leads to an increase in fuel consumption. This effect is especially visible for the conventional ICE vehicles using standard lead batteries vs LFP batteries.

Figure 1-1 displays the overall GWP per battery technology and vehicle type. It can be appreciated that PbB have a lower impact than LFP to the Global Warming potential in the three batteries types under the assumptions taken in the baseline scenario of the study.

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

In the manufacturing stage for PbB, lead production and electricity use are most often the primary drivers of impacts. Sulfuric acid and plastic parts can also have a noticeable contribution. For LFP batteries, cell raw materials and electronics have a higher contribution to the manufacturing stage, while crash protection and car cabling have minor contributions to all impact categories analysed. Under the baseline scenario described in Table 2-3, the environmental impacts of manufacturing the LFP battery compared to manufacturing the lead-based battery are roughly greater by a factor of 4.At EoL, the collection rate is set to 99% for PbB and LFP within the analysed applications (BCI, 2019),.[2] 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.

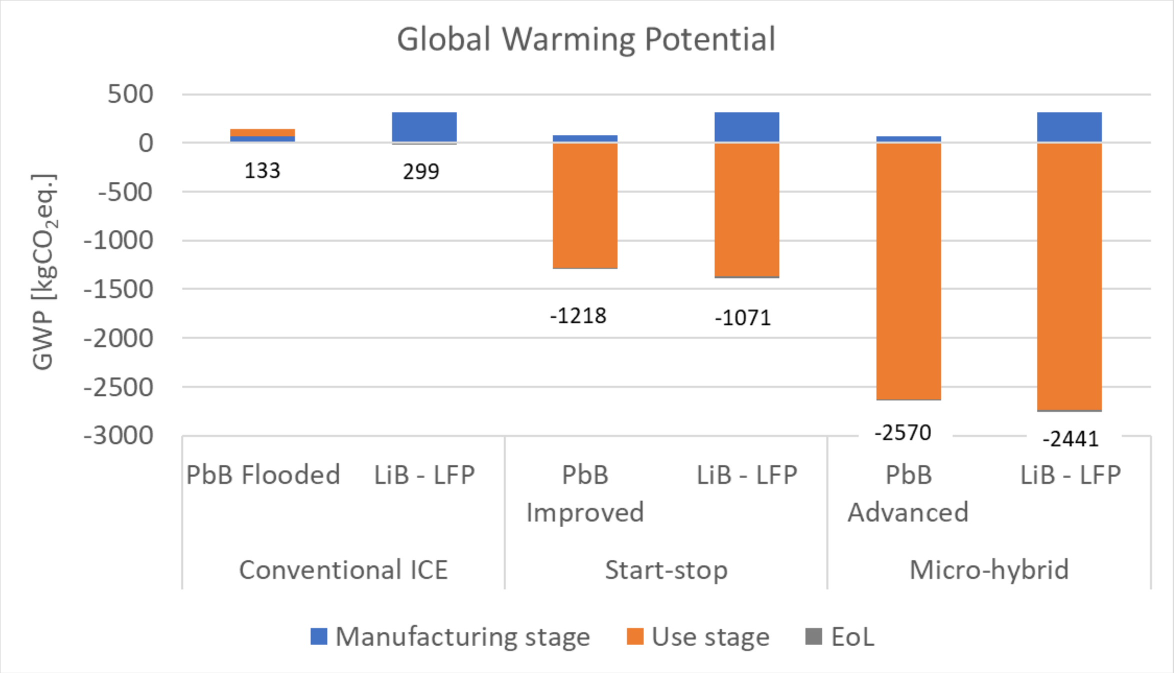

Figure 1-1: Overall Life Cycle GWP per battery technology and type of vehicle application

Conclusions and recommendations

The results of this study are only applicable to lead and LFP batteries used for the described automotive 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 representativity 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.

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

This study shows that:

- Battery applications in start-stop and micro hybrid vehicles offer substantial life cycle benefits over internal combustion engines (ICE) technologies.
- Lower battery weight and higher lifespan are recommended to reduce the impacts of battery manufacturing and maximize in-use benefits.
- The study highlights current challenges in recycling lithium-ion battery waste and is limited by the lack of economic viability analysis for recovering materials like iron and phosphate
- Most impact categories showed small differences between all batteries assessed, with lead batteries performing better in the baseline scenario due to lower burdens in manufacturing (ranging from 90% to 39% depending on the impact category). However, when significant parameters such as battery weight and lifetime are considered, the overall environmental performance of the 12v LFP reaches roughly the same level as a lead battery.

It is recommended to:

- Study lithium-ion battery types comprising cathode materials other than LFP;
- More specifically study the use phase impacts of batteries;
- Study LiB – LFP with primary industry data rather than relying on secondary information from the available literature.

1. Goal of the Study

The goal of the study is to assess the comparative life cycle environmental profile of two different 12v battery chemistries used in the automotive sector. This study assesses the cradle-to-grave environmental impacts of a lead-based battery compared to an LFP automotive battery within North America. The study is conducted according to ISO 14040/44, the international standards on life cycle assessment (LCA).

The study was commissioned by Battery Council International (BCI) and the International Lead Association (ILA), to improve their understanding of the environmental impact of 12v 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 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 among others, includes BCI, ILA and its members, 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 from the Industrial Ecology Consultants, and Arpad Horvath.[3]

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

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 System(s)

The document assesses three type of vehicle systems: internal combustion engines (ICE), start-stop, and micro-hybrid. Three different types of lead batteries are assessed for these applications (standard, Enhanced Flooded Battery (EFB) and Absorbent Glass Mat (AGM). EFB and AGM are more suitable to the vehicle requirements in start-stop and micro-hybrid applications. One type of lithium-ion battery is assessed for the three vehicle system types. This is a lithium iron phosphate battery (LiB – LFP), which can be used in all three vehicle system types. The following paragraphs describe the batteries more in detail and the data used in this study can be found in the LCI section 3 of the present report.

Lead-based batteries applied to vehicles

Lead batteries are long-established for automotive applications, they are used to start the engine and to provide energy if other power sources become unavailable. The technical requirements for automotive service have become more onerous in the last few years as car manufacturers have adapted vehicle powertrains to reduce emissions. This has required batteries to be able to provide multiple engines starts and recover energy in operation for stop and start or micro-hybrid service. Lead batteries have been successfully developed to provide reliable performance for these conditions. (Ricardo Strategic Consulting (RSC), 2020)

Battery life has been improved and better manufacturing technology has resulted in greater efficiencies both in production and materials used. Lead batteries are also very effectively recycled at end-of-life. Lead is the most efficiently recycled commodity metal and lead batteries are the only battery system that is almost completely recycled, with over 99% of lead batteries being collected and recycled in US (BCI, 2019)

Lead batteries all share the same basic chemistry. The active materials are lead and lead dioxide and the electrolyte is an aqueous solution of dilute sulfuric acid. The active materials both react with sulfuric acid on discharge to form lead sulphate. The current collectors are lead or lead alloys and the battery containers are moulded polymers. The positive and negative plates are separated by microporous plastic or microfibre glass separators. Lead batteries may be flooded with free electrolytes with vents that allow passage of gas to and from the cells. At top of charge, flooded lead batteries evolve some hydrogen and oxygen from the electrolysis of water.

This is minimised in modern automotive batteries by the design of the battery such that water loss is not a failure mode in normal service. Positive grid corrosion may occur but lead alloy selection ensures this is at a rate that permits a full-service life. Lead batteries may also be valve-regulated lead-acid (VRLA) variants that are sealed in operation and where water loss is reduced by internal recombination of oxygen gas. These types have a one-way valve to allow small quantities of hydrogen to be vented but do not permit air to enter the cells. Two types are used: one has absorptive glass mat (AGM) separators with the electrolyte immobilised in the active materials and the separator; the other has microporous polymeric separators with the electrolyte gelled with fine silica powder and the remainder immobilised in the active materials.

All VRLA batteries operate in the same way with oxygen generated at the positive plate at top of charge diffusing through connected porosity in the separator to be chemically recombined at the negative plate. In this way, water loss is reduced to very low levels. Hydrogen evolution is minimised by careful materials selection which also limits positive grid corrosion. VRLA AGM batteries are widely used in automotive and industrial applications, but VRLA gel batteries are principally used for industrial applications.

Lithium batteries applied to vehicles

Li-ion batteries share several common features but there is wide variation in the active materials used. The electrolyte is a solution of lithium salt in an organic solvent mixture. The dissociating salt provides ionic conductivity to the electrolyte. The positive electrode active material is a lithium compound coated onto aluminium foil and the negative electrode material coats a copper foil. The separator is a thin microporous polymer membrane. Cells may be in cylindrical cans, prismatic metal cans, or in aluminised polymer foil pouches.

The lithium compounds used as positive active materials may be lithium cobalt oxide (LCO), lithium nickel-cobalt-manganese oxide (NMC), lithium nickel-cobalt-aluminium oxide (NCA), lithium manganese oxide (LMO), or lithium iron phosphate (LFP). The positive active materials can reversibly release and store lithium, which enters the electrolyte undergoing charge-transfer reactions, to pass as Li+ ions to the negative electrode. Corresponding to the positive active material, the negative active material is able for reversible acceptance, storage, and release of lithium (intercalation). Materials used are carbon, graphite, silicon, lithium titanate (LTO), and mixtures thereof.

Automotive batteries applications

The following automotive batteries applications are assessed in this study:

- **Conventional combustion ICE;** batteries are used in most conventional vehicles to provide starter, lighting, and ignition (SLI) functions.
- **Start-stop** - batteries are used in vehicles with an idle start-stop (ISS) system, which allows the ICE to automatically shut down under braking and rest and then to restart.
- **Micro-hybrid** - batteries used in vehicles with a micro-hybrid system, which combines start-stop functionality with regenerative braking (a system to recover and restore energy from braking), and other micro-hybrid features. This type of duty requires higher resilience of the battery with deep-cycling and a high rate of charge acceptance.

For these 3 different automotive battery applications, a comparison is made between different lead batteries (PbB) vs. lithium iron phosphate batteries (LFP). The following battery technologies are analysed:

- **Lead (Pb) 12 V, 70 Ah**
  - Standard Technology - flooded lead-based batteries are used as standard technology batteries in the majority of conventional vehicles. Flooded lead-based batteries are characterized by a vented design and an excess of free-flowing aqueous electrolyte between and above the electrode stack.
  - Improved Technology-enhanced flooded (EFB) or Absorbent Glass Matt (AGM) lead-based batteries used in vehicles with a start-stop system.
  - Advanced Technology - EFB or AGM lead-based batteries are used in vehicles with a micro-hybrid system.
- **Li-ion (LFP) 12 V, 60 Ah** – it is assumed that LFP battery cells are used for all three applications.

12 V lead batteries for automotive applications are grouped into three types; conventional SLI (starting, lighting and ignition), EFB (enhanced flooded batteries), and AGM (absorptive glass mat). SLI batteries are used for vehicles without stop and start/idle stop-start/micro-hybrid system. They provide one cold engine start per journey and reserve power as required. EFB and AGM batteries are used for vehicles with stop

and start systems. In addition to cranking the cold engine and providing reserve power, in these applications they have the capability of multiple warm engine starts so that the engine may be stopped when the vehicle is stationary and restarted automatically when the vehicle moves off to reduce emissions and improve fuel economy. They are not fully charged in operation so that the battery can accept charge for energy recovery as well as provide power on discharge to supply vehicle systems when the engine is stopped. For the purposes of this study, EFB and AGM batteries are regarded as equivalent although AGM types are generally regarded as technically superior.

EFB batteries differ from SLI batteries in that they retain a flooded construction with free electrolyte while SLI batteries have inactive material formulation, active material retention, the use of additives in the negative plates, and have an electrochemical design. AGM batteries use special separators which immobilise the electrolyte and permit the battery to operate in a fully sealed manner such that any oxygen evolved in operation is chemically recombined and hydrogen loss is suppressed by the electrochemical design. This construction provides higher cycle life in stop and start systems so that for more arduous service, AGM batteries are preferred.

Within this study, for all 3 different types of applications, internal combustion engines (ICE), start-stop and micro-hybrid, the same design of 12 V LFP battery is considered – other than the lead battery, which has different designs specific to each application. Lithium-ion batteries can be used for vehicles with or without stop and start systems. If the vehicle has a stop and start system, it will operate in a partially discharged condition like an EFB or an AGM battery for the same reason. If the vehicle has no stop and start capability, it can be fully charged in the same manner as a lead-type SLI battery. Li-ion batteries for 12 V service generally use lithium iron phosphate (LFP) cathodes rather than nickel-manganese-cobalt (NMC) cathodes because their cell voltage (3.2 V per cell) allows for a good match to the vehicles electrical system voltage of ~15V max when combined with carbon as a negative material (4 cells in series). Other combinations of positive and negative active materials are less appropriate (e. g. NMC vs. C with 3.7 V per cell).

The functional unit in the study is “Rechargeable storage of energy to fulfil the service lifetime of a vehicle”. A lead battery of 70 Ah is utilized in these applications. The current lithium-ion offering on the market which meets the functional unit is an LFP battery of 60 Ah (BCI internal survey, 2021)[4] . Hence these two technologies have been compared in the document.

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[4] BCI consulted their memberships and they agreed with the assessment

Automotive Batteries Use Stage

The following Table 2-1 provides the main technical parameters per battery type and technology. Table 2-2 shows the total fuel saving per year considered as baseline for the use stage modelling and calculation of results. (EPA, 2016)

The following parameters are representative of North American weather conditions and light duty vehicles.

Table 2-1: Automotive Batteries Technical Parameters[5]

Application	ICE		Start-stop		Micro-hybrid	
Battery type	Pb Standard	Li-ion LFP	Pb Improved	Li-ion LFP	Pb Advanced	Li-ion LFP
Battery nominal capacity	70 Ah	60 Ah	70 Ah	60 Ah	70 Ah	60 Ah
Cold starts per day	3					
Cold starts per year	1000					
Vehicle life	11 years					
Cold engine start	3 kW for 3 s, 2.5 kWh per year					
Warm starts per day	None		12			
Warm starts per year	None		4000			
Warm engine cranking events	-		2 kW for 0.5 s = 1.12 kWh per year			
Additional duty	-		20 h in stop phase at 0.24 kW = 4.8 kWh		1.5 kW of battery ancillary loads, 25% of operating time (80 h) = 120 kWh	
Battery discharge	50% SoC 5 times per year, 420 Wh x 5 = 2.1 kWh (35 Ah for PbA but LFP discharged to 42% SoC if 60 Ah nominal capacity)					
Vehicle drives	13,000 miles per year, average speed 40 mph, operates 325 h per year, 80 h city driving, 245 h highway driving					
Top-of-charge current	3 mA/Ah at top of charge	Shuts down at top of charge, no	Maintained at 80-85% SoC in normal operation with a narrow range of SoC above and below set point, never reaches top of charge			

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[5] Geoffrey May Focus Consulting 2020 and ACEA, JAMA, KAMA Survey 2020,
Ricardo (2020) Lead Battery Automotive Trends Review-Final Report RD19-001611-11,
A123 UltraPhosphate Lithium Ion 12v 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.

		overcharge current				
Self-discharge (at 25°C per month)	2.5% = 21 Ah per year	1% = 7.2 Ah per year	2.5% = 21 Ah per year	1% = 7.2 Ah per year	2.5% = 21 Ah per year	1% = 7.2 Ah per year
Charging efficiency	90%	95%	90%	95%	90%	95%

For start-stop and micro-hybrid with EFB or AGM batteries, the baseline duty cycle is the same as SLI batteries. There is one cold start per journey. The vehicle is used for 300 h per year and it has 50% discharges per year; same goes over a 10-year life. The difference is that in city driving, the ISS system operates, and 100 h of city driving are assumed.

The battery is operated in a partial state-of-charge (PSoC) of 80-85% such that it can always accept charge and can provide power when required. It will not reach top of charge.

More information regarding the fuel saving approach choice is available under section 3.3.

Table 2-2: Use stage total fuel saving per Functional Unit

Application	ICE[6]		Start-stop		Micro-hybrid	
Battery type	Pb Standard	Li-ion LFP	Pb Improved	Li-ion LFP	Pb Advanced	Li-ion LFP
Fuel economy (mpg)	44.2		46.05		48.04	
Percentage of fuel saving (%)	0		4%[7]		8%[8]	
Fuel saving (US gallons / total vehicle lifetime)	0		129		258	

The figures presented for fuel economy in Table 2-2 are considered conservative. A reference point for reasonably high level of fuel efficiency for a North American family car is taken. However, in North America there is a spread of vehicle types from cars of all types to large SUVs and pick-up trucks decreases average fuel economy-this is also reflected in the figures. The fuel savings resulting from start-stop and micro-hybrid technology remain the same in percentage terms with larger vehicles and so the fuel savings increase.

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[6] Derived from average fuel consumption values for MPV from www.fuelmileage.co.uk

[7] EPA, Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation: Technical Support Document (3 - 5%), page 4-20

[8] EPA, Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation: Technical Support Document (7 – 9. 5%), page 4-22

The EPA's Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation includes an analysis of the fuel savings that can be achieved using start-stop and micro-hybrid technology.

According to this analysis, the fuel savings for start stop technology is around 3-5% in city driving conditions and in the case of micro-hybrid technology is around 7-9,5%. The weight differences have a slightly impact on the fuel savings which has been taken into account in the assessment, as shown in Table 3-3.

It has been assumed that in vehicles currently available on the market, the energy/fuel savings for lead batteries and LFP batteries in start-stop and micro-hybrid vehicles are similar. This is because existing energy management systems are not able to realize the full potential of enhanced charge acceptance seen in LFP batteries. This assumption is based on an ACEA survey of members, and confirmed by BCI members, where 75% of respondents reported that the CO_2 savings in the use phase of micro-hybrids would be of the same magnitude when using a lead or LFP battery. However, given some companies reported there may be up to a 1% difference in favour of LFP, a sensitivity assessment of this has been undertaken in section 5.3. (European Automobile Manufacturers Association – ACEA internal Member Survey, 2020)

2.2. Product Function(s) and Functional Unit

The rechargeable batteries considered in this study are designed to store energy for automotive purposes and to deliver energy to the applications as required.

Rechargeable batteries for all applications must provide power measured in kilowatts (kW) for the required time to deliver energy-kilowatt hours (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 is also be referred to as capacity turnovers.

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 fulfil the service lifetime of a vehicle (11 years / 143,000 miles)

Table 2-3: Battery reference flows per Functional Unit

Lead battery type / application	Weight (kg)	Capacity (Ah)	Life-time (years)	No. of batteries vehicle lifetime	Li-ion battery type	Weight (kg)[9]	Capacity (Ah)	Life-time (years)	No. of batteries vehicle lifetime
Standard/ Conventional ICE	18	70	5	2.2	LFP	12	60	8	1.38

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[9] The LFP battery weight of 12 kg has been chosen as the baseline and representative of most 60 Ah LFP 12 V SLI batteries on the market based on available literature references. Some lighter LFP batteries of approximately 10 kg may be available and we have therefore conducted a sensitivity assessment at this weight (see section 2. 8)

Lead battery type / application	Weight (kg)	Capacity (Ah)	Life-time (years)	No. of batteries vehicle lifetime	Li-ion battery type	Weight (kg)[9]	Capacity (Ah)	Life-time (years)	No. of batteries vehicle lifetime
Improved/ Start-stop	19	70	5.5	2.0	LFP	12	60	8[10]	1.38
Advanced/ Micro-hybrid	20	70	6	1.83	LFP	12	60	8	1.38

Note that the total LIB full weight system is 15 kg, including the car protection as indicated in Table 3-3.

Lead battery lifetime differs according to real world conditions (i.e. average temperature, usage patterns) and a single representative value does not exist. The average lifetime values used in this LCA report were taken from end-of-life surveys carried out by BCI[11] (BCI, 2020).

The lifetime of a battery also depends on various parameters including temperature, charging voltage, floating voltage and discharge cycles. It is assumed that all batteries operate under stable temperature conditions of 20°C. It may be necessary to add heating or cooling devices to LFP batteries used in hot or cold territories depending on the location of the battery in the vehicle, but this is outside the scope of this study.[12].

The LFP battery weight indicated in Table 2-3 considers the weight of one battery with electronics. Additional components required in the vehicle such as crash protection and car cabling are also included in the assessment, but not included in the weight; their use is independent from the battery lifetime and does not influence the number of batteries needed to match the functional unit.

The lead-based batteries weight and production data represents the average inventory profiles from BCI participating companies.

2.3. System Boundary

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

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[10] (Ricardo Strategic Consulting (RSC), 2020) (A123 Systems LLC, 2020)

[11] The 2020 report shows that there were no major technological breakthroughs in the five to six years preceding the survey, but battery designs and vehicle battery management systems have continued to improve. The figures used in the report are generally conservative for the reference year.

