On behalf of EUROBAT and ILA

Life Cycle Assessment of Automotive Lead Batteries – Europe

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On behalf of Sphera Solutions Inc. and its subsidiaries

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List of Acronyms

ADP	Abiotic Depletion Potential
AGM	Absorbent-Glass Matt
AP	Acidification Potential
BEV	Battery Electric Vehicle
CFC	Chlorofluorocarbon
CTU	Comparative Toxic Units
CML	Centre of Environmental Science at Leiden
ELCD	European Life Cycle Database
EFB	Enhanced Flooded Batteries
EoL	End-of-Life
EP	Eutrophication Potential
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
ICE	Internal Combustion Engine
ILA	International Lead Association
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PED	Primary Energy Demand
PEF	Product Environmental Footprint
PM	Particulate Matter
POCP	Photochemical Ozone Creation Potential

SLI	Starter, Lighting, and Ignition
VOC	Volatile Organic Compound
xEV	Electric Vehicles (all types)

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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 3.17)

Closed-loop and open-loop allocation of recycled material

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

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

(ISO 14044:2006, section 4.3.4.3.3)

Foreground system

"Those processes of the system that are specific to it … and/or directly affected by decisions 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 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).

1. Goal of the Study

The goal of the study was to assess the life cycle environmental profile of four different lead-based battery technologies for the automotive sector, produced in Europe. The cradle-to-gate environmental impact of each battery type has been evaluated, based on the production mass weighted-average results from participating manufacturers. Additionally, two other scenarios have been assessed, one including the use stage of the batteries and a second considering the end-of-life (EoL) of the batteries. The study has been conducted according to ISO 14040/44, the international standards on life cycle assessment (LCA).

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

The intended audience for this study includes EUROBAT, ILA, lead and battery producers, legislators, customers, environmental practitioners and non-governmental organizations.

This study is not intended to support comparative assertions intended to be disclosed to the public. It is acknowledged that the data provided might be used by others for comparative assertions. 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).A third party critical review of the study according to ISO 14040, ISO 14044 and ISO/TS 14071 will be carried out by two experts, i.e. Matthias Finkbeiner from Technical University Berlin[1], and Jeffrey Spangenberger from Argonne National Lab (ANL). The final review statements are documented in Annex A.

This technical report will be publicly available and can be made accessible to interested parties upon request to the study commissioners (EUROBAT and ILA). The study commissioners may use the study report to prepare and provide information materials, e.g. a technical summary of the report, a flyer addressing the major outcomes of the study, etc.

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

2. Scope of the Study

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

2.1. Product Systems

Lead-based batteries can be used for a variety of applications. The following automotive lead-based batteries have been assessed within this study:

- **Standard technology** – flooded lead-based batteries are used as standard technology batteries in the majority of conventional vehicles to provide starter, lighting, and ignition (SLI) functions. 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 are used in vehicles with a start-stop[2] system, which allows the internal combustion engine (ICE) to automatically shut down under braking, rest, and then restart.
- **Advanced technology** – EFB or AGM lead-based batteries are used in vehicles with a micro-hybrid[3] system, which combines start-stop functionality with regenerative braking (a system to recover and restore energy from braking), and other micro-hybrid features that require higher deep-cycle resistance and charge recoverability from the battery.
- **Auxiliary**[4] – flooded/AGM lead-based batteries are used in hybrid electric vehicles (xEV) of all types (Battery electric vehicle (BEV), start-stop and mild-hybrid) to provide power for engine control, safety and security systems. They are also used for transient load response for safety related systems in vehicles with 12 V power systems with conventional or micro-hybrid architectures to provide redundancy in the event of failure of the main battery or alternator.

The assessment of the batteries has been done in three levels/systems:

A. **Cradle-to-gate system**: includes the extraction or processing of the raw materials and associated transport, the production of battery parts, and final assembly.

B. **Cradle-to-gate + use stage**: includes the cradle-to-gate battery System A and the use stage.

C. **Cradle-to-gate + EoL of Battery**: includes battery System A and EoL scenarios

For each battery different scenarios have been developed according to the battery technology and corresponding use stage (application). Figure 2-1 presents, schematically, all the systems that have been considered within the study.

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[2] Start-stop vehicle (S/S). These vehicles feature a low level of electrification. In addition to conventional SLI functions, the battery must also support stop-start functionality (the engine is shut down when the vehicle is stationary) (Ricardo Strategic Consulting (RSC), 2020)

[3] *Micro-hybrid vehicle (micro-hybrid).* These vehicles feature a low level of electrification. In addition to stop-start functionality, these vehicles also feature some regenerative braking capability (Ricardo Strategic Consulting (RSC), 2020)

[4] The auxiliary batteries are only shown in Annex C for system A

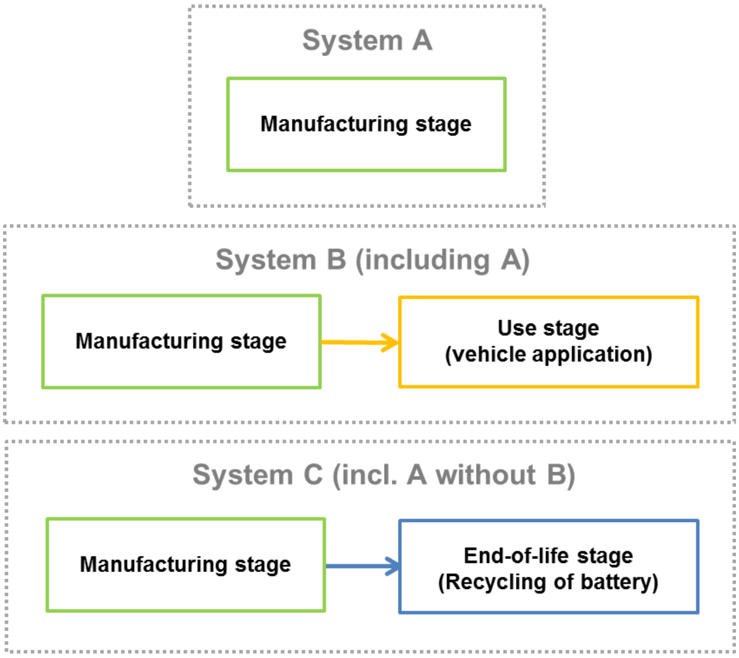


Figure 2-1: Product systems analysed

2.2. Product Functions and Functional Unit

The rechargeable batteries under study have the function of providing electric energy to vehicles to cover several functionalities (e.g. starting, regenerative braking, lighting, etc.) available in conventional and micro-hybrid vehicles, which have the function of providing transport services.

The functional unit and reference flow for systems A and C is one lead-based battery with the capacity and power listed in Table 2-1. An unweighted average of the masses of the batteries produced by the participants has been selected to define the reference flow, in order to calculate the environmental impacts. The functional unit for system B is the provision of energy over the vehicle lifetime of 150,000 km and 10 years. The different systems reflect the results with different functional unit. System A and C show the results for the 3 types of batteries and the potential recycling benefits. The focus is on the manufacturing and its benefits due to recycling, while the functional unit of System B refers to the use of battery in the application and intend to reflect the energy saving over the life time of the car due to the different batteries can be analyse.

Table 2-1: Automotive Batteries Technical characteristics – system A / C

Battery type	Average battery mass (kg)	Capacity (Ah)	Voltage (V)	Life span (years)	Application
Standard Technology	18	70	12	5	Conventional SLI
Improved Technology	19	70	12	5.5	Start-stop
Advanced Technology	20	70	12	6	Micro-hybrid

The reference flows are the number of batteries needed during the lifetime of the vehicle as shown in the last column of Table 2-2.

In the use stage, the battery is studied in the context of a vehicle. For the vehicle data (e.g. km/lifetime), literature sources have been consulted to calculate the fuel consumption and reduction due to the different vehicles' applications. The following Table 2-2 provides the parameters used, the functional unit is the lifetime of the vehicle.