[12] (Dr Geoffrey May, 2022) (J Garche, 2017)

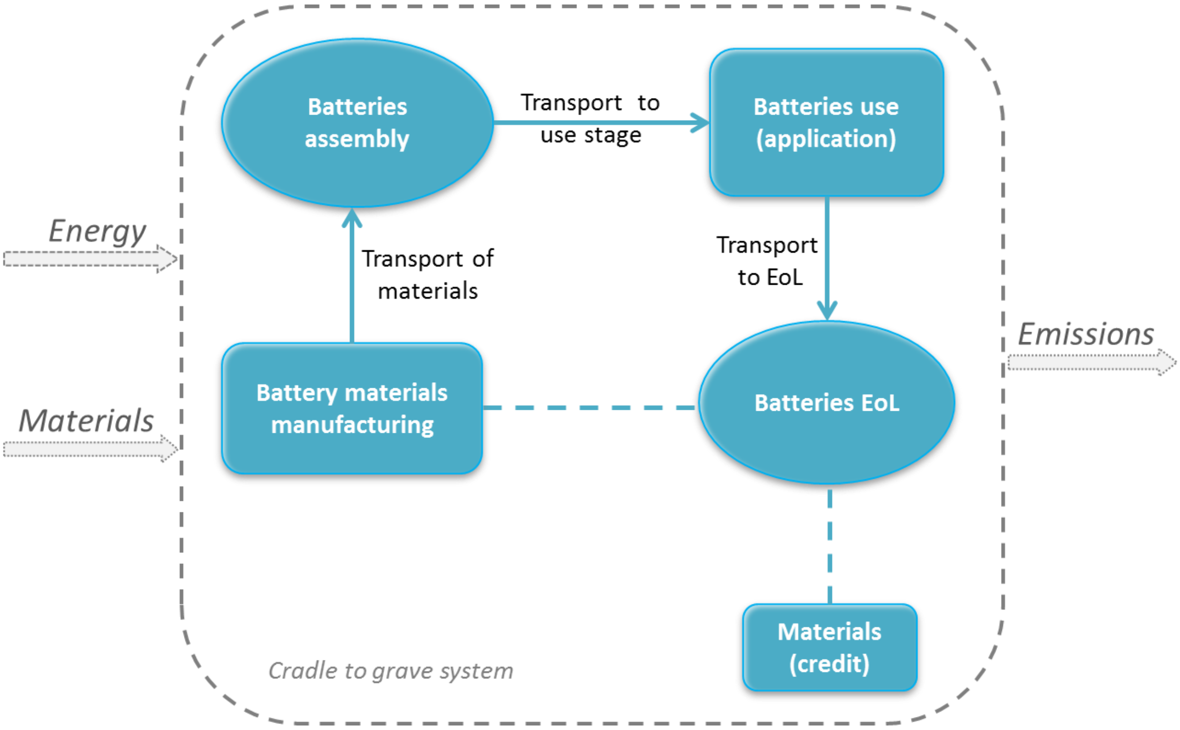


Figure 2-1: System boundary

Inclusions and exclusions to the system boundary are listed in Table 2-4

Table 2-4: System boundaries

Included	Excluded
✓ Extraction and processing of materials ✓ Electronics and crash protection in the application (only for LFP battery) ✓ Car cabling ✓ All associated energy and fuels ✓ Transportation of raw and processed materials ✓ Transport to customer ✓ Use stage ✓ End-of-life (collection, recycling, treatment)	× Production and maintenance of capital equipment and infrastructure (e.g. buildings, machinery) × Manufacturing facilities (e.g. heating, lighting, services, water, and wastewater, waste management, and similar operating costs) × Labour × Packaging × Production for the application (vehicles)

Electronics and crash protection are only required for LFP batteries and are not for lead-based batteries. Car cabling has been considered for both battery types in the same way.

Packaging of raw materials and the final product is excluded from the study as it is expected to have a minimal contribution to the total impact. Production and maintenance of capital goods are also excluded from the study for the same reason. It is expected that these impacts are negligible compared to the impacts associated with running the equipment over its operational lifetime. (Sphera Solutions Inc., 2021)

The EoL includes the collection of batteries and its treatment for the recovery of materials, please see section 2.5.2 for details on EoL approach.

2.3.1. Time Coverage

The results of this study are intended to represent the year 2021. They are relevant for 2020/21 (the year in which the study was conducted) and are expected to be relevant until such time as there is a significant change in the production mix, energy mix, or manufacturing technology.

2.3.2. Technology Coverage

This study assesses the cradle-to-grave impacts of lead-based and LFP batteries including the battery production, its use within an application (automotive), and their eventual EoL based on the current North American technology mix. For the lead batteries, primary average data have been used from BCI members to ensure that the model used to assess the environmental impact of lead 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 3-6, to Table 3-9 for more information on the background data used.

2.3.3. 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 is 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 all battery types are assumed to be in NA.

2.4. Cut-off Criteria

No specific cut-off criteria are defined for the foreground of this study. As summarized in section 2.3, 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 choice of proxy data is documented in the LCI chapter. The influence of these proxy data on the results of the assessment has been carefully analysed and is discussed in the LCI Chapter.

Cut-off-criteria applied to background data (energy and materials) taken from the GaBi 2020 databases is documented online (Sphera Solutions Inc., 2020).

2.5. Allocation

2.5.1. Multi-output Allocation

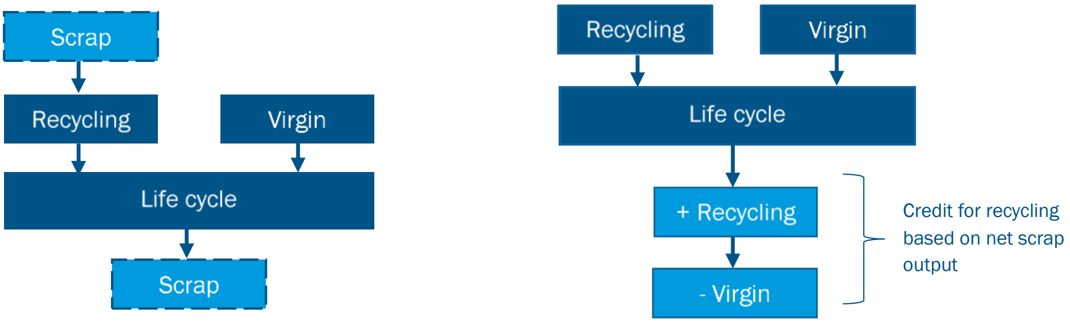
Multi-output allocation generally follows the requirements of ISO 14044, section 4.3.4.2. When allocation becomes necessary during the data collection phase, the allocation rule most suitable for the respective process step is applied and documented along with the process in Chapter 3. No multi-output allocation has been applied for the foreground data used in this study. Allocation of background data (energy and materials) taken from the GaBi 2021 databases is documented online at http://www. gabi-software. com/international/databases/gabi-databases/

2.5.2. End-of-Life 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 i. e., 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 opened EoL battery and secondary materials inputs. After collection of the current batteries at the EoL stage, a recycling process is applied. The original burden of the primary material input (lead in batteries and car cabling) is allocated between the current and subsequent life cycle using the mass of recovered secondary lead to scale the substituted primary material. The batteries EoL allocation approach applied is described in greater detail in the LCI section.

LFP batteries contain no economically valuable metals and thus have very low incentive for recycling. For other Lithium-ion battery chemistries, such as NMC, economic incentives for material recycling varies, but cobalt and nickel content are typically the primary driving factors.

In the case of Europe, to meet the 50% recycling targets of the Battery Directive (Official Journal of the European Union , 2006) LFP cells are usually mixed with other battery chemistries with larger amounts of valuable materials to ensure that the total recycling efficiency of the recovery process meets requirements. In some cases, where including in a recycling process is not possible, LFP cells may be sent for incineration and burnt for energy recovery. Typically, after collection, all Lithium-ion batteries are dismantled; the cells are removed from the rest of the pack, and the structural material and electronics in the packs are sent to separate recycling. In general, it is not economically viable to recover the materials lithium, iron and phosphate from the cathode of the LFP battery system and produce $LiFePO_4$ again. Therefore, for the baseline of this study, and to ensure a fair comparability, the recycling efficiency of the LiB LFP is estimated from maximum recycling possible from the other battery components, which represent approximately 30% of the battery.

In the case of US and according to EPA reports (EPA, 2016), it is currently unlikely that the Lithium batteries are recycled, and that recycling rates have to be interpreted as forecast figures. Moreover, some literature indicates a recycling rate of 5% (Gaines & Linda, 2012) ((EERE), June 2019). In this study, chapter 5.3.5, a scenario with a collection rate of 15% of the LFP batteries have been calculated, doing so a recovery rate of 4,5% is achieved since only the passive components, as well as electronics and battery case are recycled, while the LFP cell is incinerated.

It is recognised that Lithium-ion battery recycling is in its infancy and in the future, it may be technically feasible to increase the recycling efficiency of processes for recovering materials from spent LFP batteries. Therefore, a scenario analysis has been completed (section 5.4) considering the technical potential for future recovery of materials in LFP cells. It must be stressed that although such processes could provide benefits through reducing the extraction and refining of virgin sources, it is unlikely that such processes will be economically driven and may not produce battery grade materials that can be reused in new battery manufacturing.

There is ongoing research and development to improve the recycling of Lithium-ion batteries. The cathode (active material) is treated in the hydrometallurgical process after all these separation processes[13]. They also state that the other materials after disassembly of the battery will have a higher recovery rate separately, e. g. stainless steel or copper.

Other lithium recovery from LFP cathodes is possible, but not common. One of these, is the acid leaching of the LFP with different precipitation stages where the output of the process is lithium carbonate and iron phosphate. This process brings the LFP into a solution with sulfuric acid (as it is done for lithium recover out of spodumene) where in the end, lithium carbonate is received through a precipitation process. In earlier stages $FePO_4$ would be precipitated.

The lithium carbonate could then be reused as an input material into new batteries if the required purity of the carbonate can be assured and the secondary residues can be dealt with.

At the University of Fuzhou in China, research has been conducted where the final products are Li_3PO_4 and $FePO_4$[14]. As stated by the author in the conclusion of this report, this could be a process feasible for industrial applications, but there is doubt in terms of the volumes.

Ferro-phosphorus could be produced in EAF/SAFs and then be used in the manufacture of high phosphorus steels, but more detailed research needs to be done about the $FePO_4$ produced from the recycling process and, in any event, the value of the recovered material is likely to be low.

Additionally, the following parameters are to be considered in the modelling of the batteries respectively:

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[13] (Forte & Federica, 2021)

[14] Huan Li et al.; Fuzhou University; https://link. springer. com/article/10. 1007/s11581-019-03070-w

- The recycled content of the active material in the batteries is 75% for Pb (25% primary and 75% secondary routes) and 0% for lithium (primary materials are used). It should also be noted that lead batteries can be produced from 100% secondary lead sources. Primary lead is produced alongside zinc as the concentrates for zinc production are polymetallic,
- The collection rate for all battery types is assumed to be the same as reported for lead batteries (i.e. 99%,) (BCI, 2019)
- Recycling efficiency based on battery weight is 99% (BCI, 2019) for PbB, and 30% for LiB (estimated from the BOM, and assuming that currently no recycling of the LFP cells occurs).

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. Credits are assigned to power and heat outputs substituting 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, and utilisation rates (flaring vs. power production). A credit is assigned for power output substituting the regional grid mix.

2.6. 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 25 and Table 26.

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 and are added in the Annex B: as additional information.

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, et al., 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[15] 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 have been eliminated, while complete phase out of less active HCFCs (hydrochlorofluorocarbons) will be achieved by 2030[16]. 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.

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, et al., 2009).

Table 25: 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 cause an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	(IPCC, 2013)
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	

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

[16] ((UNEP), 2016)

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 26: 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, et al., 2002)
Water	A measure of the total fresh water consumption (excluding hydropower)	kg	(thinkstep, 2019)

It should 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 section 4.8, 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.

2.7. Interpretation to Be Used

The results of the LCI and LCIA were 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

Interpretation is also subject to uncertainties in the model, assumptions, and data.

2.8. Sensitivity and Scenario Analysis

Sensitivity and scenario analyses compare results between discrete sets of parameter settings or model choices. During the data collection some parameters where identified as possible variations from the baseline considered according to the references consulted. The following sensitivity and scenario analysis have been done:

- LFP battery weight variation (from 12 kg to 10 kg) including electronics but excluding the crash protection
- LFP battery lifetime (baseline 8 years), however a scenario with 10 and 15 years has been tested
- It has been assumed that same energy/fuel savings for PbB and LiB in start-stop and micro-hybrid. Nevertheless, an assumption has been made and is tested via a scenario analysis where 1% benefit for LiB vs PbB.
- Vehicle lifetime base scenario considers 11 years. As an alternative scenario, 15 years is analysed
- An EoL scenario on recycling efficiency; where a variation of 50% for LFP batteries is tested by comparing the baseline with potential future recycling process (currently not applied commercially)
- A sensitivity analysis about the cut-off EoL approach have been done

Sensitivity and scenario analysis results are shown in section 5.3 and 5.4.

2.9. 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.

- 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 LiB 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 matches 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 US), best-available proxy data were employed. Detailed description in section 2.3.1 to 2.3.3.

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

2.10. 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 GaBi LCA software through the GaBi professional database.

2.11. Software and Database

The LCA model was created using the GaBi 10 Software system for life cycle engineering, developed by Sphera GmbH. The GaBi 10 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

2.12. 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.[17] The critical review of the external expert is performed after completion of 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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[17] 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 was collected in the context of the verified NAM LCA Lead batteries study commissioned by BCI reviewed by Matthias Finkbeiner[18] from Technical University Berlin, Germany to ensure conformity with ISO 14040/44[19].

In this study, the production data of 4 North American batteries companies where collected the LCA results of this study can only be applied in the NA region.

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 UltraPhosphate Lithium-ion 12 V starter battery specifications downloaded from http://www.a123systems. com/automotive/products/systems/12v-starter-battery/ on 18/6/2020
- Previous EU 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 (Dr Geoffrey May, 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) (Recharge, 2018)

This information was reviewed and approved by the members of BCI.

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 each battery, including all processes and on-site wastewater treatment. All lead and

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

[19] (BCI, Battery Council International; Sphera Solutions, 2022)

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 GaBi 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: Average gate-to-gate data for one production volume average Lead batteries

Type	Flow	Standard	Improved	Advanced	Unit
Input	Expander	0.0522	0.0556	0.0585	kg
	Glass fibers	0.0132	0.0126	0.0133	kg
	Glass mats	-	0.458	0.482	kg
	Paper	0.045	-	-	kg
	Lead	7.84	7.87	8.28	kg
	Lead alloys	3.88	5.63	5.93	kg
	Other plastics	0.0308	0.00631	0.00664	kg
	Polypropylene part (PP)	1.10	0.762	0.802	kg
	Sodium sulfate	0.0425	0.0406	0.0427	kg
	Sulfuric acid (100%)	2.86	2.27	2.39	kg
	Water (desalinated; deionised)	2.14	1.90	2.00	kg
	Water (ground water)	11.9	14.0	14.7	kg
	Water (tap water)	13.2	24.6	25.9	kg
	Electricity	50.2	73.8	77.7	MJ
	Thermal energy from natural gas	27.6	32.5	34.2	MJ
	Aluminum sulfate for WWT	1.93E-04	2.31E-04	2.43E-04	kg
	Flocculants for WWT	1.44E-04	1.72E-04	1.81E-04	kg
	Sodium hydroxide for WWT	0.00575	0.00285	0.00300	kg
Output	Lead acid battery	18.0	19.0	20.0	kg
	Lead scrap	0.0120	0.0285	0.0300	kg
	Hazardous waste for further processing	0.0137	0.0378	0.0398	kg
	Waste for disposal	0.00418	0.00198	0.00208	kg
	Waste for recovery	0.00111	6.03E-05	6.35E-05	kg
	Waste water to municipal treatment	4.32	19.4	20.4	kg

Type	Flow	Standard	Improved	Advanced	Unit
	Water, cooling, to river	2.74	0.233	0.245	kg
Emissions to air	Antimony	1.30E-05	2.92E-06	3.07E-06	kg
	Arsenic	1.51E-05	3.55E-06	3.74E-06	kg
	Dust (>PM10)	7.38E-04	9.56E-04	1.01E-03	kg
	Lead	1.08E-05	2.65E-05	2.79E-05	kg
	NMVOC	1.94E-04	2.78E-05	2.93E-05	kg
	Sulfur dioxide	9.12E-05	8.29E-05	8.73E-05	kg
	Sulfuric acid	5.50E-04	6.82E-04	7.18E-04	kg
	Water vapour	17.4	16.6	17.5	kg
Emissions to water	Arsenic	1.58E-07	1.19E-06	1.25E-06	kg
	Cadmium	3.02E-07	3.26E-07	3.43E-07	kg
	Copper	6.73E-07	9.86E-07	1.04E-06	kg
	Iron	4.39E-12	1.14E-09	1.20E-09	kg
	Lead	1.93E-06	1.81E-06	1.91E-06	kg

3.2.2. LFP battery

It was not possible to obtain manufacturers' data for 12V automotive LFP batteries currently on the market.

Table 3-2 lists the bill of material and production data for one LFP battery that was constructed as described in section 3.1.2.

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 EU PEFCRProduct 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 2.5.2.

Table 3-2: Bill of Material and production data for one LFP battery

Input parameter	Amount	Unit
ASSEMBLY DATA		
Energy		
Electricity CN[20] (cell electrodes production & forming)	492	MJ

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[20] Electricity grid mix for China

Electricity US[21] (battery assembly)	2.4	MJ
Emissions to air		
Dust to air	190	µg
SO_2 to air	72	µg
NOx to air	1.0	µg
Auxiliary materials		
Water deionized (anode + production)	4.4	kg
N-Methylprolidone (cathode)	1.7	kg
Waste treatment in manufacturing		
Total 5% of cell weight	0.42	kg
Plastic (battery case + other internal components)	0.045	kg
Internal clamps, Stainless steel	0.006	kg
Copper wire	0.012	kg
Electronics	0.045	kg
BATTERY COMPONENTS		
Total battery weight (w/o) crash protection and car cabling	**12.0**	**kg**
Anode		
Copper foil	1.09	kg
Graphite	1.01	kg
Cathode		
Aluminium	0.67	kg
LFP	2.28	kg
Carbon black	0.12	kg
Binder (PVDF)	0.12	kg
Electrolyte		
EC/DMC	1.26	kg
$LiPF_6$	0.25	kg
Separator		
Polypropylene (PP)	0.5	kg
Cell case, foil pouch		
Al	1.09	kg
Battery case		
Polypropylene	1	kg
Passive components		
Internal clamps, fastenings (stainless steel)	0.20	kg
Internal connectors and terminals (copper)	0.40	kg
Connectors & cables	0.40	kg
EMC Shielding	0.50	kg
Electronic circuit boards	0.40	kg
Power semiconductor	0.08	kg

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[21] Electricity grid mix for US

Plastic part	0.12	kg
Other components (PP)	0.50	kg
External accessories for LFP (not included in battery weight, calculated in Manufacturing results)		
Crash protection (Steel sheet)	3	kg
Cabling car (Polypropylene / copper wire)	0.7	kg

3.3. Use stage

The use stage has been modelled based on the information provided by the automotive sector.However, the authors acknowledge that other factors might contribute to use phase savings, such as other vehicle components' weight (apart from battery components) and the drivers' behaviour.

Two scenarios are modelled for the use phase.

- The different weight of the batteries systems which can lead to additional fuel consumption.
- The different technologies start-stop and micro-hybrid systems which can contribute to a reduced fuel consumption.

Both issues are addressed separately in the following section.

Table 2-1 and Table 2-2 define the characteristic lifetime and fuel consumptions for the three battery-applications under study. This data was provided by the study participants based on standard averages in the automotive industry. The data refers to passenger vehicles with no more than 8 seats, weighing less than 3.5 tonnes. [22]

Although the battery is an integral component of start-stop and micro-hybrid systems, it is not possible to isolate its specific contribution to these fuel reduction values. Other components are also installed in start-stop and micro-hybrid systems such as starter and ring-gear reinforcement, the installation of a battery state sensor plus wires/connectors, additional sensors for gear shift neutral and pedal position, and restart voltage quality countermeasures (i.e. a dc/dc converter). Therefore, the given fuel reduction values refer to an overall system level. These total savings are attributed to the battery for the purposes of this study (best case assumption) as the key enabler for storing and releasing the vehicle's energy within the start-stop/micro-hybrid system.

This study attempts to isolate the contribution of the start-stop/micro-hybrid system (of which improved or advanced technology lead-based batteries are an integral part) from other technologies used to improve fuel efficiency within the vehicle i.e. base engine updates, engine downsizing, reduced roll resistance tires, vehicle weight reduction, and aerodynamic improvements. From current information, the specific contribution of the start-stop/micro-hybrid system to the vehicle's overall reduction in fuel consumption can range from 3.0-9.5%, dependent on the system type provided. Improved or advanced technology lead-based batteries are an essential part of these systems, with the required type and performance differing significantly in conventional vehicles. Stop-Start and Micro-hybrid vehicles and their deep-cycle resistance and charge recoverability are progressively increasing in market share.