Table 2-2: Automotive Batteries Functional units – system B

Battery type	Application	Type of vehicle[5]	Lifetime of vehicle [Distance (km) & time (years)]	Litre/100km	N° Batteries during lifetime of vehicle
Standard Technology	Conventional SLI	Small MPV	150,000 km – 10 years	5.1[6]	2[7]
Improved Technology	Start-stop	Small MPV	150,000 km – 10 years	5.0-4.85[8]	1.8
Advanced Technology	Micro-hybrid	Small MPV	150,000 km – 10 years	4.85-4.6[9]	1.7

2.3. System Boundaries

The system boundary of the study varies depending on the scenario being assessed. System A looks at only a cradle-to-gate scope. This includes raw material extraction and/or processing, inbound transport to the production facility, battery materials manufacturing, and battery assembly. System B includes the use of the battery over the lifetime of the vehicle or system. Finally, System C combines the cradle-to-gate scope with EoL treatment. Figure 2-2 presents all potential life cycle stages.

[5] 'Small MPV' is a Euro NCAP structural-class classification (http://www.euroncap.com/small_mpv.aspx)
[6] Derived from average fuel consumption values for MPV from www.fuelmileage.co.uk
[7] Corresponding to vehicle lifetimes of 150,000 km
[8] 2-5% reduction in fuel consumption due to use of improved technology batteries (Johnson Controls, UK)
[9] 5-10% reduction in fuel consumption due to use of advanced technology batteries (Johnson Controls, UK)

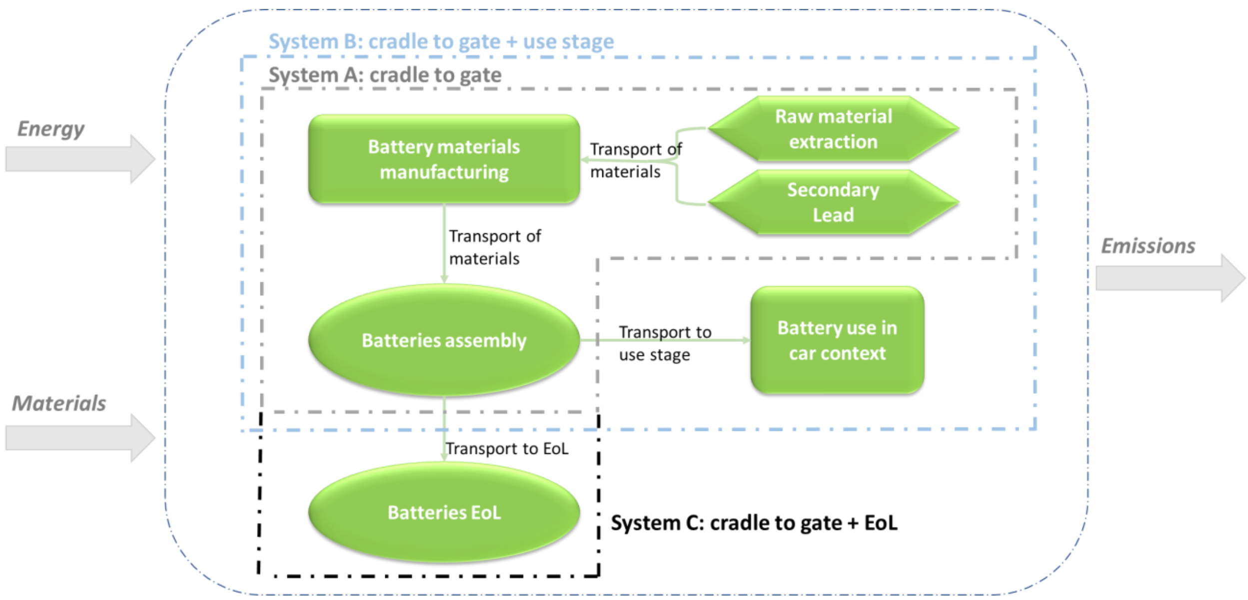


Figure 2-2: System boundary

Inclusions and exclusions to the system boundary are listed in Table 2-3.