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[22] The ELV directive (2000/53/EC) of the European Commission is applicable to category M1 vehicles. "'vehicle' means any vehicle designated as category M1 or N1 defined in Annex IIA to Directive 70/156/EEC, and three-wheel motor vehicles as defined in Directive 92/61/EEC, but excluding motor tricycles" -

To avoid overestimation or bias, a conservative 4% reduction in fuel consumption from the installation of start-stop systems using improved technology batteries, and an 8% reduction in fuel consumption from installation of Micro-hybrid systems (start-stop, regenerative braking, passive boosting) using advanced technology batteries was used in the study.[23]

The assumptions were applied to the reference case, which is a compact sedan representative of the US market, as selected by US BCI battery members. This reference case reports a fuel economy for the conventional battery application of 44.2 mpg (see Table 2-2). A representative lifetime of 11 years and/or 143,000 miles has also been assumed and is in line with the parameters selected as standard by the car industry for several vehicle LCAs. (Dr Geoffrey May, 2022)

In the use stage, the weight difference between the PbB and LiB LFP has been accounted for in the calculation of results. Table 3-3 shows the additional gasoline amounts considered; these were calculated based on fuel reduction formula published by Volkswagen. (Christoph Koffler, 2009)

‘It has been shown that the fuel consumption required to move a mass of 37 gallons over 62.14 miles, can be obtained based on the NEDC driving cycle and the differential efficiency of gasoline and diesel engines. It has also been shown that it is advisable to utilize mass differences rather than mass ratios when calculating the lightweight effect on fuel consumption during the use stage’. (Rohde-Brandenburger, 2009)

Table 3-4 lists the emissions to air considered in the calculation of the use stage; these emissions correspond to a passenger car with a gasoline engine technology and with typical driving behaviour of MPV mainly in urban areas.

When comparing the impact of the weight difference between the LFP and PbB batteries, only fuel dependent emissions such as CO_2 and SO_2 have been considered. Other emissions such as CO, NOx and NMVOC’s have not been considered since they are not linked to fuel usage. For example, there is no difference in emissions of CO, NOx and NMVOC’s if more gasoline is used per miles since the limitation of the emissions are related to the km. Therefore, only comparison between CO_2 and SO_2 during use phase has been undertaken. However, for fuel production (exploration until the point of use) CO, NOx, NMVOC will be dependent on the volume of gasoline produced. This is reflected in the assessment below.

Table 3-3: Additional fuel consumption due to battery weight difference

Application	PbB weight (kg)	LiB LFP with crash protection weight (kg)	Weight difference (kg)	Add. fuel consumption for PbB per FU (US gallons)	Total fuel saving (US gallons / total vehicle lifetime)
ICE	18	15	3	3.5	3.5
Start-stop	19	15	4	4.6	126
Micro-hybrid	20	15	5	5.8	974

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[23] EPA, Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation, page ES-10

Table 3-4: Combustion emission factors 1 kg gasoline consumed (passenger car)

Emission to air	Amount	Unit
Carbon dioxide	2.98	kg
Carbon dioxide (biotic)[24]	0.16	kg
Sulphur dioxide	2.0E-05	kg

3.4. End of Life Stage

3.4.1. LFP batteries EoL

In this study, the baseline was set 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.

Currently there are no commercial processes specifically designed for LFP cell recovery. The current process is for LFP cells to be mixed into the metallurgical processes where NMC batteries are recovered. In the context of overall recovery,50% as required by the EU Battery Directive can be achieved for LiB in general. This includes the BMS, housing, etc.

As described in section 2.5.2, the LFP battery cell is incinerated (with material and energy recovery as described in Table 3-5) and only the passive components, electronics, battery case are recycled. By doing so a recycling efficiency of 30% is achieved. The car cabling and crash protection is 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. (In the case of the PbB only car cabling is considered, since no crash protection is required).

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 aluminium foils and copper in the cells increases the recovery rate to approximately 40%, taking into consideration a collection rate of 99%.

Table 3-5: End of Life Cycle – 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 the thermal treatment and corresponding processes, such as disposal of air	Electricity / Thermal energy
Copper foil	1.09	kg		
Graphite	1.01	kg		
CATHODE				
Al	0.67	kg		
LFP	2.28	kg		

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[24] US Gasoline dataset includes ~6,5% share of bio-components (bio-ethanol and bio-diesel).

Carbon black	0.1 2	kg	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.	
Binder (PVDF)	0.1 2	kg		
ELECTROLYTE				
EC/DMC	1.26	kg		
$LiPF_6$	0.25	kg		
SEPARATOR				
PP	0.5	kg		
Cell case, foil pouch				
Al	1.09	kg		
Battery case				
PP	1	kg	recycling plastic granulate	Polypropylene granulate
Passive components (electronics)				
Internal clamps, fastenings (stainless steel)	0.20	kg	recycling	Stainless steel
Internal connectors and terminals (copper wire)	0.40	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
Other internal components (PP)	0.50	kg	recycling plastic granulate	Polypropylene granulate
External accessories for LFP (not included in battery weight, calculated in EoL results)				
Cabling car	0.7	kg	metal recycling, plastic incineration	Copper / Electricity / Thermal energy
Crash protection	3	kg	metal recycling	Steel billet

3.4.2. Lead-based batteries EoL

The substitution approach (close 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 is considered in the recycling stage.

On average, the lead used in the manufacturing of the batteries comes from two main routes: secondary 75% and 25% primary. The secondary lead dataset has opened EoL battery and secondary materials inputs. After collection of the current batteries, these are looped back to the production stage replacing the net amount of EoL batteries as input to the secondary lead dataset (recycling). 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. The car cabling recycling and recovery of copper and energy (plastic incineration) has also been considered. Figure 3-1 depicts the approach applied.

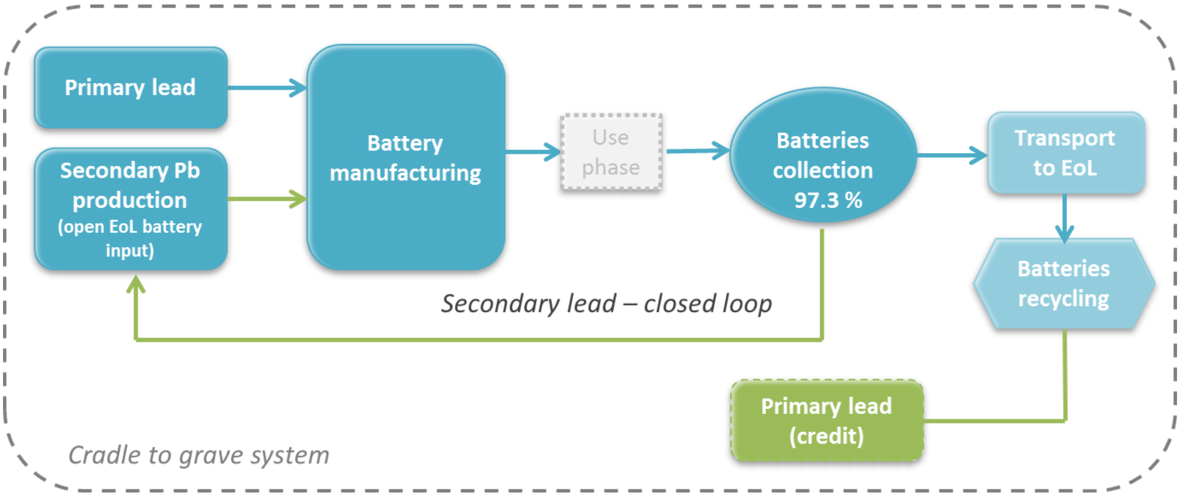

Figure 3-1: Lead batteries EoL – Material recycling (substitution approach)

3.5. Background Data

Documentation for all GaBi datasets can be found online (Sphera Solutions Inc., 2020)

3.5.1. Fuels and Energy

National or regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2021 databases. Table 3-6 shows the most relevant LCI datasets used in modelling the product systems. Electricity consumption for LiB batteries was modelled using China country grid mix for the battery cell production and US/NAM for the assembly of the battery components.

Table 3-6: 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 GaBi 2021vdatabase. Table 3-7 shows the most relevant LCI datasets used in modelling the product systems.

Table 3-7: Key material and process datasets used in inventory analysis for Lead Battery

Material / Process	Geo.	Dataset	Data Provider	Reference Year	Proxy?

ABS	US	Acrylonitrile-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	Ethylene 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 Fibres (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	Geo.
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	-
Waste water treatment	US	Municipal waste water treatment (mix)	Sphera	2021	-
Injection molding	GLO	Plastic injection moulding (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	Vulcanisation of synthetic rubber (without additives)	Sphera	2021	-
Water	US	Tap water from groundwater	Sphera	2021	-

Table 3-8: 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	-

	GLO	Aluminium 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	-
	GLO	Aluminium part	Sphera	2021	-
	GLO	Water (desalinated; deionised)	Sphera	2021	-
	JP	Lithium Hexafluorophosphate ($LiPF_6$)	Sphera	2021	geo.
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.
EoL	EU-28	Copper scrap values (average scrap) - EoL recycling potential	Sphera	2021	-
	GLO	Recycling of stainless-steel scrap	Sphera	2021	-
	EU-28	Recycling of polypropylene (PP) plastic	Sphera	2021	-
	EU-28	Hazardous waste in waste incineration plant	Sphera	2021	-
	EU-28	Polypropylene granulate (PP) mix	Sphera	2021	-
	DE	Incineration of electronics scrap (Printed Wiring Boards, PWB)	Sphera	2021	-

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 0 – 6 mix truck	GLO	Truck-trailer, Euro 0 - 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 vehicle datasets

Mode / fuels	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Passenger car (gasoline combustion)	GLO	Car petrol, Euro 6, engine size up to 1.4l ts (10 ppm sulphur, 5.60 wt.% bio components)	Sphera	2018	-
Gasoline (production)	US	Gasoline mix (regular) at refinery	Sphera	2018	-

3.6. Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the “outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment”. As the complete inventory comprises hundreds of flows, the below table only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results.

Table 3-11: LCI results of total battery life cycle per battery type and FU –ICE application (units in kg unless otherwise noted)

		Conventional ICE application	
Type	Flow	PbB Standard	LiB - LFP
Resources	Crude oil (resource) [MJ]	778	587
	Hard coal (resource) [MJ]	215	1954
	Lignite (resource) [MJ]	-16,23	51,26
	Natural gas (resource) [MJ]	737	760
	Uranium (resource) [MJ]	149,48	175
	Renewable energy resources [MJ]	129	592
	Non-renewable elements	-1,40	4,12
	Non-renewable resources	-166	952
	Renewable resources	3475	43544
	Fresh water	0,128	7,09
	Ground water	1188	345
	Lake water	147,50	2,36
	Lake water to turbine	4,30	1020
	Rainwater	1488	651
	River water	3091	2362
	River water to turbine	-110	17699
	Sea water	891	n/a
Emissions to air	Ammonia	2,51E-03	8,74E-03
	Carbon dioxide	-2354	274
	Carbon monoxide	0,73	0,34
	Nitrogen dioxide	6,89E-04	1,97E-03
	Nitrogen monoxide	5,83E-03	4,02E-03
	Nitrogen oxides	0,02	0,67
	Nitrous oxide (laughing gas)	8,23E-04	5,38E-03
	Sulphur dioxide	0,21	0,78
	Sulphur hexafluoride	7,24E-11	2,25E-11
	Sulphur oxides	2,57E-09	6,23E-06
	Lead	2,40E-04	4,95E-04
	Methane	0,25	0,68
	Methane (biotic)	3,24E-03	7,82E-03
	Dust (> PM10)	1,32E-02	1,06E-01
	Dust (PM10)	8,85E-04	8,13E-03
	Dust (PM2.5 - PM10)	1,89E-03	9,37E-02
	Dust (PM2.5)	5,66E-02	6,73E-02
	Biological oxygen demand (BOD)	1,34E-03	3,29E-03

Emissions to water	Chemical oxygen demand (COD)	4,84E-02	6,14E-01
	Total dissolved organic bound carbon (TOC)	-9,67E-09	2,02E-05
	Total organic bound carbon (TOC)	2,73E-04	4,12E-04
	Nitrate	-1,21E-07	2,90E-07
	Nitrogen organic bound	1,03E-06	1,85E-06
	Phosphate	2,79E-03	7,46E-03
	Phosphorus	3,15E-04	2,13E-04
	Sulphate	3,50E-01	4,98E-01
	Sulphuric acid	-1,40E-07	3,16E-04
	Collected rainwater to river	3,06E+01	3,00E+01
	Cooling water to river	-1,40E+03	2,82E+02
	Processed water to groundwater	-4,26E+00	9,74E+00
	Processed water to lake	-5,47E-04	-4,08E-04
	Processed water to river	-8,53E+02	3,64E+02
	Turbined water to river	4,78E+03	2,05E+04

Table 3-12: LCI results of total battery life cycle per battery type and FU – Start-Stop application (units in kg unless otherwise noted)

		Start-Stop application	
Type	Flow	PbB Improved	LiB - LFP
Resources	Crude oil (resource) [MJ]	-13139	-13736
	Hard coal (resource) [MJ]	83,04	1722
	Lignite (resource) [MJ]	10,83	30,18
	Natural gas (resource) [MJ]	-2379	-2380
	Uranium (resource) [MJ]	86,20	34,88
	Renewable energy resources [MJ]	-1275	-901
	Non-renewable elements	0,17	0,91
	Non-renewable resources	278,84	728,40
	Renewable resources	-37548	9048
	Fresh water	-0,166	6,82
	Ground water	677	295
	Lake water	117,13	1,94
	Lake water to turbine	-1,29	1014,73
	Rainwater	-28144	-29893
	River water	1427	1200
	River water to turbine	135	17597
	Sea water	31	n/a
	Ammonia	-1,90E-03	1,83E-03

Emissions to air	Carbon dioxide	124	-1040
	Carbon monoxide	0,01	0,14
	Nitrogen dioxide	1,98E-03	1,15E-03
	Nitrogen monoxide	-6,41E-04	-1,05E-02
	Nitrogen oxides	-0,18	0,26
	Nitrous oxide (laughing gas)	-2,28E-02	-2,12E-02
	Sulphur dioxide	0,16	0,61
	Sulphur hexafluoride	-3,45E-11	-3,54E-11
	Sulphur oxides	-5,04E-09	6,22E-06
	Lead	3,37E-04	4,84E-04
	Methane	-1,38	-0,97
	Methane (biotic)	-2,58E-02	-2,35E-02
	Dust (> PM10)	6,76E-03	1,00E-01
	Dust (PM10)	-3,87E-04	7,48E-03
	Dust (PM2.5 - PM10)	-1,45E-02	7,34E-02
	Dust (PM2.5)	9,83E-03	5,66E-02
Emissions to water	Biological oxygen demand (BOD)	-3,47E-03	-1,38E-03
	Chemical oxygen demand (COD)	-7,03E-02	4,96E-01
	Total dissolved organic bound carbon (TOC)	4,89E-09	2,01E-05
	Total organic bound carbon (TOC)	-2,70E-03	-2,69E-03
	Nitrate	8,48E-08	2,80E-07
	Nitrogen organic bound	-1,36E-05	-1,31E-05
	Phosphate	-5,20E-02	-4,85E-02
	Phosphorus	7,70E-05	1,64E-04
	Sulfate	-1,12E-01	1,86E-01
	Sulphuric acid	2,97E-08	3,16E-04
	Collected rainwater to river	9,76E+00	2,49E+01
	Cooling water to river	1,32E+03	2,22E+02
	Processed water to groundwater	9,25E+00	6,87E+00
	Processed water to lake	-9,74E-04	-8,33E-04
	Processed water to river	-2,71E+02	-7,73E+02
	Turbined water to river	1,13E+03	2,04E+04

Table 3-13: LCI results of total battery life cycle per battery type and FU – Micro-hybrid application (units in kg unless otherwise noted)

		Micro-hybrid application	
Type	Flow	PbB Advanced	LiB - LFP

Resources	Crude oil (resource) [MJ]	-27234	-28060
	Hard coal (resource) [MJ]	-156,24	1490
	Lignite (resource) [MJ]	-11,06	9,10
	Natural gas (resource) [MJ]	-5489	-5520
	Uranium (resource) [MJ]	-59,64	-104,88
	Renewable energy resources [MJ]	-2748	-2395
	Non-renewable elements	-3,09	-2,29
	Non-renewable resources	44,63	505,26
	Renewable resources	-129250	-25443
	Fresh water	-0,437	6,54
	Ground water	600	245
	Lake water	112,14	1,94
	Lake water to turbine	-6,42	1014,73
	Rainwater	-58197	-60437
	River water	187	38
	River water to turbine	26	17496
	Sea water	-778	n/a
Emissions to air	Ammonia	-8,87E-03	-5,09E-03
	Carbon dioxide	-1143	-2354
	Carbon monoxide	-0,19	-0,06
	Nitrogen dioxide	1,06E-03	3,25E-04
	Nitrogen monoxide	-1,55E-02	-2,51E-02
	Nitrogen oxides	-0,59	-0,14
	Nitrous oxide (laughing gas)	-4,90E-02	-4,77E-02
	Sulphur dioxide	-0,02	0,44
	Sulphur hexafluoride	-9,22E-11	-9,34E-11
	Sulphur oxides	-1,28E-08	6,21E-06
	Lead	3,15E-04	4,74E-04
	Methane	-3,00	-2,62
	Methane (biotic)	-5,67E-02	-5,47E-02
	Dust (> PM10)	1,12E-03	9,52E-02
	Dust (PM10)	-1,04E-03	6,83E-03
	Dust (PM2.5 - PM10)	-3,47E-02	5,31E-02
	Dust (PM2.5)	-1,38E-03	4,60E-02
Emissions to water	Biological oxygen demand (BOD)	-8,09E-03	-6,05E-03
	Chemical oxygen demand (COD)	-1,88E-01	3,78E-01
	Total dissolved organic bound carbon (TOC)	-2,31E-09	2,01E-05
	Total organic bound carbon (TOC)	-5,75E-03	-5,78E-03
	Nitrate	7,14E-08	2,70E-07

	Nitrogen organic bound	-2,83E-05	-2,81E-05
	Phosphate	-1,07E-01	-1,05E-01
	Phosphorus	2,40E-05	1,15E-04
	Sulphate	-4,26E-01	-1,27E-01
	Sulphuric acid	1,68E-07	3,16E-04
	Collected rainwater to river	4,22E+00	1,99E+01
	Cooling water to river	1,21E+03	1,62E+02
	Processed water to groundwater	5,97E+00	4,00E+00
	Processed water to lake	-1,37E-03	-1,26E-03
	Processed water to river	-1,42E+03	-1,91E+03
	Turbined water to river	9,77E+02	2,03E+04

4. Life Cycle Impact Assessment

This chapter contains the results for primary energy demand, global warming potential, acidification potential, eutrophication potential, and photochemical ozone creation potential, as well as additional metrics defined in section 4. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so.

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

4.1. Overall Results Summary

Results for the total life cycle of lead and LFP batteries are displayed in Table 4-1. Negative values in LCIA results are derived from the application of system expansion (environmental credits) in the model. This is a commonly applied methodological choice to address the recovery of secondary materials or energy avoiding its production through primary routes. System expansion is sometimes referred as an “avoided impact approach”. Negative values in LCIA results are derived from both the application of EoL system expansion (environmental credits) and fuel saving credits in the model. The avoided fuel consumption and recycling credits lead in some cases to a higher credit than the environmental burdens associated with producing the batteries.

Table 4-1: Total Life Cycle LCIA for Lead and LFP batteries per vehicle application and FU

Application	Conventional ICE		Start-stop		Micro-hybrid	
Impact / Indicator	PbB Standard	LIB - LFP	PbB Improved	LIB - LFP	PbB Advanced	LIB - LFP
GWP 100, excl biogenic CO2 [kg CO2 eq.]	1,3E+02	3,0E+02	-1,2E+03	-1,1E+03	-2,6E+03	-2,4E+03
Primary energy demand from ren. and non ren. resources (net cal. value) [MJ]	2,1E+03	4,1E+03	2,1E+03	-1,5E+04	-3,6E+04	-3,5E+04
Primary energy from non renewable resources (net cal. value) [MJ]	1,9E+03	3,5E+03	1,9E+03	-1,4E+04	-3,3E+04	-3,2E+04
Primary energy from renewable resources (net cal. value) [MJ]	1,7E+02	5,9E+02	1,7E+02	-9,0E+02	-2,8E+03	-2,4E+03
Acidification [kg SO2 eq.]	3,4E-01	1,4E+00	3,4E-01	9,2E-01	-7,1E-01	4,2E-01
Eutrophication [kg N eq.]	2,8E-02	1,1E-01	2,8E-02	-2,5E-01	-6,8E-01	-6,1E-01
Human Health Impacts from Exposure to Particulate Matter [kg PM2.5 eq.]	6,2E-02	1,5E-01	6,2E-02	1,2E-01	1,9E-02	9,5E-02
Photochemical Smog Formation [kg O3 eq.]	2,8E+00	1,7E+01	2,8E+00	6,3E+00	-2,0E+01	-4,4E+00

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 different, vehicle application and FU for each life cycle stage is displayed.