Table 2-3: System boundaries

Included	Excluded
✓ Extraction and processing of materials ✓ All associated energy and fuels ✓ All associated emissions ✓ Transportation of raw and processed materials ✓ Transport to customer (system B only) ✓ Use stage (system B only) ✓ End-of-life (system C only)	× Production and maintenance of capital equipment and infrastructure × Overhead (heating, lighting, etc.) of manufacturing facilities × Human labour × Packaging × Production of the application e.g. vehicles

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

2.3.1. Time Coverage

The results of this study are intended to represent the year 2017. They are relevant for 2022 (the year in which the study is completed) and are expected to be relevant until such time as there is a significant change in the production mix, energy mix, or manufacturing technology.

2.3.2. Technology Coverage

This study assesses the cradle-to-gate impacts of lead-based battery production, the use of lead-based batteries in their specified capacity, and their eventual EoL based on the current European technology mix. Primary site data have been gathered from EUROBAT's members to ensure that the models used to assess the environmental impact of lead-based batteries are technologically representative for each stage of the production process.

2.3.3. Geographical Coverage

The results of this study are intended to represent lead-acid battery production in Europe. As production is not uniformly distributed in this region, the upstream data on energy and fuels are based on the relevant country of production for each site, with country-specific or region-specific data used wherever possible.

Regional EU-28 data have been used where national data are unavailable. These data have been combined with primary data gathered from manufacturing sites to ensure that the data and models are representative for the relevant region.

2.4. Allocation

2.4.1. Multi-output Allocation

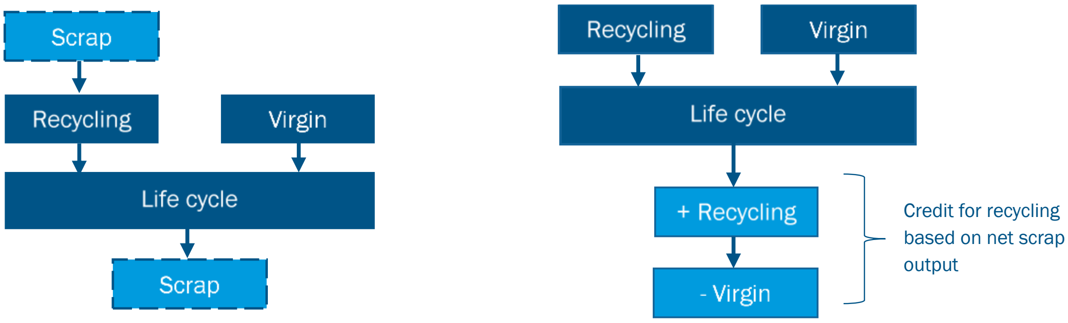
Multi-output allocation generally follows the requirements of ISO 14044, section 4.3.4.2. When allocation becomes necessary during the data collection phase, the allocation rule most suitable for the respective process step has been applied and is documented along with the process in the LCI chapter (chapter 3). Where there is more than one type of battery produced at a site, mass allocation was applied to the data provided by each company before creating the production-weighted average. Allocation of background data (energy and materials) taken from the GaBi 2019 databases is documented online at http://www. gabi-software. com/international/databases/gabi-databases/

2.4.2. End-of-Life and Waste Allocation

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

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

- Substitution approach (also known as 0:100, closed-loop approximation, recyclability substitution or end of life approach) – this approach is based on the perspective that material that is recycled into secondary material at end of life will substitute for an equivalent amount of virgin material. Hence a credit is given to account for this material substitution. However, this also means that burdens equivalent to this credit should be assigned to scrap used as an input to the production process, with the overall result that the impact of recycled granulate is the same as the impact of virgin material. This approach rewards end of life recycling but does not reward the use of recycled content.
- Cut-off approach (also known as 100:0 or recycled content approach) – burdens or credits associated with material from previous or subsequent life cycles are not considered 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 2-3: 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 or 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. This remaining net scrap is then sent to material recycling. The original burden of the primary material input is allocated between the current and subsequent life cycle using the mass of recovered secondary lead to scale the substituted primary material. The battery recycling process also accounts for the recovery of plastics by assigning environmental credits. The batteries EoL allocation approach applied will be described in greater detail in the LCI section.

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

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

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

2.5. Cut-off Criteria

No specific cut-off criteria have been defined for the foreground system 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 production and maintenance of capital goods, overhead, and human labour have been excluded from the study. It is expected that these impacts will be negligible compared to the impacts associated with running the equipment over its operational lifetime.