Table 4-2: Primary energy demand from ren. and non ren. Resources (PED) [MJ]

	conventional ICE		Start-stop		Micro-hybrid	
Life Cycle Stage	PbB	LiB - LFP	PbB	LiB - LFP	PbB	LiB - LFP
Manufacturing stage	1230	4530	1260	4530	1220	4530
Use stage	962	0	-18100	-19400	-37100	-38700
EoL	-135	-407	-256	-407	-247	-407
Total Life Cycle	**2057**	**4123**	**-17096**	**-15277**	**-36127**	**-34577**

As in the rest of analysed impact categories and indicators, the use stage dominates the overall results for the start-stop and micro-hybrid application. For the ICE, the manufacturing stage is dominant for LFP and PbB. As described in section 3.3, the use stage refers to the fuel saving due to the battery technology on car level, independent of the battery chemistry. In the case of PbB the weight difference compared to LFP batteries has also been considered.

In Figure 4-1 the overall results per battery technology and vehicle application according to the functional unit is displayed.

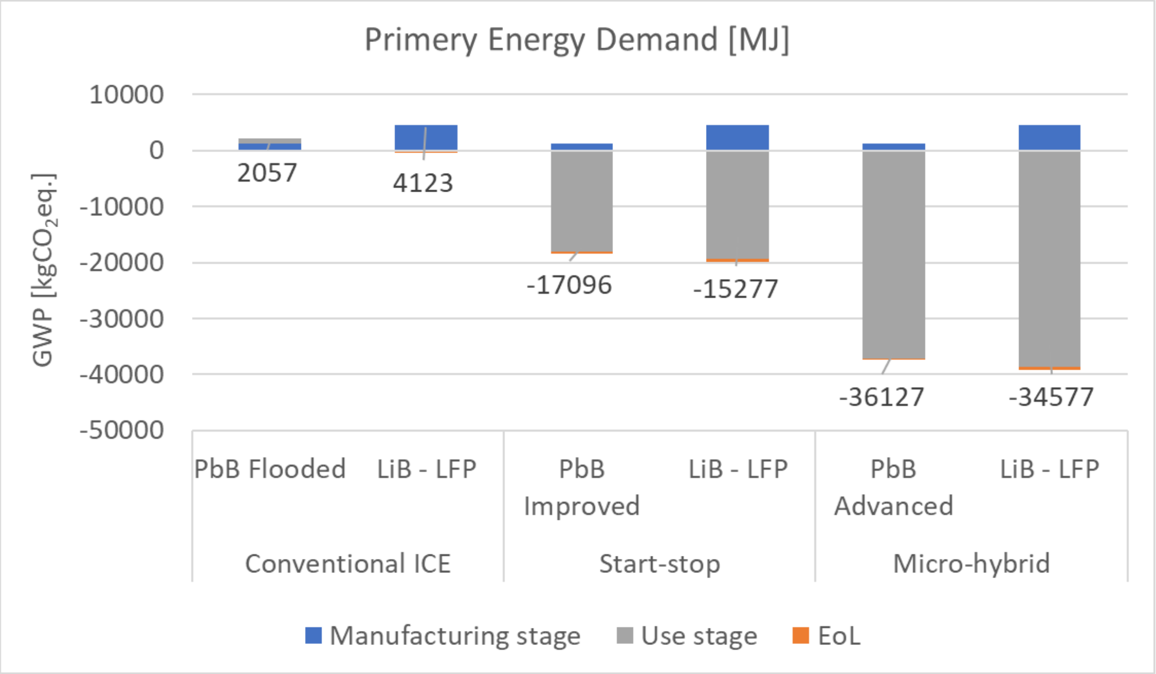

Figure 4-1: Overall Life Cycle PED per battery technology, vehicle application and FU

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

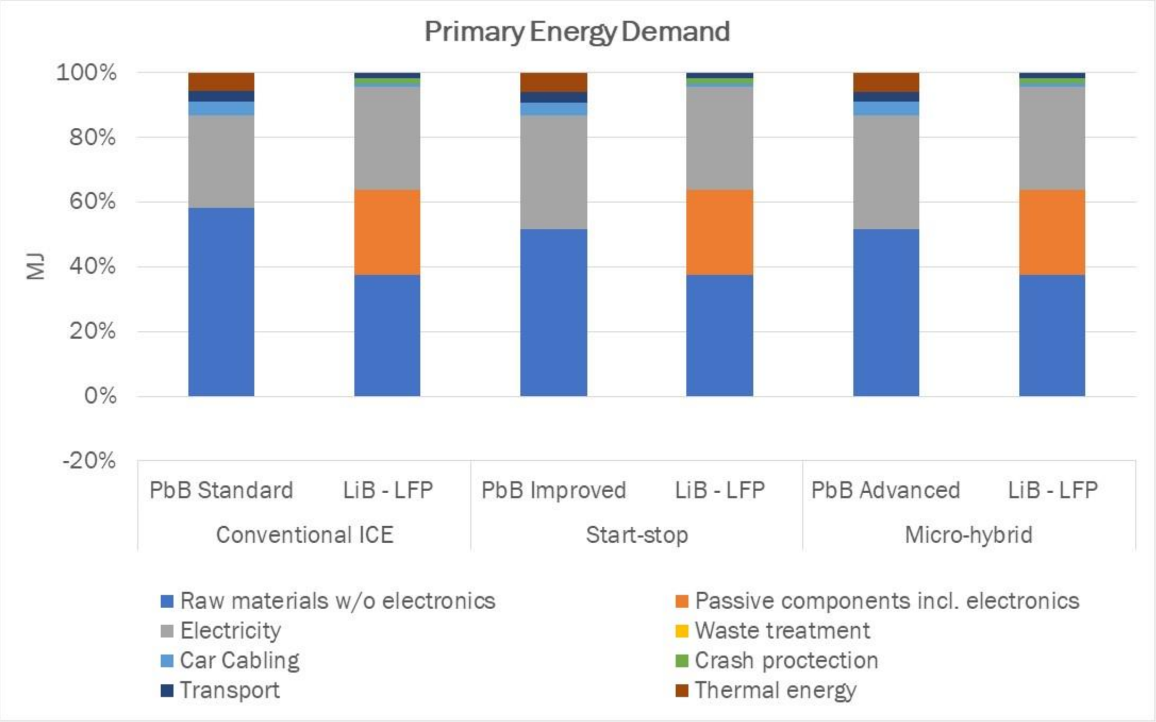

Figure 4-2: Main contributors to the PED (manufacturing stage) per battery technology, vehicle application and FU

For all battery types the manufacturing stage is dominated by the raw materials (approx. 58%-52% for PbB and 38% for LiB - LFP) followed by electricity (approx. 29%-35% for PbB and 32% for LiB - LFP). In the case of LiB -LFP the electricity is followed by the passive components including electronics (approx. 26%). Other components such as car cabling (approx. .4% for PbB and 1% for LiB - LFP) and crash protection (1%) have a lower contribution to the manufacturing stage results.

4.3. Global Warming Potential

As the name suggests, the mechanism of the greenhouse effect can be observed on a small scale in a greenhouse; incoming solar energy is trapped, causing the internal temperature to rise. This effect also occurs on a global scale. When short-wave ultraviolet radiation from the sun meets the Earth's surface some energy is re-emitted as longer wave infrared radiation. Instead of directly heading back out to space, some of this infrared radiation is absorbed by greenhouse gases in the troposphere and re-radiated in all directions, including back to earth. This results in a warming effect at the earth's surface. In addition to the natural mechanism, the greenhouse effect is enhanced by human activities. Greenhouse gases that are caused or increased, anthropogenically include, carbon dioxide, methane and CFCs. Since the residence time of the gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified; a period of 100 years is customary.

In Table 4-3 the GWP for the lead and LFP batteries according to the different technologies and vehicle application per FU for each life cycle stage is displayed.

Table 4-3: Global Warming Potential [kg CO_2 eq.]

	Conventional ICE		Start-stop		Micro-hybrid	
Life Cycle Stage	PbB	LiB - LFP	PbB	LiB - LFP	PbB	LiB - LFP
Manufacturing stage	73	316	75	316	72	316
Use stage	68	0	-1280	-1370	-2630	-2740
EoL	-7	-17	-13	-17	-12	-17
Total Life Cycle	**133**	**299**	**-1218**	**-1071**	**-2570**	**-2441**

As in the rest of analysed impact categories and indicators, the use stage dominates the overall results for the start-stop and micro-hybrid application. For the internal combustion engines (ICE) ICE, the manufacturing stage is dominant for LFP and for PbB both manufacturing and use stage are in the same magnitude. As described in section 3.3, the use stage refers to fuel saving due to the battery technology on car level, independent of the battery chemistry. In the case of PbB the weight difference compared to LFP batteries has also been considered.

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

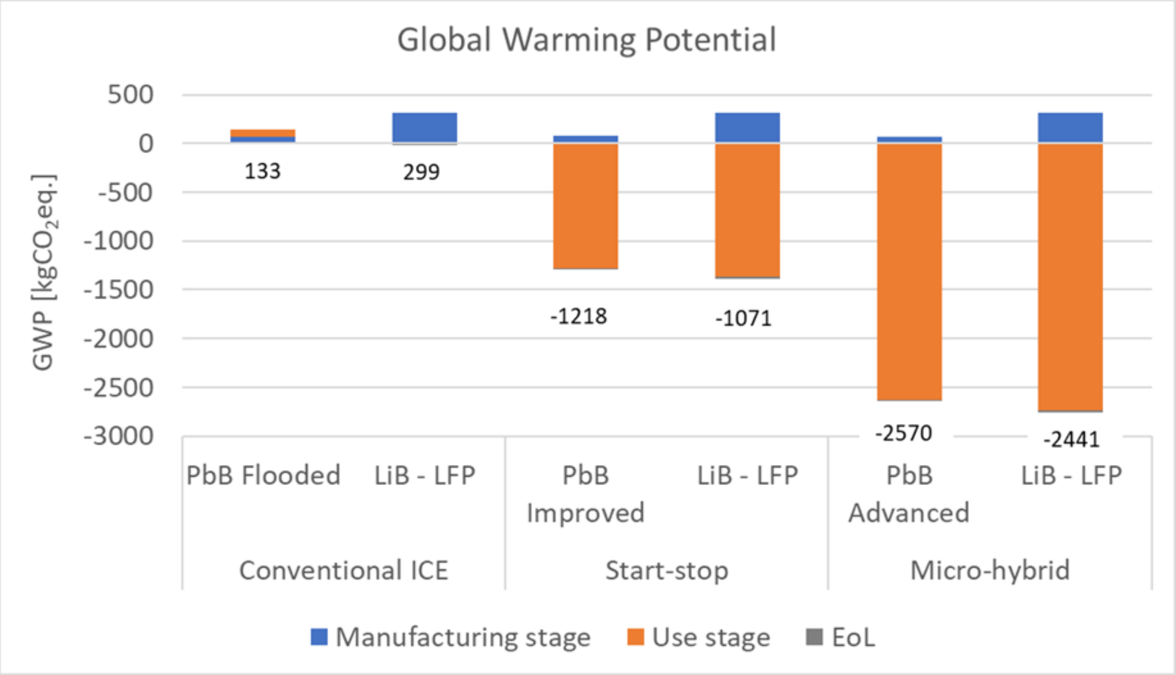

Figure 4-3: Overall Life Cycle GWP per battery technology, vehicle application and FU

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

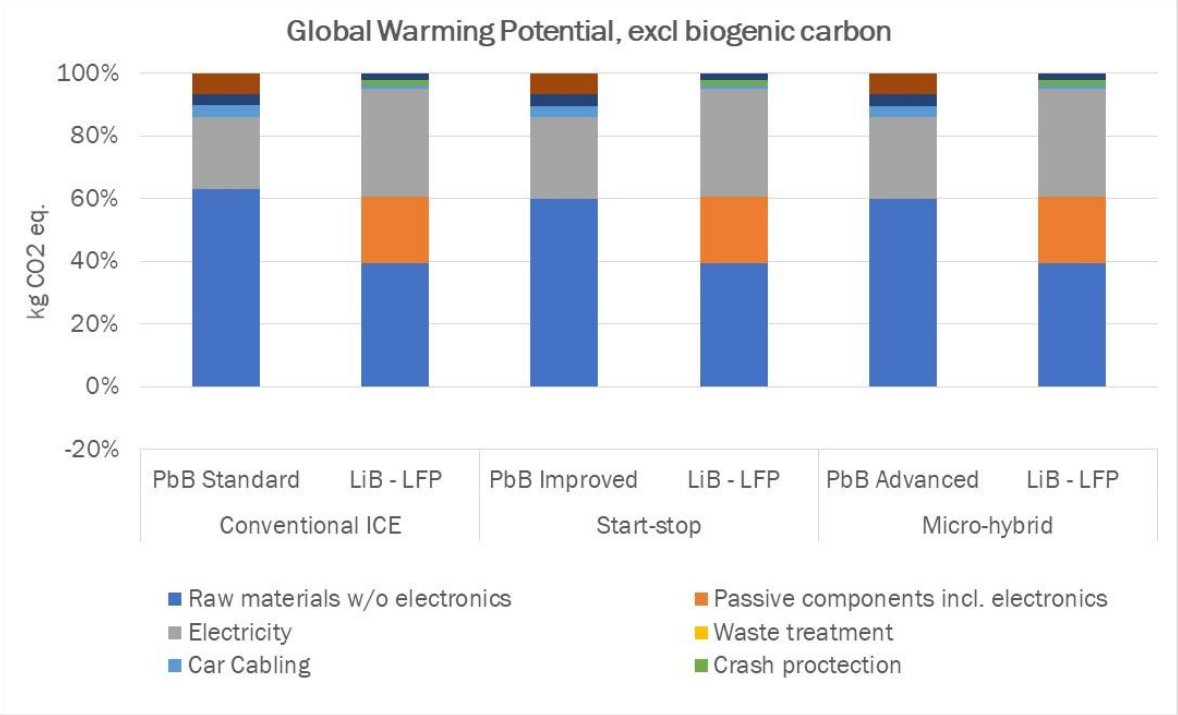

Figure 4-4: Main contributors to the GWP (manufacturing stage) per battery technology, vehicle application and FU

For PbB the manufacturing stage is dominated by the raw materials (approx. 60-63%) followed by electricity (approx. 23%-26%). In the case of LiB - LFP, the electricity and raw materials dominate the manufacturing stage (approx. 35% and 39%, respectively) followed by the passive components including electronics (approx. 21%). Other components such as car cabling (approx. 4% for PbB and 1% for LiB - LFP) and crash protection (2% for LiB - LFP) have a lower contribution to the manufacturing stage results.

4.4. Acidification Potential

The acidification of soils and waters occurs predominantly through the transformation of air pollutants into acids. This leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and below. Sulphur dioxide and nitrogen oxide and their respective acids (H_2SO_4 und HNO_3) produce relevant contributions. This damages ecosystems, whereby forest dieback is the most well-known impact.

Acidification has direct and indirect damaging effects (such as nutrients being washed out of soils or an increased solubility of metals into soils). But even buildings and building materials can be damaged. Examples include metals and calcium carbonate-based rocks (e. g. marble, limestone), which are corroded or disintegrated at an increased rate.

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

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

	Conventional ICE		Start-stop		Micro-hybrid	
Life Cycle Stage	PbB	LiB - LFP	PbB	LiB - LFP	PbB	LiB - LFP
Manufacturing stage	0,41	1,6	0,4	1,6	0,41	1,6
Use stage	0,025	0	-0,47	-0,50	-1,0	-1,0
EoL	-0,10	-0,17	-0,16	-0,17	-0,16	-0,17
Total Life Cycle	0,34	1,4	-0,21	0,92	-0,71	0,42

In contrary to the rest of analysed impact categories and indicators, the use stage begins to dominate the overall results for the micro-hybrid (PbB and LiB - LFP) application. For the conventional ICE (PbB and LiB - LFP) and start-stop (LiB - LFP), the manufacturing stage is dominant. As described in section 3.3, the use stage refers to the fuel saving due to the battery technology on car level, independent of the battery chemistry. In the case of PbB the weight difference compared to LFP batteries has also been considered.

In Figure 4-5 the overall results per battery technology and vehicle application according to the functional unit is displayed.

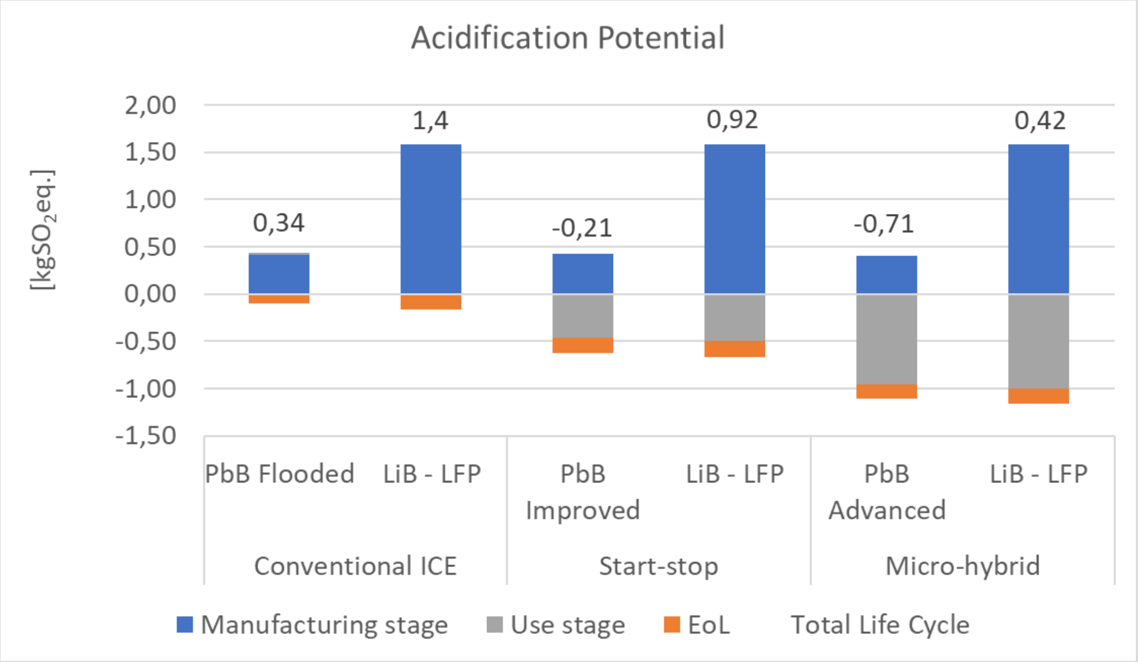

Figure 4-5: Overall Life Cycle AP per battery technology, vehicle application and FU

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

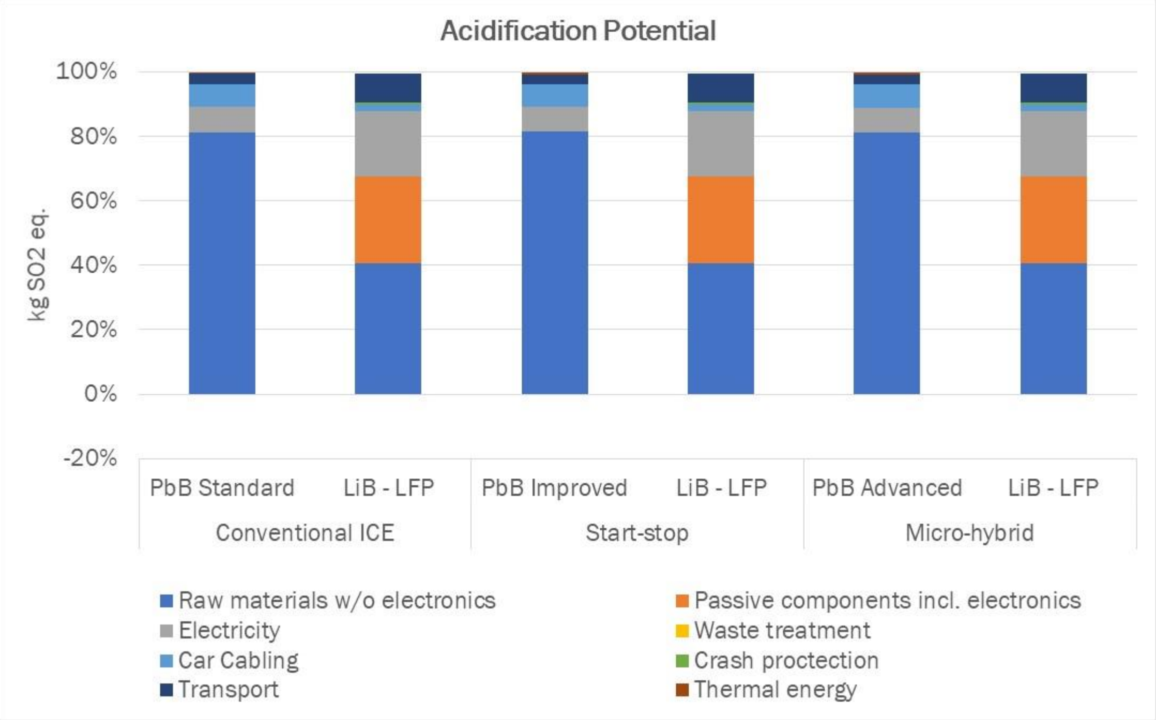

Figure 4-6: Main contributors to the AP (manufacturing stage) per battery technology, vehicle application and FU

For all battery types the manufacturing stage is dominated by the raw materials (approx. 81% - PbB and 41% - LFP) followed by electricity (approx. 8% for PbB and 21% LiB - LFP). In the case of LFP the electricity is followed by the passive components including electronics (approx. 27%). Other components such as; car cabling (approx. 7% PbB and 2% LiB - LFP) and crash protection (1% for LiB - LFP) have a lower contribution to the manufacturing stage results.

4.5. Eutrophication Potential

Eutrophication is the enrichment of nutrients in the environment. Eutrophication can be aquatic or terrestrial. Air pollutants, wastewater and fertilization in agriculture all contribute to eutrophication.

The result in water is an accelerated algae growth, which in turn, prevents sunlight from reaching the lower depths. This leads to a decrease in photosynthesis and less oxygen production. In addition, oxygen is needed for the decomposition of dead algae. Both effects cause a decreased oxygen concentration in the water, which can eventually lead to fish dying and to anaerobic decomposition (decomposition without the presence of oxygen). Hydrogen sulphide and methane are thereby produced, further damaging the eco-system.

Overly nutrient enriched soils may result in an increased susceptibility of plants to diseases and pests as well as degradation of plant stability. If the nutrification level exceeds the amounts of nitrogen necessary for a maximum harvest, it can lead to an enrichment of nitrate. This can cause, by means of leaching, increased nitrate content in groundwater and may also end up in drinking water. Nitrate at low levels is harmless from a toxicological point of view. However, nitrite, a reaction product of nitrate, is toxic to humans.

In Table 4-5 the EP for the lead and LFP batteries according to the different technologies, vehicle application and FU for each life cycle stage is displayed.

Table 4-5: Eutrophication Potential (EP) [kg N eq.]

	Conventional ICE		Start-stop		Micro-hybrid	
Life Cycle Stage	PbB	LiB - LFP	PbB	LiB - LFP	PbB	LiB - LFP
Manufacturing stage	0,013	0,12	0,01	0,12	0,014	0,12
Use stage	0,018	0	-0,34	-0,36	-0,69	-0,72
EoL	-0,0033	-0,0041	-0,0060	-0,0041	-0,0058	-0,0041
Total Life Cycle	0,028	0,11	-0,33	-0,25	-0,68	-0,61

As in almost all of analysed impact categories and indicators, the use stage dominates the overall results for the start-stop and micro-hybrid application. For the internal combustion engines (ICE), the manufacturing stage is dominant for LiB - LFP and PbB. As described in section 3.3, the use stage refers to the fuel saving due to the battery technology on car level, independent of the battery chemistry. In the case of PbB the weight difference compared to LFP batteries has also been considered.

In Figure 4-7 the overall results per battery technology and vehicle application according to the functional unit is displayed.

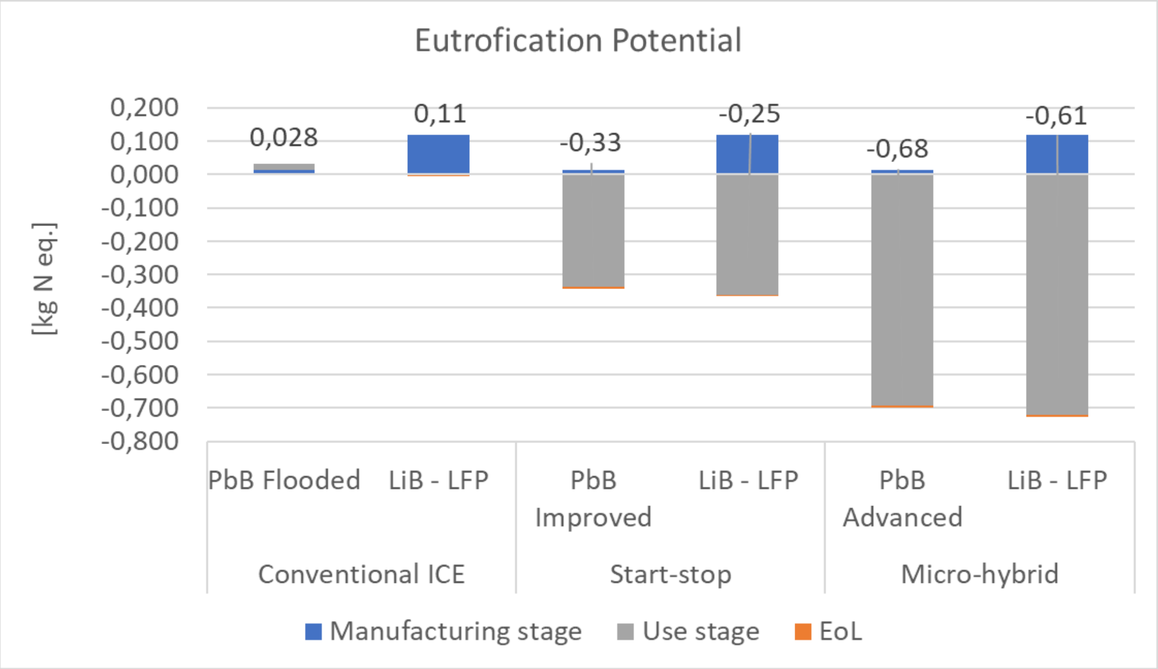

Figure 4-7: Overall Life Cycle EP per battery technology, vehicle application and FU

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

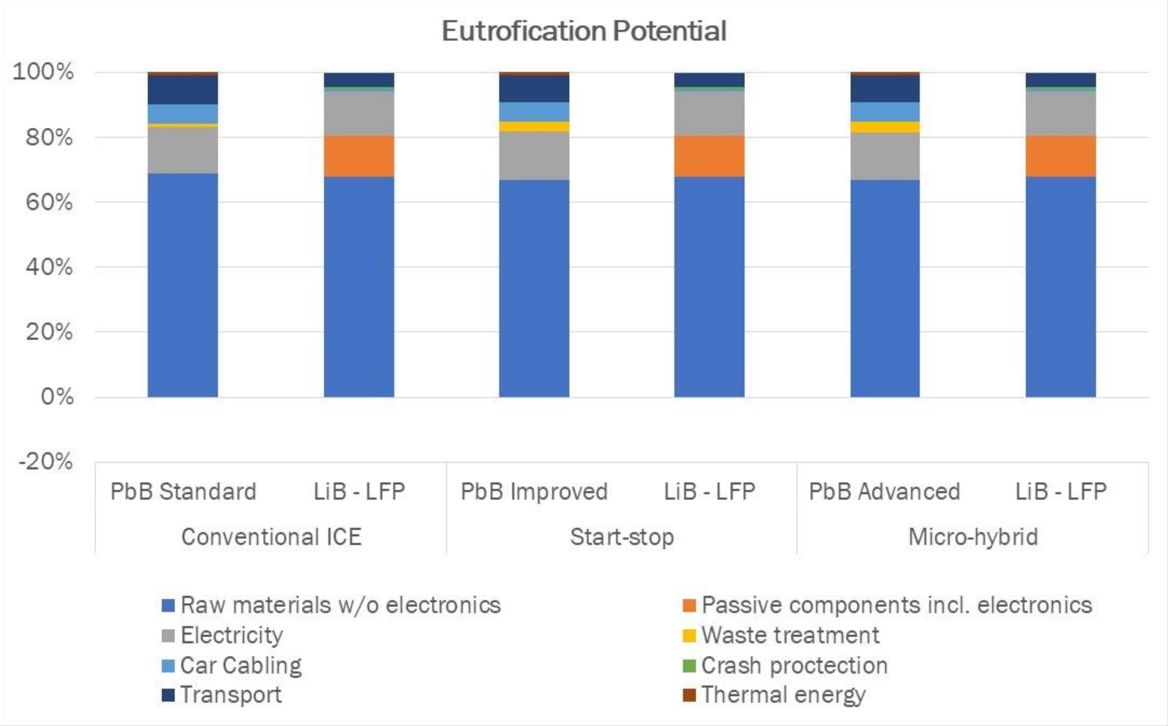

Figure 4-8: Main contributors to the EP (manufacturing stage) per battery technology, vehicle application and FU

For PbB the manufacturing stage is dominated by the raw materials (approx. 67%-69%) followed by electricity (approx. 14%). In the case of LiB – LFP, the raw materials (approx. 68%) dominates the manufacturing stage followed by the electricity (approx. 14%) and the passive components including electronics (approx. 13%). Other components such as; car cabling (approx. 6% for PbB and 1% for LiB - LFP) and crash protection (1% for LiB - LFP) have a lower contribution to the manufacturing stage results.

4.6. Human Health Impacts from Exposure to Particulate Matter Human

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,' category used in TRACI 2.1 has been applied, which uses $PM_{2.5}$ as a reference substance.

In Table 4-6 the Human Health Impacts from Exposure to Particulate Matter, for the lead and LFP batteries according to the different technologies, vehicle application and FU for each life cycle stage is displayed.

Table 4-6: Human Health Impacts from Exposure to Particulate Matter, (POCP) [$PM_{2.5}$]

	Conventional ICE		Start-stop		Micro-hybrid	
Life Cycle Stage	PbB	LiB - LFP	PbB	LiB - LFP	PbB	LiB - LFP
Manufacturing stage	0,054	0,16	0,055	0,16	0,053	0,16
Use stage	0,0013	0,00	-0,024	-0,026	-0,050	-0,052
EoL	0,0067	-0,016	0,017	-0,016	0,017	-0,016
Total Life Cycle	0,062	0,15	0,048	0,12	0,019	0,095

In contrary to the rest of analysed impact categories and indicators, the use stage begins to dominate the overall results for the micro-hybrid (PbB and LiB - LFP) application. For the internal combustion engines (ICE) (PbB and LiB - LFP) and start-stop (LiB - LFP), the manufacturing stage is dominant. As described in section 3.3, the use stage refers to the fuel saving due to the battery technology on car level, independent of the battery chemistry. In the case of PbB the weight difference compared to LFP batteries has also been considered.

In Figure 4-9 the overall results per battery technology and vehicle application according to the functional unit is displayed.

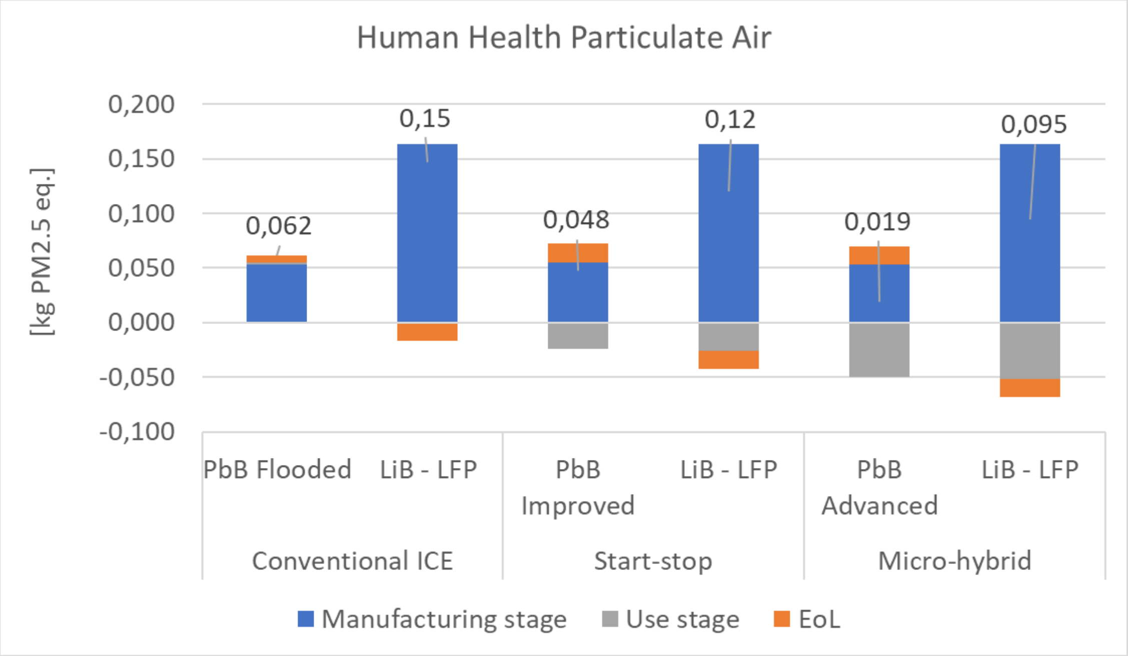

Figure 4-9: Overall Life Cycle Human Health Impacts from Exposure to Particulate Matter, per battery technology, vehicle application and FU

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

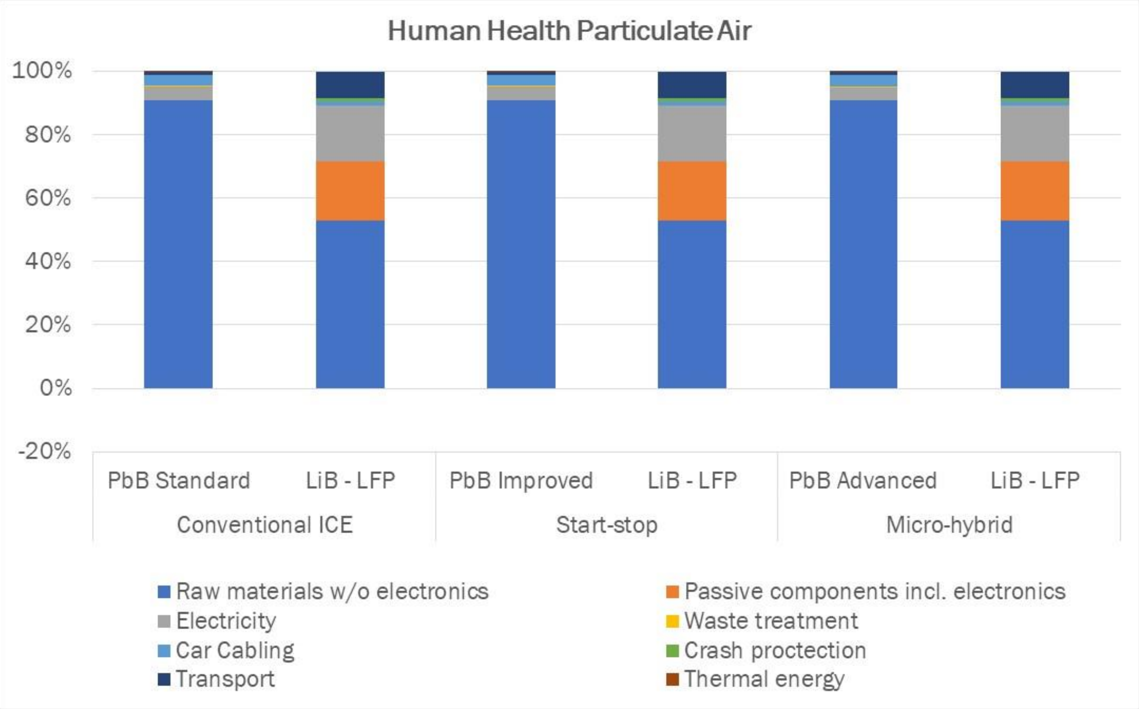

Figure 4-10: Main contributors to the Human Health Impacts from Exposure to Particulate Matter, (manufacturing stage) per battery technology, vehicle application and FU

For PbB the manufacturing stage is dominated by the raw materials (approx. 91%) followed by electricity (approx. 4%). In the case of LiB – LFP, the raw materials dominate the manufacturing stage (approx. 53%), followed by the electricity (approx. 18%) and the passive components including electronics (approx. 19%). Other components such as; car cabling (approx. 4% for PbB and 1% for LiB - LFP) and crash protection (1% for LiB - LFP) 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 4-6 the Photochemical Smog Formation for the lead and LFP batteries according to the different technologies, vehicle application and FU for each life cycle stage is displayed.

Table 4-7: Photochemical Smog Formation (POCP) [kg O_3]

	Conventional ICE		Start-stop		Micro-hybrid	
Life Cycle Stage	PbB	LiB - LFP	PbB	LiB - LFP	PbB	LiB - LFP
Manufacturing stage	3,7	18	3,7	18	3,6	18
Use stage	0,53	0,0	-10	-11	-21	-21
EoL	-1,5	-1,4	-3,0	-1,4	-2,9	-1,4
Total Life Cycle	2,8	17,0	-9,3	6,3	-19,9	-4,4

In contrary to the rest of analysed impact categories and indicators, the use stage begins to dominate the overall results for the micro-hybrid (PbB and LiB - LFP) application. For the conventional ICE (PbB and LiB - LFP) and start-stop (LiB - LFP), the manufacturing stage is dominant. As described in section 3.3, the use stage refers to the fuel saving due to the battery technology on car level, independent of the battery chemistry. In the case of PbB the weight difference compared to LFP batteries has also been considered.

In Figure 4-9 the overall results per battery technology and vehicle application according to the functional unit is displayed.