Cut-off-criteria applied to background data (energy and materials) taken from the GaBi 2019 databases is documented online (thinkstep, 2019).

The choice of proxy data is documented in chapter 3. The influence of these proxy data on the results of the assessment has been carefully analysed and is discussed in chapter 3.

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 2-4 and Table 2-5.

Various impact assessment methodologies are applicable for use in the European context including CML (Guinée, et al., 2002), ReCiPe (Goedkoop, et al., 2009), and selected methods recommended by the ILCD (ILCD, 2011). This assessment is predominantly based on the CML impact assessment methodology framework (CML 2001 update April 2015). CML characterisation factors are applicable to the European context, are widely used and respected within the LCA community, and required for Environmental Product Declarations under EN 15804.

The Product Environmental Footprint (PEF) method (European Union, 2013) which is being developed by the European Commission and is currently in the transition phase requires compliant assessments to take account of 16 LCIA methods. The use of a predefined list of impact categories is aimed at driving comparability between assessments of different products. Given the likely importance of PEF for European businesses in the future, these methods were considered for inclusion in this study. However, a number of the methods are currently not considered to be very mature (Lehmann, Bach, & Finkbeiner, 2016) and remain either in revision or awaiting update. Given these issues, in this study the CML impact categories are favoured as these are well-established and remain the impact methodologies favoured by the metals industry for the European context (PE International, 2014).

For impact categories where CML 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, and deemed to be among the most pressing environmental issues of our time. The global warming potential impact category has been assessed based on the latest IPCC 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 photochemical ozone creation 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 CML impact category method.

Additionally, this project includes measures of toxicity and particulate matter/respiratory inorganics. These categories are all subject to significant uncertainties and are presented for internal use only in an annex.

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. This impact category is based on the method recommended by the ILCD and the European Commission (ILCD 2011). The method in question is based on the RiskPoll method (Rabl & Spadaro, 2004) and assesses the effect on human health of ammonia, carbon monoxide, NOx, SOx, dust and particulate matter.

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 (chloroflourocarbons), the most harmful chemicals have been eliminated, while complete phase out of less active HCFCs (hydrochlorofluorocarbons) will be achieved by 2030. 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.

The present study excludes the assessment of resources. Resource shortages are driven by various factors that are not captured well by current metrics. Accordingly, resource criticality has emerged as a separate tool to assess resource consumption (Nassar, et al., 2012; Graedel & Reck, 2015). As a complete criticality assessment is out of scope for this work this impact category has been excluded from the assessment.

In general, impacts related to resource depletion, toxicity to humans and ecosystems, land use change, and water scarcity are not recommended to be reported for metal LCAs. Among these, all are labelled as level II or III within the ILCD handbook (JRC, 2010), meaning that they are recommended by ILCD but in need of some improvements or to be applied with caution. Although these impacts are relevant environ-mental concerns, it is the position of the metal industry that the characterization of these impacts from the inventory data does not adequately support decision-making. As the supporting science improves and the LCI data becomes more robust (e. g., higher spatial resolution), inclusion of these impact categories should be periodically reconsidered. (Hendry, 2016).

Given the importance of mineral resources for society and the persistent debate about how mineral resource use should be addressed in life cycle assessment (LCA), a wide variety of impact assessment methods have been developed, each of which assesses different aspects of mineral resource use. Within the “global guidance for life cycle impact assessment (LCIA) indicators and methods” project of the Life Cycle Initiative hosted by UN Environment; a task force has been established to develop recommendations on the LCIA of mineral resource use. (Berger, 2020) and (Sonderegger, 2020)

Table 2-4: Impact category descriptions

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

Impact Category	Description	Unit	Reference
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 PO_4^{3-} equivalent	(Guinée, et al., 2002)
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	
Photochemical Ozone Creation Potential (POCP)	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 C_2H_4 equivalent	
Human toxicity Eco-toxicity	A measure of toxic emissions which are directly harmful to the health of humans and other species.	Comparative toxic units (CTU_h, CTU_e)	(Rosenbaum, et al., 2008)

Table 2-5: 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 freshwater consumption (excluding hydropower)	kg	(thinkstep, 2019)

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

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 are interpreted according to the Goal and Scope. The interpretation addresses the following topics:

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

2.8. 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 considered to be 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.
- 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 are able to 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 a certain country), best-available proxy data were employed.