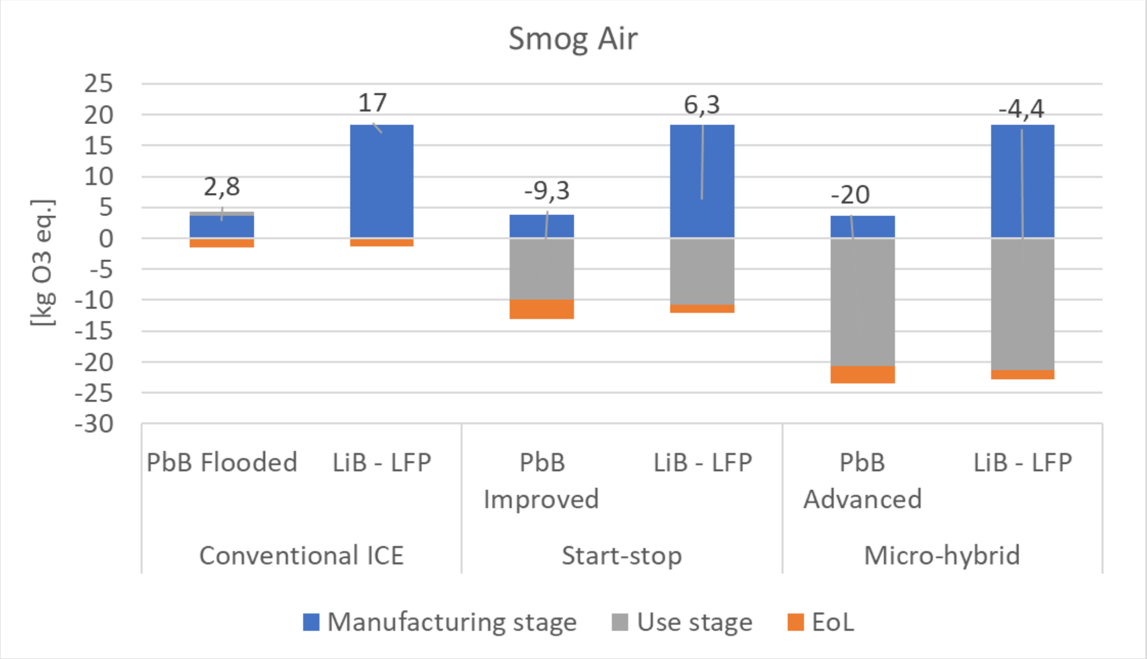

Figure 4-11: Overall Life Cycle Photochemical Smog Formation per battery technology, vehicle application and FU

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

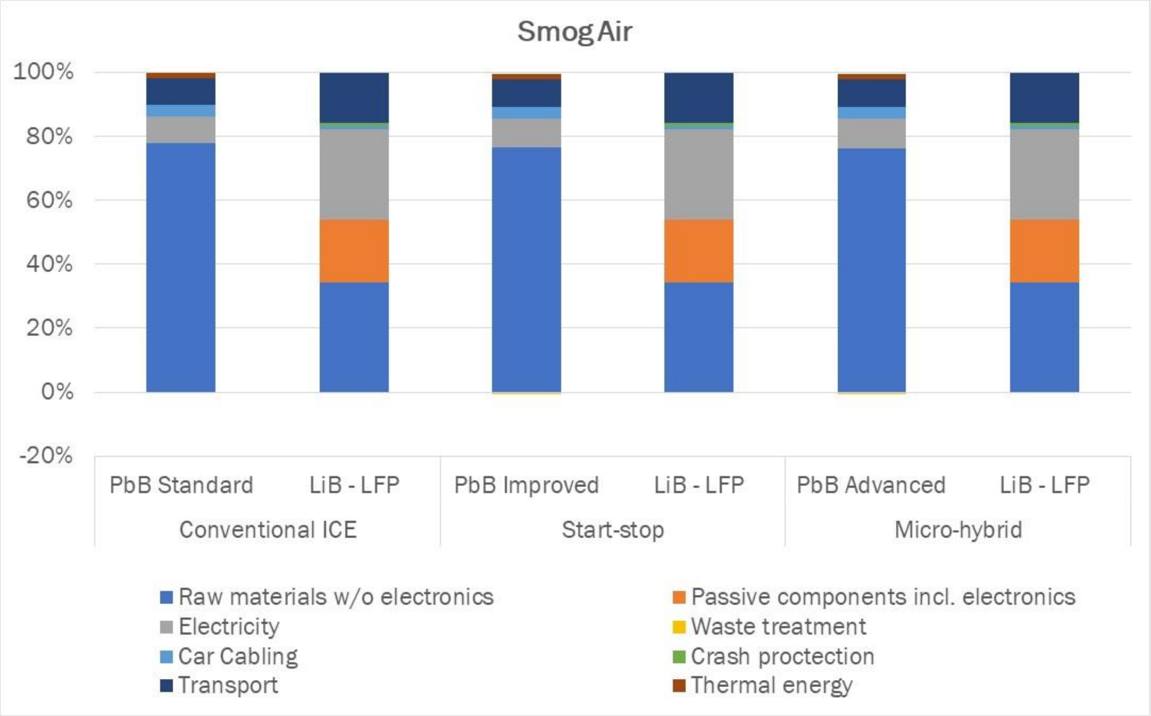

Figure 4-12: Main contributors to the Photochemical Smog Formation (manufacturing stage) per battery technology, vehicle application and FU

For PbB the manufacturing stage is dominated by the raw materials (approx. 78%) followed by electricity (approx. 8%). In the case of LiB – LFP, the raw materials dominate the manufacturing stage (approx. 34%), followed by the electricity (approx. 29%) and the passive components including electronics (approx. 20%). Other components such as; car cabling (approx. 4% for PbB and 1% for LiB - LFP) and crash protection (1% for LiB - LFP) have a lower contribution to the manufacturing stage results.

4.8. Blue water consumption

In Table 4-8 the blue water consumption for the PbB and LFP batteries according to the different technologies, vehicle application and FU for each life cycle stage is displayed.

Table 4-8: Blue water consumption [kg]

	Conventional ICE		Start-stop		Micro-hybrid	
Life Cycle Stage	PbB	LiB - LFP	PbB	LiB - LFP	PbB	LiB - LFP
Manufacturing stage	467	2020	484	2020	466	2020
Use stage	431	0	-8100	-8670	-16600	-17300
EoL	88,3	-141	220	-141	212	-141
Total Life Cycle	**986**	**1879**	**-7396**	**-6791**	**-15922**	**-15421**

In contrary to the rest of analysed impact categories and indicators, the use stage begins to dominate the overall results for the micro-hybrid (PbB and LiB - LFP) application. For the conventional ICE (PbB and LiB

- LFP) and start-stop (LiB - LFP), the manufacturing stage is dominant. As described in section 3.3, the use stage refers to the fuel saving due to the battery technology on car level, independent of the battery chemistry. In the case of PbB the weight difference compared to LFP batteries has also been considered.

In Figure 4-9 the overall results per battery technology and vehicle application according to the functional unit is displayed.

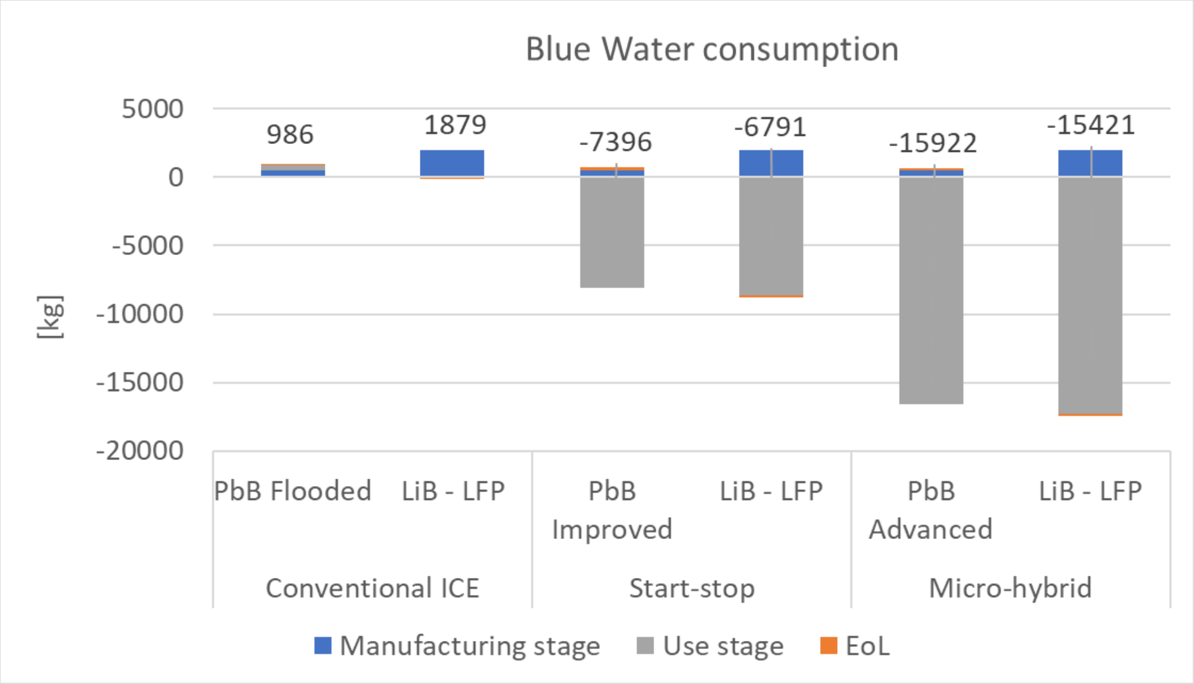

Figure 4-13: Overall Life Cycle Blue Water consumption per battery technology, vehicle application and FU

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

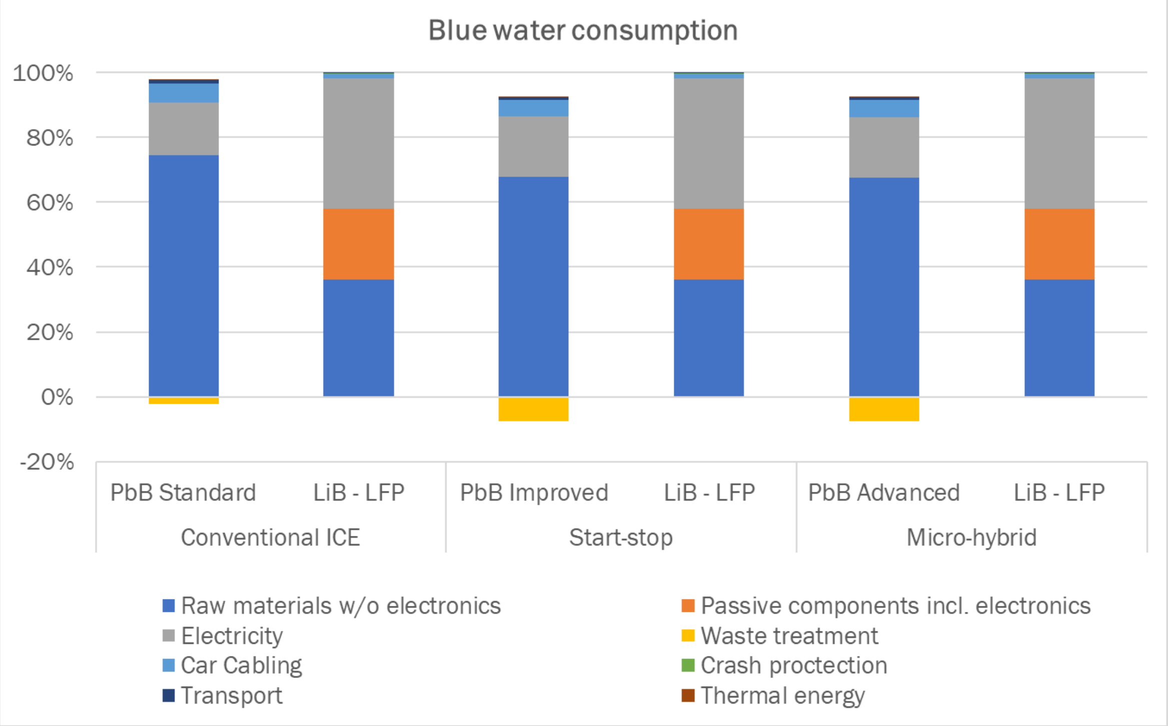

Figure 4-14: Main contributors to the Blue Water consumption (manufacturing stage) per battery technology, vehicle application and FU

For PbB the manufacturing stage is dominated by the raw materials (approx. 91%) followed by electricity (approx. 4%). In the case of LiB – LFP, the raw materials dominate the manufacturing stage (approx. 53%), followed by the electricity (approx. 18%) and the passive components including electronics (approx. 19%). Other components such ascar cabling (approx. 4% for PbB and 1% for LiB - LFP) and crash protection (1% for LiB - LFP) have a lower contribution to the manufacturing stage results.

5. Interpretation

5.1. Identification of Significant Aspects

The 12v batteries assessed in this study are required in internal combustion engines (ICE), start-stop and micro-hybrid vehicles. Based on the assumptions defined for the study, the use stage dominates the overall life cycle for all battery types (Pb and LFP) particularly for start-stop and micro-hybrid due to the fuel saving properties of these vehicles. Lead batteries have a higher weight compared to the LFP batteries, which leads to an increase in fuel consumption. This effect is especially visible for the conventional ICE vehicles using standard lead batteries vs LFP batteries.

In the manufacturing stage, lead production and electricity use are most often the primary drivers of impacts for lead batteries. 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, while the crash protection and car cabling have minor contribution to all impact categories analysed.

In the EoL, a collection rate of 99% is assumed for all battery types and applications (based upon quantitative data available for Pb batteries). 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 to the impact categories. Table 5-2 displays the significant aspects for the Primary Energy Demand. Further details can be found in the sections above.

Table 5-1: Summary of results main contributors for all battery types, vehicle applications and FU in percentage

Impact category	Main LC contributing to overall results	Main contributor to manufacturing results	Main input/output contributing to overall results
GWP	PbB Use stage: 46% (conventional ICE) 92% (Start-stop) 98% (micro hybrid) Manufacturing: 49% (conventional ICE) LiB - LFP Use stage: 80% (Start-stop) 89% (micro hybrid) Manufacturing: 94% (conventional ICE)	PbB Raw materials without electronics 63%-60% / Electricity 23%-21% LiB - LFP Electricity 35% / Raw materials without electronics 39% / Passive components with electronics 21%	PbB Carbon dioxide emission to air 94 - 99% LiB - LFP Carbon dioxide emission to air 88 - 99%

Photochemical Smog Formation	PbB Use stage: 60% (Start-stop) 77% (micro hybrid) Manufacturing: 63% (conventional ICE) LiB - LFP Use stage: 35% (Start-stop) 52% (micro hybrid) Manufacturing: 93% (conventional ICE) 60% (Start-stop) 44% (micro hybrid)	PbB Raw materials without electronics 78% / Electricity 8% LiB - LFP Electricity 29% / Raw materials without electronics 34% / Passive components with electronics 20%	PbB Nitrogen oxides 96%-49% Nitrogen monoxide 17% Cyanide 20% LiB - LFP Nitrogen oxides 100%-80%
AP	PbB Use stage: 44% (Start-stop) 63% (micro hybrid) Manufacturing: 90% (conventional ICE) LiB - LFP Use stage: 35% (Start-stop) 52% (micro hybrid) Manufacturing: 90% (conventional ICE) 70% (Start-stop) 58% (micro hybrid)	PbB Raw materials without electronics 81% / Electricity 8% LiB - LFP Electricity 21% / Raw materials without electronics 41% / Passive components with electronics 27%	PbB Sulphur dioxide emission to air 65 - 83% LiB - LFP Sulphur dioxide emission to air 68 - 76%
EP	PbB Use stage: 51% (conventional ICE) 95% (Start-stop) 98% (micro hybrid) Manufacturing: 39% (conventional ICE) LiB - LFP Use stage: 75% (Start-stop) 86% (micro hybrid) Manufacturing: 98% (conventional ICE)	PbB Raw materials without electronics 58%-52% / Electricity 29%-35%% LiB - LFP Electricity 32% / Raw materials without electronics 38% / Passive components with electronics 26%	PbB Emission to fresh water 95 - 97% LiB - LFP Emissions to fresh water 73 - 89%
Human Health Impacts from Exposure to Particulate Matter,	PbB) Manufacturing: 87% (conventional ICE)	PbB Raw materials without electronics 91% LiB - LFP	PbB Nitrogen oxides - 56%, sulfur dioxide 50% - 17% Dust (PM 2,5) 18% - 78%

	58% (Start-stop) 53% (micro hybrid) Use stage: 25% (Start-stop) 41% (micro hybrid <u>LiB - LFP</u> Manufacturing: 90% (conventional ICE) 80% (Start-stop) 71% (micro hybrid) Use stage: 13% (Start-stop) 22% (micro hybrid)	Electricity 18% / Raw materials without electronics 53% / Passive components with electronics 19%	<u>LiB - LFP</u> Sulfur dioxide 28% - 33% Dust (PM 2,5) 49% - 46%

Table 5-2: Summary of the main contributors for all battery types, vehicle applications and FU in percentage for the Primary Energy Demand

Impact category	Main LC contributing to overall results	Main contributor to manufacturing results	Main input/output contributing to overall results
PED	<u>PbB</u> Use stage: 40% (conventional ICE) 92% (Start-stop) 98% (micro hybrid) Manufacturing: 52% (conventional ICE) <u>LiB - LFP</u> Use stage: 80% (Start-stop) 90% (micro hybrid) Manufacturing: 91% (conventional ICE)	<u>PbB</u> Raw materials without electronics 58% -52% / Electricity 29%-35% <u>LiB - LFP</u> Raw materials without electronics 38% / Electricity 32% / Passive components with electronics 26%	<u>PbB</u> Non-renewable energy resources 84 -96% <u>LiB - LFP</u> Non-renewable energy resources 96 - 98%

5.2. Assumptions and Limitations

The main limitation of the data used for both batteries types has 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 3.1.2).

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 (except car cabling and crash protection) has been included in the model and results. This approach has been taken from the PEFCR of rechargeable batteries[25]. The same reference has been taken to include the manufacturing electricity, water, auxiliary materials and emissions.

The net reduction in fuel consumption is a result of the application engine technology, of which the battery forms an integral part. The fuel savings presented, in Table 2-1, represent a best-case assumption for the battery, as the benefit is not exclusively due to the merit of the batteries. However, it should be stressed that batteries do enable the use of this engine technology.

The emission profile of the vehicle due to the combustion of the gasoline only considers the contribution of the CO_2 to the GWP and SO_2 to the Acidifiation Potential and provides a representative picture of the contribution of the burning of fuel in the engine to the GWP and AP stemming from use of the vehicle.

At the EoL stage a collection rate of 99% has been applied for both 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 have been assumed to be hoarded. This means the batteries are collected but not recycled straightaway. In this case collectors may hold on to their spent batteries (hoarded), waiting for the scrap value to increase.

Uncertainties associated with the assumptions on the weight of LFP battery, vehicle lifetime, fuel saving for start-stop and micro-hybrid have been assessed via the sensitivity analysis in the sections below.

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 this results.

5.3.1. LFP battery weight reduction

As LFP batteries may have the potential of a lower weight, a variation of the weight of the battery from 12 kg to 10 kg has been assessed. The reduction of the weight has been done by reducing the amount of battery components equally and proportionally to match the 10 kg weight in the manufacturing and EoL stages. As in the base scenario, this weight includes the electronics and excludes the crash protection and car cabling which remain the same regardless of this variation. The use stage remains the same as the data used is not linked to the battery weight rather the fuel saving according to the vehicle technology and battery specifications.

Table 5-3: Battery reference flows per Functional Unit (LFP battery weight reduction)

Battery application	Li-ion battery type	Weight (kg) baseline	Weight (kg) scenario	Capacity (Ah)	Lifetime (years)	No. of batteries vehicle lifetime
Conventional ICE	LFP	12	10	60	8	1.4
Start-stop	LFP	12	10	60	8	1.4
Micro-hybrid	LFP	12	10	60	8	1.4

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

Table 5-4: Global Warming Potential [kg CO_2 eq.] – LFP weight sensitivity

Total LC GWP (kg CO_2 eq.) results per FU - sensitivity analysis				
Application	Battery type	Weight (12 kg) baseline	Weight (10 kg) scenario	Variation (%)
Conventional ICE	LiB – LFP	299	257	-14%
Start-Stop	LiB – LFP	-1071	-1114	4%
Micro-hybrid	LiB – LFP	-2421	-2460	2%

The results in Table 5-4 above and Figure 5-1 show that the reduction of the LFP battery weight have no meaningful impact on the total Life Cycle of start-stop and micro-hybrid applications. The reason is due to the dominant impact of the use stage. The slightly positive effect of the weight reduction can be observed in the ICE battery application with a reduction of 14%. This reduction is a result of the consumption of less materials and therefore also of waste treatment in the EoL.

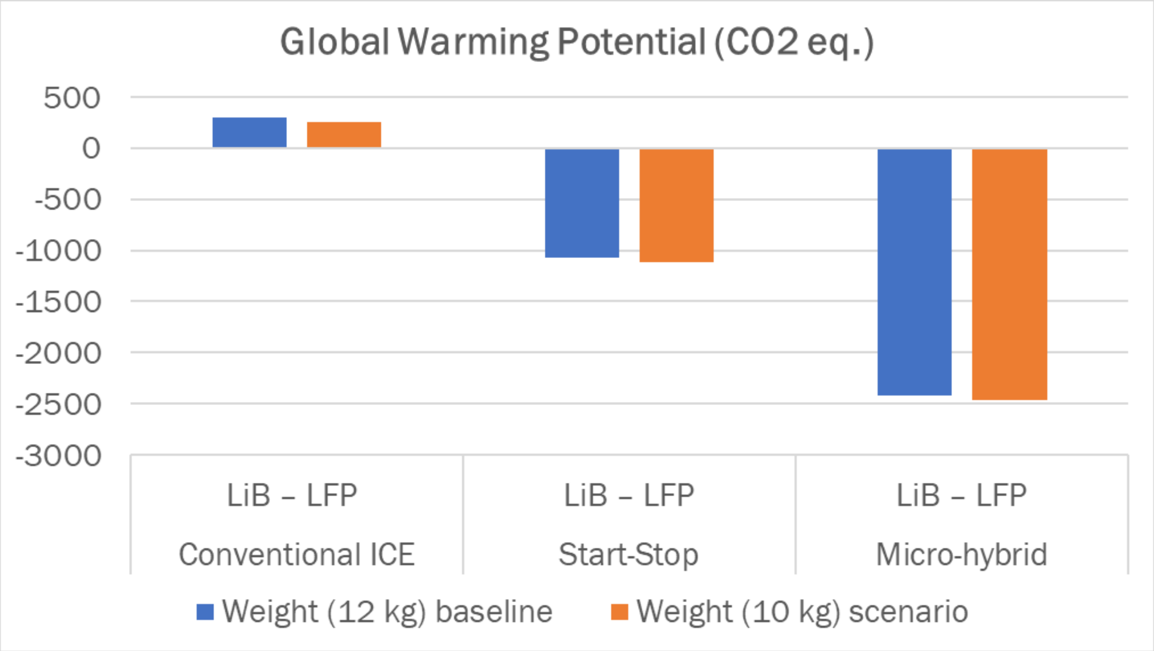

Figure 5-1: Sensitivity analysis – total GWP – LFP battery weight reduction

5.3.2. LFP battery lifetime increase

A variation of the LFP battery lifetime increase (from 8 years to 11 years and 15 years) has been assessed. The lifetime has a direct influence on the reference flow (number of batteries with electronics) required to fulfil the function of the vehicle lifetime (11-year, 143,000 miles).