An evaluation of the data quality with regard to these requirements is provided in chapter 5 of this report.

2.9. 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 in 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 EUROBAT 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.

2.10. Software and Database

The LCA model was created using the GaBi 9 Professional Software system for life cycle engineering, developed by Sphera GmbH. The GaBi 2019 LCI database provides the life cycle inventory data for the majority of the raw and process materials obtained from the background system.

2.11. Critical Review

In accordance with ISO 14044 section 6.2 and ISO/TS 14071, a critical review of this study has been undertaken by Matthias Finkbeiner from Technical University Berlin, Germany, to ensure conformity with ISO 14040/44. This critical review has been undertaken concurrently, i.e. after goal and scope definition and final reporting. . The analysis and the verification of software model and individual datasets were outside the scope of this review.

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

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

All primary data were collected using customized data collection templates, which were sent out by email to the respective data providers in the participating companies. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. If gaps, outliers, or other inconsistencies occurred, Sphera engaged with the data provider to resolve any open issues.

Questionnaires included data requests regarding battery composition, battery manufacturing process, and the inbound transport of raw materials. Table 3-1 list of participating battery producers.

Table 3-1: Participating battery producers and corresponding country

Company	Country
EXIDE	ES
MIDAC	IT
FIAMM	IT
EnerSys	FR
Moll Batteries	DE
Clarios	DE

3.2. Production Stage

Manufacturers' data were weighted based on production volumes to create average batteries, which were then scaled to the average battery mass defined in Table 2-1.

Table 3-2 lists the inputs and outputs associated with the production of each battery, including all processes and on-site waste water treatment. All lead and lead alloy compounds are derived from primary and secondary production of lead. Water sent through on-site waste water treatment was subsequently sent to municipal waste water 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 dataset. For emissions to water, arsenic, cadmium, copper, and lead were approximated using an average of other companies if not reported by a site.

Table 3-2: Average gate-to-gate data for battery production

Type	Flow	Standard	Improved	Advanced	Unit
Input	Lead (incl. alloys, red lead and oxide)	10.5	10.23	11.65	kg
	Glass fibers	6.30E-03	1.16E-03	0.03	kg
	Polyethylene part (PE)	0.38	0.19	0.25	kg
	Polypropylene part (PP)	0.76	0.59	0.77	kg
	Secondary Prolypropylene	0.18	0.15	0.12	kg
	Sodium sulfate	2.42E-03	1.78E-04	3.56E-04	kg
	Sulfuric acid (100%)	4.35	3.23	3.70	kg
	Water (desalinated; deionised)	4.74	3.90	3.33	kg
	Water (ground water)	52.16	20.08	17.57	kg
	Water (tap water)	8.68	13.88	13.11	kg
	Electricity	38.34	35.88	35.94	MJ
	Thermal energy from natural gas	35.52	31.31	51.23	MJ
	Iron Chloride for WWT	2.42E-02	-	3.47E-03	kg
	Flocculants for WWT	8.89E-03	0.01	3.44E-04	kg
	Sodium hydroxide incl. for WWT	6.89E-03	0.03	0.84	kg
Output	Lead acid battery	18	19	20	kg
	Lead scrap	0.74	1.31	0.57	kg
	Hazardous waste for further processing	9.97E-03	2.73E-03	0.014	kg
	Waste for recovery	0.61	1.32	0.58	kg
	Waste water to municipal treatment	13.06	9.46	12.48	kg
Emissions to air	Dust (>PM10)	4.59E-04	4.37E-04	2.27E-04	kg
	Lead	3,57E-05	3,55E-04	1,87E-06	kg
	Sulfuric acid	1.98E-04	1,98E-05	7.95E-05	kg
	Nitorgen dioxide	2.08E-04	1.07E-04	5.02E-06	kg
	Water vapour	9.59	7.73	9.20	kg
Emissions to water	Nickel	2.88E-08	6.46E-09	2.39E-08	kg
	Zinc	3.31E-07	1,.9E-08	6.25E-08	kg
	Sulphate	9.29E-03	8.23E-03	1.12E-02	kg
	Lead	4.99E-06	2.65E-06	2.33E-06	kg

3.3. Use stage

The use stage has been modelled considering the available information from the automotive sector, nevertheless, the authors acknowledge other factors that might contribute to these savings, such as other vehicle components' weight (apart from battery components) and the drivers' behavior.