Table 5-5: Battery reference flows per Functional Unit (LFP battery lifetime increase)

Battery application	Li-ion battery type	No. of batteries vehicle lifetime baseline (8 yr. battery)	No. of batteries vehicle lifetime scenario A (11 yr. battery)	No. of batteries vehicle lifetime scenario B (15 yr. battery)
Conventional ICE	LFP	1.38	1	0.73

Battery application	Li-ion battery type	No. of batteries vehicle lifetime baseline (8 yr. battery)	No. of batteries vehicle lifetime scenario A (11 yr. battery)	No. of batteries vehicle lifetime scenario B (15 yr. battery)
Start-stop	LFP	1.38	1	0.73
Micro-hybrid	LFP	1.38	1	0.73

Table 5-6: Global Warming Potential [kg CO_2 eq.] – LFP lifetime sensitivity – scenario A

Total LC GWP (kg CO_2 eq.) results per FU - sensitivity analysis				
Application	Battery type	Lifetime (8 yr.) baseline	Lifetime (11 yr.) scenario	Variation to baseline (%)
Conventional ICE	LiB – LFP	295	214	-27%
Start-Stop	LiB – LFP	-1076	-1157	7%
Micro-hybrid	LiB – LFP	-2448	-2528	3%

Table 5-7: Global Warming Potential [kg CO_2 eq.] – LFP lifetime sensitivity – scenario B

Total LC GWP (kg CO_2 eq.) results per FU - sensitivity analysis				
Application	Battery type	Lifetime (baseline 8 y)	Lifetime (15 y) scenario B	Variation to baseline (%)
Conventional ICE	LiB – LFP	295	157	-47%
Start-Stop	LiB – LFP	-1076	-1214	13%
Micro-hybrid	LiB – LFP	-2448	-2586	6%

The results in Table 5-6, Table 5-7 and Figure 5-2 below show that a higher lifetime for the LFP batteries would benefit its profile gradually as less batteries are needed to fulfil the service life of the application.

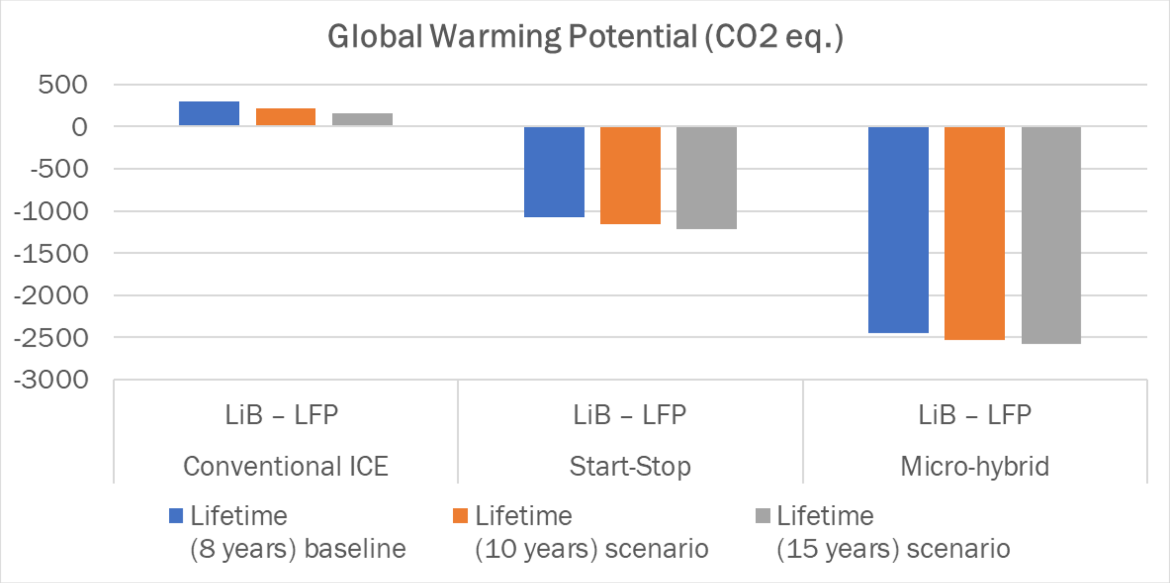

Figure 5-2: Sensitivity analysis – total GWP – LFP battery lifetime increase

5.3.3. Energy/fuel savings increase for LiB - LFP

In the use stage, it has been assumed that same energy/fuel savings apply for PbB and LiB - LFP in start-stop and micro-hybrid application. As LiB - LFP may have an additional saving potential, an assumption has been made and tested 1% benefit[26] for LiB – LFP (see Table 5-8) vs PbB (see Table 4-3).

Table 5-8: Global Warming Potential [kg CO_2 eq.] –1% fuel savings sensitivity

Life Cycle Stage	Start-Stop			Micro-hybrid		
	LiB – LFP baseline	LiB - LFP 1% scenario	Variation (%)	LiB – LFP baseline	LiB - LFP 1% scenario	Variation (%)
Manufacturing stage	316	316	0%	316	316	0%
Use stage	-1370	-1696	24%	-2740	-3052	11%
EoL	-17	-17	0%	-17	-17	0%
Total Life Cycle	**-1071**	**-1397**	**30%**	**-2441**	**-2754**	**13%**

Figure 5-3 show the baseline results for PbB and LiB – LFP batteries, compared to a scenario where LFP battery would benefit from a higher energy/fuel saving in the use stage for Start-stop and Micro-Hybrid vehicle applications. The fuel saving increase of 1% would result in an overall benefit within the range of 14 to 30% for LiB – LFP batteries.

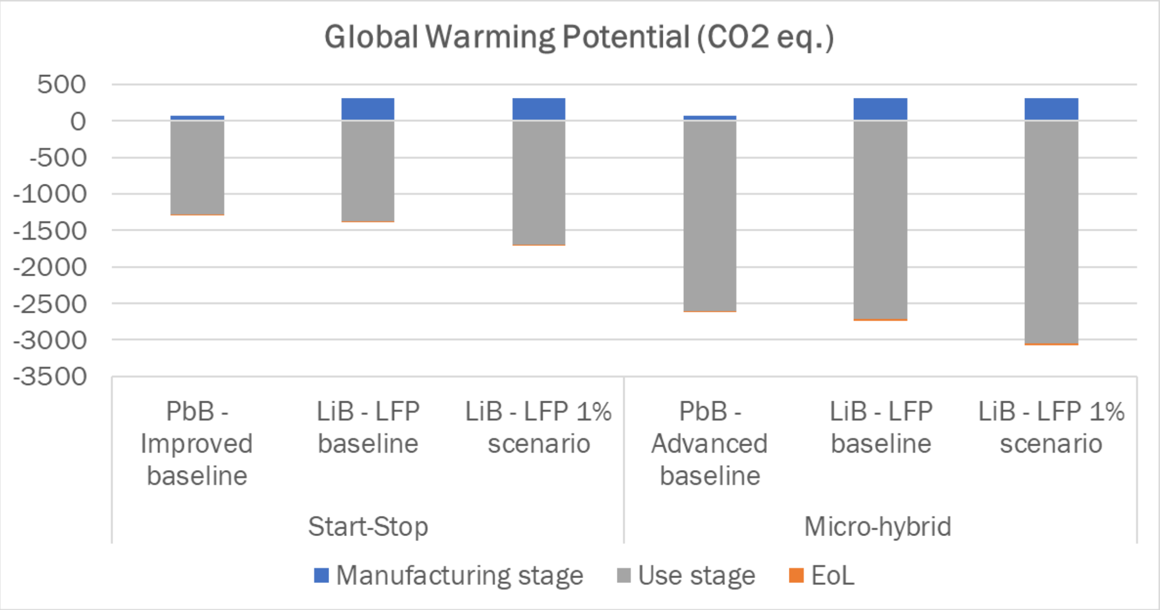

Figure 5-3: Sensitivity analysis – GWP per LC stage for PbB and LiB - LFP for Start-stop and Micro-hybrid vehicles – 1% higher fuel saving for LiB - LFP battery

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[26] Information provided by ACEA members.

5.3.4. Vehicle lifetime increase

The functional unit considers a 1-year lifetime of a vehicle with 143.000 miles, a 11-year lifetime has been analysed. It has been assumed the total driving distance during the vehicle life is unchanged, although the lifetime has been increased. The table below show the number of batteries needed to fulfil this lifetime for lead-based and LFP batteries.

Table 5-9: Battery reference flows per Functional Unit (vehicle lifetime increase)

Lead battery type				Li-ion LFP battery		
Vehicle application	Lifetime years	No. of batteries vehicle lifetime (11 yr.)	No. of batteries vehicle lifetime (15 yr.)	Lifetime years	No. of batteries vehicle lifetime (11 yr.)	No. of batteries vehicle lifetime (15 yr.)
Standard / Conventional ICE	5	2.6	3	8	1.4	1.9
Improved / Start-stop	5.5	2.3	2.7	8	1.4	1.9
Advanced / Micro-hybrid	6	2.1	2.5	8	1.4	1.9

Table 5-10: Global Warming Potential [kg CO_2 eq.] – vehicle lifetime sensitivity

Total LC GWP (kg CO_2 eq.) results per FU - sensitivity analysis				
Application	Battery type	Vehicle lifetime 10 yr.	Vehicle lifetime 15 yr.	Variation (%)
Conventional ICE	PbB - Standard	133	142	7%
	LiB - LFP	299	348	17%
Start-Stop	PbB - Improved	-1218	-1209	-1%
	LiB - LFP	-1071	-1022	-5%
Micro-hybrid	PbB - Advanced	-2570	-2534	-1%
	LiB - LFP	-2441	-2392	-2%

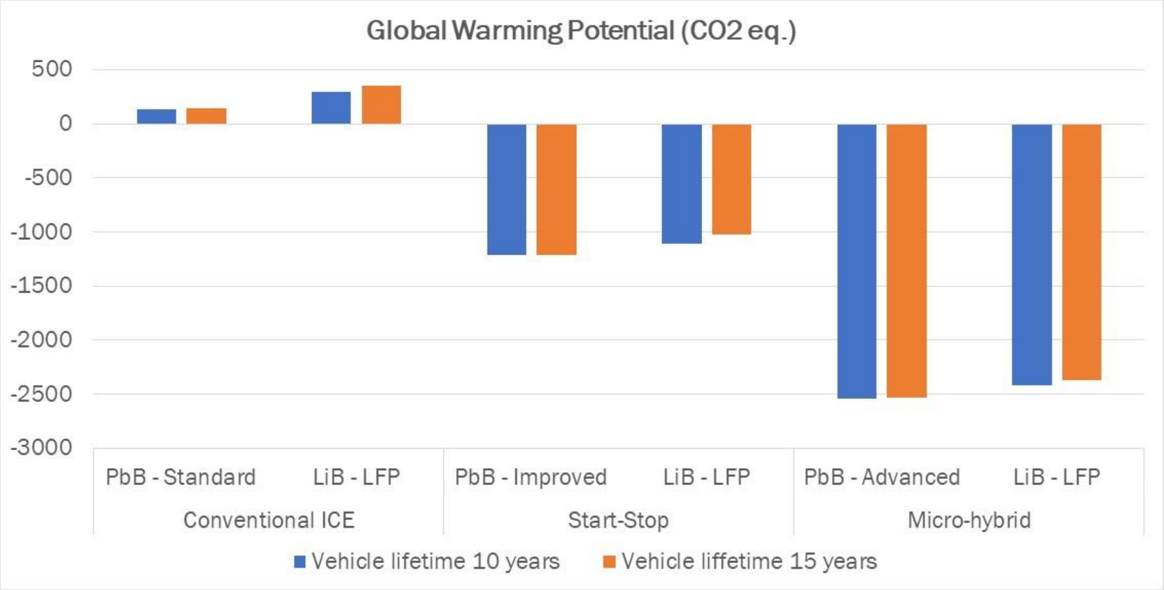

Figure 5-4: Sensitivity analysis – total GWP – vehicle lifetime increase

The results in Table 5-10 and Figure 5-4 show that for conventional vehicles, a variation of higher 17% for LiB – LFP and 7% PbB, due to the increase on the number of batteries needed to fulfil a higher vehicle lifetime. Although there is an increase on the impact for the start-stop and micro-hybrid applications during manufacturing (due to the need of more batteries), there is also an increase on EoL credits and therefore a variation on the environmental profile for all batteries.

5.3.5. EoL scenario: collection rate 15%

As described in section 2.5.2,there is an uncertainty regarding the real collection rate of the LFP batteries in the US market. Some sources[27] indicate that the current collection rate is low. Therefore, a scenario reducing the collection rate from 99% to 15% of the Lithium battery including its passive components has been calculated. Doing so, the recovery rate is 4,5%. The external accessories, car cabling and car protection has remained the same.

In Table 5-11 the Global Warming Potential for the baseline scenario as well as the calculated scenario are displayed.

Table 5-11: EoL Scenario: Battery collection rate 15%

Total GWP (CO_2 eq.) results per FU - EoL approach scenario									
	Conventional ICE			Start-stop			Micro-hybrid		
	PbB Flooded	LiB - LFP		PbB Improved	LiB - LFP		PbB Advanced	LiB - LFP	
		99% collection rate	15% collection rate		99% collection rate	15% collection rate		99% collection rate	15% collection rate
Manufacturing stage	72,5	316	316	75	316	316	72,2	316	316
Use stage	68,1	0	0	-1280	-1370	-1370	-2630	-2740	-2740
EoL	-7,42	-17,4	-7,8	-12,9	-17,4	-7,8	-12,4	-17,4	-7,8

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[27] (Gaines & Linda, 2012) (BCI, 2019) ((EERE), June 2019)

Total GWP (CO_2 eq.) results per FU - EoL approach scenario						
Total Life Cycle	133	299 308	-1218	-1071 -1062	-2570	-2441 -2432

Results in Table 5-11 show a decrease of the credit in the EoL of 55%. The decrease of the credit is due to the higher impact of the EoL of the battery, since 85% is sent to landfill instead of recycling. The recycling of the battery consists of the recovering of the metal and plastic parts and the incineration of the cell, as described in chapter 3.4.1.

The overall Global Warming Potential of the Lithium battery with 15% collection rate show an increase between 0,5% to 3% regards the baseline scenario.

5.3.6. EoL approach scenario

As described in section 2.5.2, there are two main EoL approaches commonly used in LCA studies to account for end-of-life recycling and recycled content. In Table 5-12 and Figure 5-5 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 5-12: 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 %
Conventional ICE	PbB - Standard	133	140	<10
	LiB - LFP	299	316	<5
Start-Stop	PbB - Improved	-1220	-1205	<1
	LiB - LFP	-1070	-1054	<1
Micro-hybrid	PbB - Advanced	-2540	-2532	<1
	LiB - LFP	-2420	-2404	<1

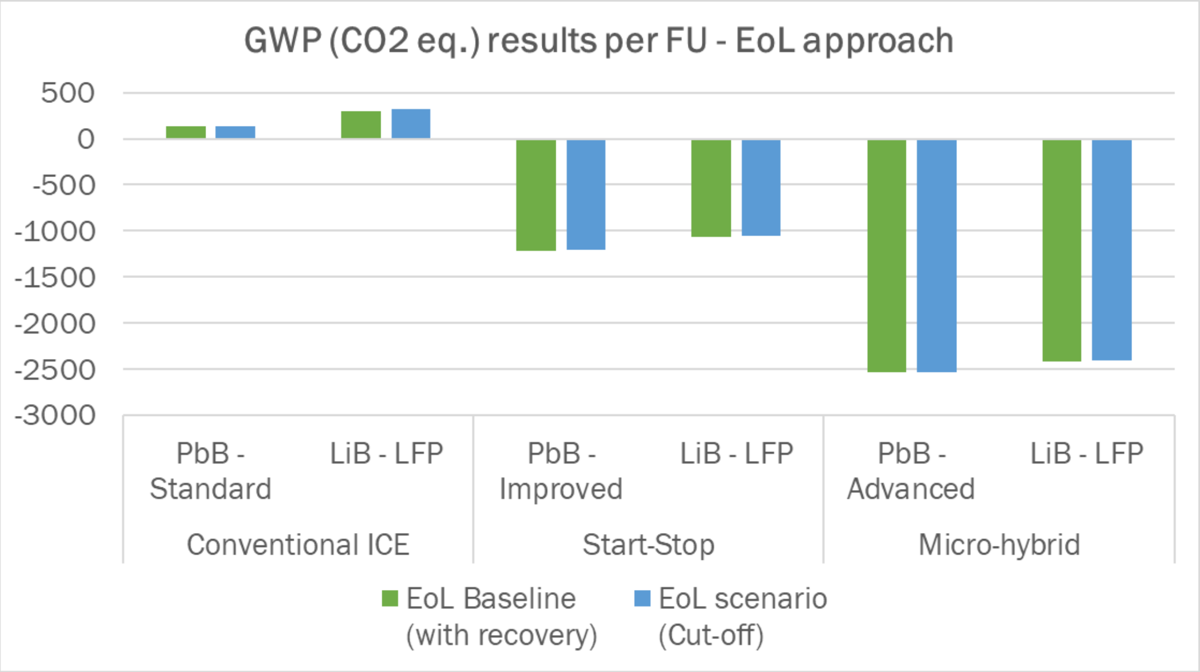

Figure 5-5: Sensitivity analysis – total GWP – EoL approach

The results in Table 5-12 and Figure 5-5 show that for conventional vehicles the variation between the two EoL approaches is lower than 5% for LiB – LFP and lower than 10% PbB. For the start-stop and micro-hybrid applications, the variation is lower than 1% for both batteries. 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. This can be seen in the conventional vehicle results due to the very low contribution of the use stage to the overall results (see Figure 4-3). 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 optimising 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[28]. 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 consumptions and losses.

The general potential recycling anticipated with existing process technology is a physical and pyrometallurgical process. In the flow chart Figure 5-6 and Figure 5-7, 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 5-6 shows the idealised physical crushing (under inert atmosphere) to remove the casing and then the application of

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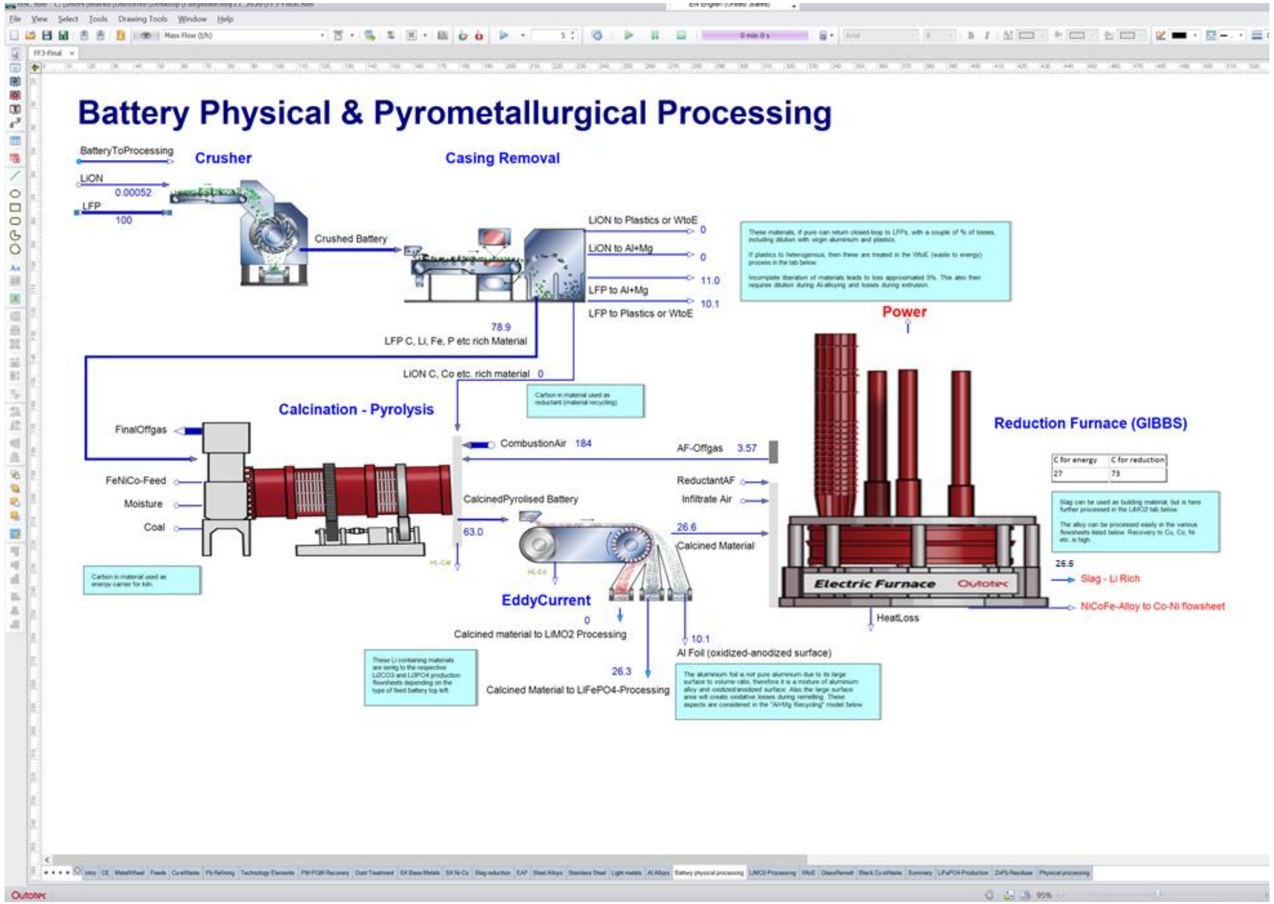
[28] https://www. outotec. com/products-and-services/technologies/digital-solutions/hsc-chemistry/

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 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 summarise, a very large simulation model for any module from consumer electronics (220 reactors, 60 elements and all their compounds, 1000 materials, 1000 streams) are an indication of the true recyclability of products and in this case, batteries. Note that the metal alloy generated in the furnace has the potential to undergo additional processing in other areas of the production chain, to produce e. g. Co, Cu and other contained valuable elements in economically viable processes.



These materials, if pure can return closed-loop to LFP's, 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)

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.

Carbon in material used as energy carrier for kiln.

These Li containing materials are sentg to the 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 5-6: LFP Battery Physical and Pyrometallurgical Processing[29]

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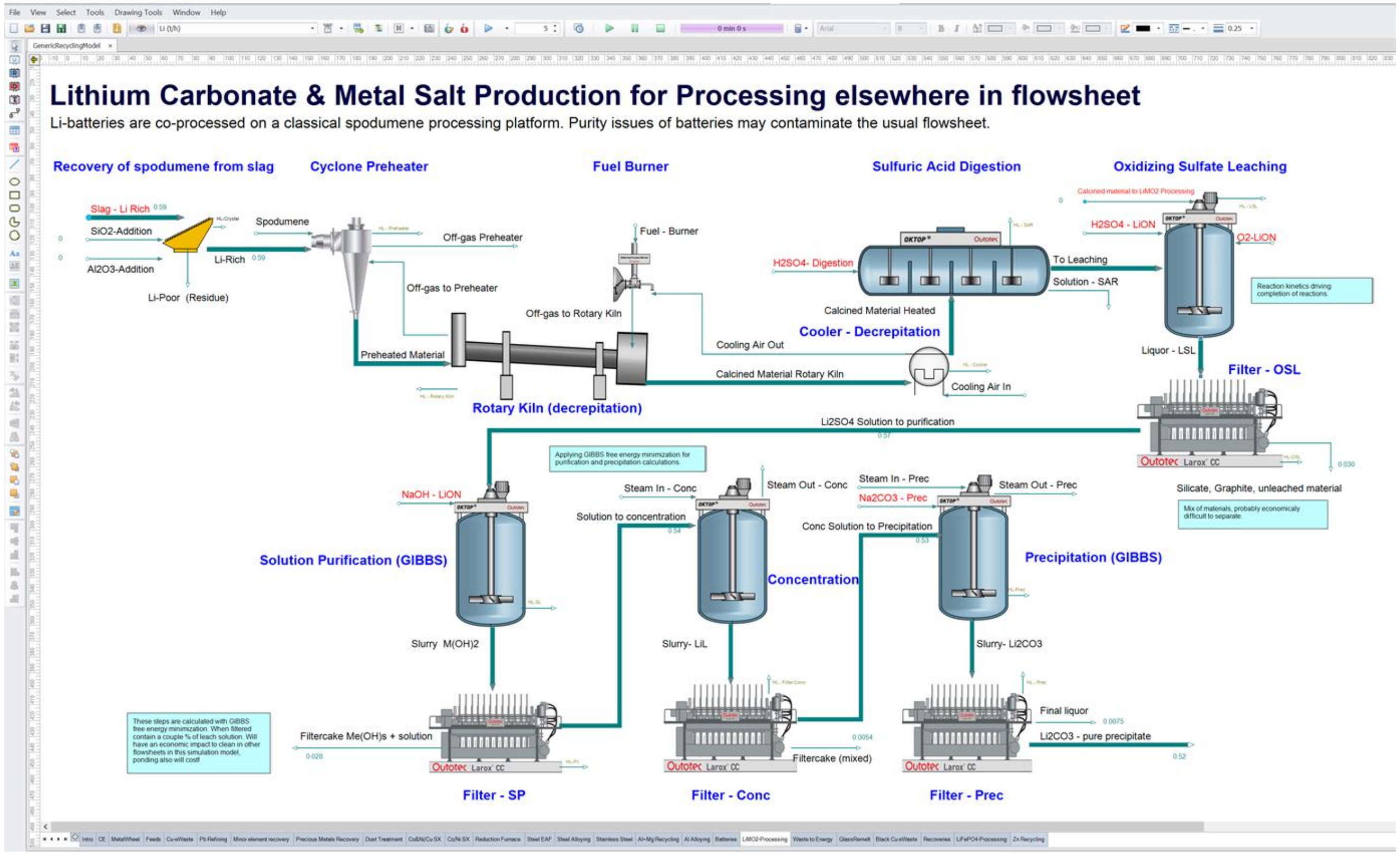
[29] https://www. outotec. com/products-and-services/technologies/digital-solutions/hsc-chemistry/



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.

Reaction kinetics driving completion of reactions.

Mix of materials, probably economicaly difficult to separate.

Applying GIBBS free energy minimization for purification and precipitation calculations.

These steps are calculated with GIBBS free energy minimization. When filtered contain a couple % of leach solution. Will have an economic impact to clean in other flowsheets in this simulation model, ponding also will cost!

Figure 5-7: Lithium Carbonate and Metal Salt Production[30]

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[30] https://www. outotec. com/products-and-services/technologies/digital-solutions/hsc-chemistry/

Table 5-13: End of Life Cycle – LFP Battery Recovery Scenario Components Treatment

Cell / battery component	Amount	Unit	EoL Treatment	Credits
ANODE				
Copper foil	1.09	kg	copper scrap remelted	copper 99,99%
Graphite	1.01	kg	used as energy source in calcination process (see Figure 5-6).	none
CATHODE				
Al	0.67	kg	The foil is 50% oxidised and the remaining is remelted with the Al casing	credited with the most common casting alloy $AlSi_9Cu_3$
LFP	2.28	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	0.12	kg	used as energy source in calcination process (see Figure 5-6).	None
Binder (PVDF)	0.12	kg		
ELECTROLYTE				
EC/DMC	1.26	kg	waste to landfill	None
$LiPF_6$	0.25	kg	waste to landfill	
SEPARATOR				
PP	0.5	kg	used in reduction furnace and lands in slag which will be treated in Spodumene process	None
CELL CASE, FOIL POUCH				
Al foil	1.09	kg	recovery via remelting to cast alloy	credited with the most common casting alloy $AlSi_9Cu_3$
BATTERY CASE				
PP	1	kg	recycling plastic granulate	virgin PP granulate

The passive components, cable and crash protection is treated as in the base scenario described in section 2.5.2 .

In the Table 5-14, 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.

Table 5-14: End of Life Cycle – LFP Battery Recovery Scenario Results

	EoL baseline	EoL scenario	Variation (%)
GWP [kg CO2 eq.]	-14,5	-28,46	-49%
PED [MJ]	-309	-406	-24%
Acidification [kg SO2 eq.]	-0,13	-0,2515	-48%
Eutrophication [kg N eq.]	-0,00326	-0,007046	-54%

	EoL baseline	EoL scenario	Variation (%)
Human Health Impacts from Exposure to Particulate Matter, [kg PM2.5 eq.]	-0,0127	-0,01766	-28%
Photochemical Smog Formation [kg O3 eq.]	-1,07	-1,855	-42%

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. Aluminium 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 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 is covering the recycling of lithium carbonate.

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 GaBi 2021 database were used. The LCI datasets from the GaBi 2021 database are widely distributed and used with the GaBi 9 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in 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 and for the LFP battery. All background data are sourced from GaBi databases with the documented precision (Sphera Solutions Inc., 2020).
- ✓ **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 GaBi databases with the documented completeness (Sphera Solutions Inc., 2020).

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[31] has been used. All background data were sourced from the GaBi 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 GaBi 2021 databases and are representative of the years 2015 - 2018. As the study intended to compare the product systems for the reference year 2018, temporal representativeness is considered to be very good.
- ✓ **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. 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:** All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were 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 GaBi 2021 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

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[31] (Recharge, 2018)

5.7. Conclusions, Limitations, and Recommendations

5.7.1. Conclusions

This study represents a comparative LCA of vehicle battery applications. Two 12 V battery chemistries have been analysed; lead-based batteries and Li-ion - LFP (lithium iron phosphate) for use in internal combustion engine (ICE), start-stop and micro-hybrid vehicles. The lead-based batteries are produced in North America and the LFP cells are produced in China with a final battery assembly in US. It is assumed that all batteries are used in vehicles placed on the market in North America and batteries at end-of-life are treated in North American recycling facilities.

The lead battery data used is representative as it is industry data representing 45% 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 bill of materials (BoM)of LFP batteries are as representative as possible. They are based on established references and the best available data validated by a range of automotive battery experts and automotive and battery related stakeholders.

To account for the complete life cycle, the use and EoL phases of the batteries were also modelled in the study. The use phase modelling accounts for differences in battery weight and includes a best-case assumption for the associated fuel savings due to start-stop and micro hybrid applications. For the EoL lead and LFP batteries, an EoL collection rate of 99 % was used. For LFP batteries, three EoL scenarios were considered: the first includes the incineration of the cell (with energy generation) and recycling for electronics and passive components, the second considered a collection rate of 15% and the third where a recycling scenario involves recovery of the lithium in form of lithium carbonate.

Key conclusions from the study over the complete life cycle from cradle-to-grave can be summarised 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, these differences are not qualified as being significant; the biggest difference was obtained for the conventional vehicles. In this case, the 12v lead battery performed better in the baseline scenario due to the lower impact and burdens in manufacturing (90%-39% depending on impact category). However, when the sensitivity of significant parameters (battery weight, lifetime, etc.) is considered, the environmental performance of LFP reaches approximately the same level as that for the lead battery.

For both the start-stop and the micro-hybrid applications, the baseline scenario shows small differences due to large dominance of the use phase savings; these were assumed to be identical in the baseline scenario (98%-25% depending on impact category). When the sensitivity of this result is assessed by assuming a higher efficiency of the LFP batteries, they demonstrate up to a 20% improvement in performance compared to lead batteries.

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 60% of the GWP for the lead batteries and Electricity with approx. 22% followed by the raw materials with approx. 39% 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 Table 4-3, the environmental impact of LFP battery manufacturing is about a 4[32] times higher than the impact of manufacturing equivalent lead batteries.

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[32] Results from dividing the GWP of LFP 373 kg CO2 eq. by the GWP of PbB 73 kg CO2 eq.

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).

The use phase was addressed in this life cycle assessment by considering the differences in battery weight and by allocating the benefits of the complete start-stop and micro hybrid systems to both types of batteries. For the internal combustion engines (ICE), the higher use phase emissions of lead battery are due to the higher weight which reduce the advantages in manufacturing significantly.

The EoL phase has a smaller influence on the total life cycle results (contribution of 1%-24% 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 12v lead battery manufacturing has a lower environmental impact compared to LiB - LFP. This benefit is maintained in the baseline scenario during the full life cycle for conventional ICE battery applications – despite the higher weight and associated use phase burdens of lead battery. The studied sensitivities of modelling parameters show that these differences may not be significant. For start-stop and micro hybrid battery applications, the model shows environmental benefit for both batteries' technologies as the use stage benefits offset the manufacturing impact. In these cases, the differences found for lead battery and LiB - LFP do not appear significant.

5.7.2. Limitations and Recommendations

The results of this study are only applicable to 12v lead and LFP batteries used in North America for the automotive 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.

This study tried to isolate the contribution of the start-stop/micro-hybrid system (of which improved or advanced technology lead-based batteries are an integral part) from other technologies used to improve fuel efficiency within the vehicle i.e. base engine updates, engine downsizing, reduced roll resistance tires, vehicle weight reduction, and aerodynamic improvements. However, the total fuel consumption is influenced by all these parameters, therefore the assumed fuel reductions have some methodological limitations.

As pointed in the conclusions, the use stage dominates the results for the battery start-stop and micro-hybrid application systems. A conservative baseline with high-efficient cars in terms of fuel savings have been chosen. In case the fuel economy is decreased to reflect more fuel consumption cars, like SUVs and pick up cars[33], the fuel savings will increase respectively. It can be expected, that in this case the use stage in both technologies, start-stop and micro-hybrid, will accordingly increase dominating even more the whole Life Cycle.

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[33] According to the U.S. Environmental Protection Agency's "Automotive Trends Report" for 2021, the average fuel economy of light-duty vehicles with conventional internal combustion engines (ICE) in the United States was 24.7 miles per gallon (MPG) in model year 2020. This represents a slight increase from the previous year's average of 24.5 MPG.

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

LFP batteries contain no economically valuable metals and thus currently have very low incentive for recycling. As of today, it is not economically viable to recover lithium, iron and phosphate from the cathode of the LFP battery system therefore the recycling efficiency of the LiB LFP can be estimated from maximum recyclability of other battery components, which is approximately 30%. 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).

The study does not address the full impact of lead on human health and the environment due to USETOX model limitations. A separate study is recommended to analyze the risks of lead exposure, utilizing various assessment methods such as experimental and observational studies as well as simulations.

This study shows that:

- Start-stop and micro hybrid vehicles offer substantial life cycle benefits over internal combustion engines (ICE) vehicles.
- Lower battery weight and higher lifespan are recommended to reduce the impacts of battery manufacturing and maximize in-use benefits; even if its benefits are very limited.
- 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
- Most impact categories showed small differences between all batteries assessed, with lead batteries performing better in the baseline scenario due to lower burdens in the manufacturing (ranging from 90% to 39% depending on the impact category. However, when significant parameters such as battery weight and lifetime are considered, the environmental performance of LFP reaches roughly the same level as lead battery.

It is recommended to:

- Study Lithium-ion battery types comprising cathode materials other than LFP;
- Study the use phase impacts of batteries more specifically; including sensitivity analysis with respect to ratio of city and highway driving, power and duration of ancillary load, etc;
- Study LiB – LFP with primary industry data rather than relying on secondary information from the available literature.
- Study the energy consumption amount for LiB - LFP cell manufacturing (as some literature sources show a lower energy consumption for cell manufacturing) (Qiang Dai, 2019)[34] than the one taken from the PEFCR document (Recharge, 2018) .

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[34] (Qiang Dai, 2019) According to the authors, cell manufacturing energy was one of the major contributors to their LCA and therefore it could have a significant impact on the manufacturing LCA results.

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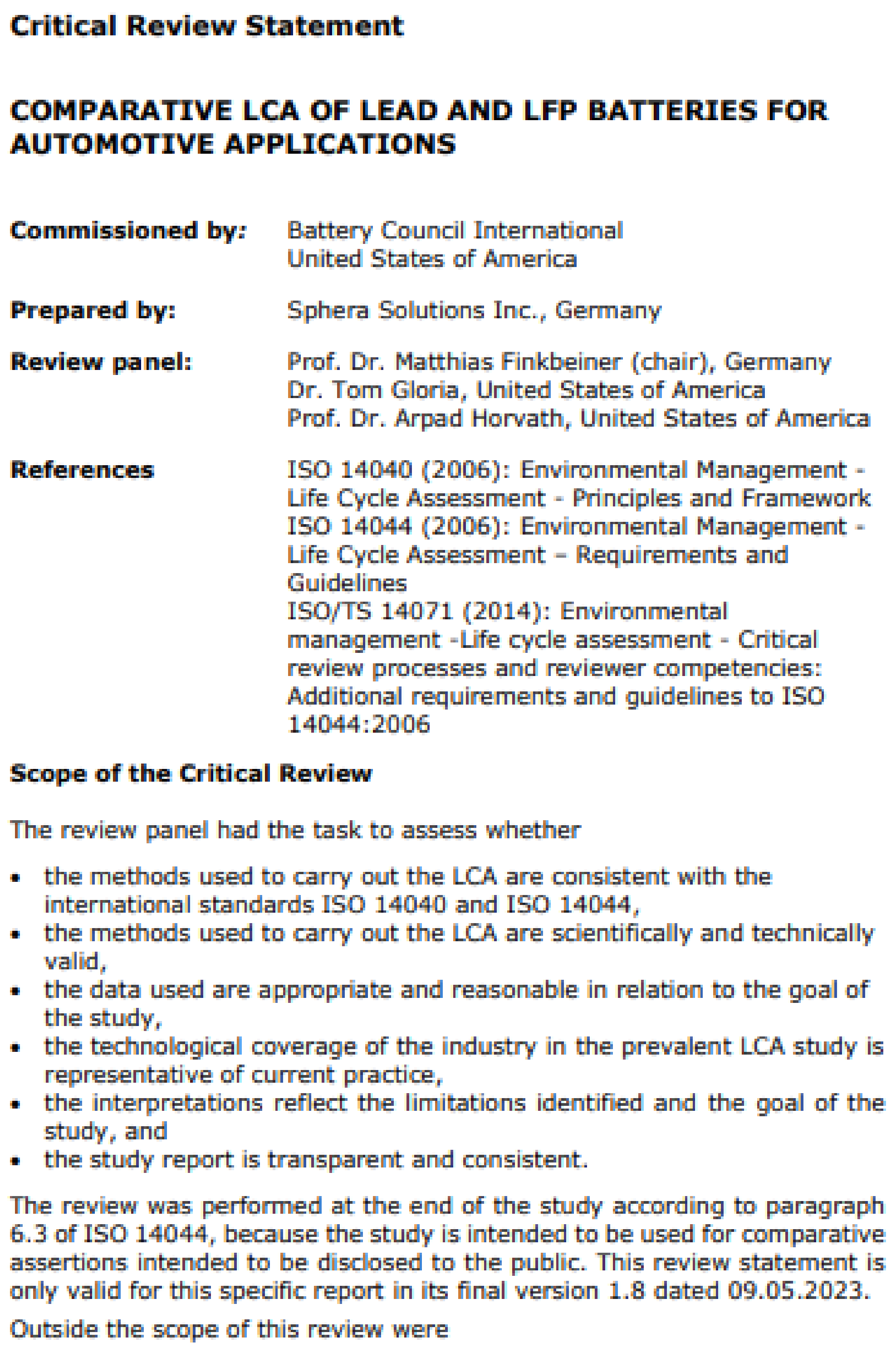
Annex A: Critical Review Statement



Critical Review Statement

COMPARATIVE LCA OF LEAD AND LFP BATTERIES FOR AUTOMOTIVE APPLICATIONS

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 1.8 dated 09.05.2023.

Outside the scope of this review were

- the verification of assumptions made for the types and properties of batteries, vehicle systems, 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 17.01.2023. The review panel provided 120 comments on the draft final report of general, technical and editorial nature and sent them to the commissioner by 02.02.2023. Sphera provided a comprehensively revised report and documentation on the implementation of the review comments on 20.04.2023. 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 23 comments and sent to Sphera on 30.04.2023.

The final version 1.8 of the report dated 09.05.2023 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 automotive 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 automotive 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 use stage benefits of the start-stop-/micro-hybrid systems depend on other technologies used to improve fuel efficiency within a vehicle, as well as the assumptions made to characterize the different vehicle systems and the vehicle operating conditions.
- 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.

Conclusion

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

17th May 2023

Matthias Finkbeiner   Tom Gloria   Arpad Horvath

(the review statement was approved by email)

Annex B: Additional information

Application	Conventional ICE			Start-stop	Micro-hybrid	
Impact / Indicator	PbB Standard	LIB - LFP	PbB Improved	LIB - LFP2	PbB Advanced	LIB - LFP3
TRACI 2.1, Human Health Impacts from Exposure to Particulate Matter, (POCP) [PM2.5]	6,2E-02	1,5E-01	6,2E-02	1,1E-01	-1,0E-02	6,4E-02
USEtox 2.12, Ecotoxicity (recommended only) [CTUe]	4,9E-01	2,9E-01	4,9E-01	-5,0E+00	-1,6E+01	-1,7E+01
USEtox 2.12, Human toxicity, cancer (recommended only) [CTUh]	1,4E-08	4,8E-07	1,4E-08	4,6E-07	4,4E-09	4,7E-07
USEtox 2.12, Human toxicity, non-canc. (recommended only) [CTUh]	1,4E-10	2,8E-09	1,4E-10	1,3E-09	-2,1E-09	4,2E-10