Table 2-2 define the characteristic lifetime and fuel consumptions for three battery-applications. This data was provided by the study participants based on prevalent standard averages in the automotive industry. The data refers to a 'Small MPV', as it is referred to in Euro NCAP[10] classification. These vehicles fall under category M1 vehicles as defined by the European Commission (passenger vehicles with no more than 8 seats, weighing less than 3.5 tonnes). [11]

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 including 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 3-9.5%, 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.

To avoid overestimation or bias, this study assumes 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[12]. (EPA, Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation, 2016)

These assumptions are applied to the reference case, a representative compact MPV using a standard technology battery, with fuel efficiency of 5.1 litre/km[13]. A representative lifetime of 10 years and/or 150,000 km has also been assumed and is in line with the parameters selected as standard by the car industry for several vehicle LCAs[14].

'It has been shown that the fuel consumption required to move a mass of 100 kg over 100 km, 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)

*Gasoline consumption per kg weight: 0.35 l/(100 km*100 kg)* → ***3,885 kg /150000 km kg***
Gasoline specific density (used for conversion from Litre to kg): 0,74 kg/l

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[10] ‚Small MPV' is a Euro NCAP structural-class classification (http://www. euroncap. com/small_mpv. aspx)
[11] 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" -
[12] The Driving Force Behind Start-Stop, Innovative Start-Stop Batteries from VARTA, Johnson Controls. UK
[13] Derived from average fuel consumption values for MPV from www. fuelmileage. co. uk
[14] Automotive LCA Guidelines – Phase 2, EUCAR

Table 3-3 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 behavior of MPV mainly in urban areas.

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

Emission to air	Amount	Unit
Carbon dioxide	3.01	kg
Carbon dioxide (biotic)[15]	0.16	kg
Sulphur dioxide	2.0E-05	kg

3.4. Background Data

Documentation for all GaBi datasets can be found online (thinkstep, 2019).

3.4.1. Fuels and Energy

National or regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2019 databases. Table 3-4 shows the most relevant LCI datasets used in modelling the product systems. Electricity consumption was modelled using national grid mixes for Spain, Italy, Germany and France.

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

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Electricity	ES	Electricity grid mix	Sphera	2016	-
	IT	Electricity grid mix	Sphera	2016	-
	DE	Electricity grid mix	Sphera	2016	-
	FR	Electricity grid mix	Sphera	2016	-
Thermal energy	ES	Thermal energy from natural gas	Sphera	2016	-
	IT	Thermal energy from natural gas	Sphera	2016	-
	DE	Thermal energy from natural gas	Sphera	2016	-
	FR	Thermal energy from natural gas	Sphera	2016	-

3.4.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2019 database. Table 3-5 shows the most relevant LCI datasets used in modelling the product systems.

[15] EU-28 Gasoline dataset includes ~5% share of bio-components (bio-ethanol and bio-diesel).

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

Material / Process	Geo.	Dataset	Data Provider	Reference Year	Proxy?
Expander	DE	Barium sulphate (BaSO4)	Sphera	2018	-
Expander	DE	Carbon black (furnace black; general purpose)	Sphera	2018	-
Glass mat	DE	Glass fibres	Sphera	2018	-
LDPE	EU-28	Polyethylene Low Density Granulate (LDPE/PE-LD)	Sphera	2018	-
PP	EU-28	Polypropylene granulate (PP)	Sphera	2018	-
Lead, primary	EU/NAM	Primary lead average production mix	ILA	2015	-
Lead, secondary	EU	Secondary lead average production mix	ILA	2015	-
Sand	DE	Limestone flour	Sphera	2018	-
Sodium sulfate	GLO	Sodium sulphate	Sphera	2018	-
Sulfuric acid	DE	Sulphuric acid (high purity)	Sphera	2018	-
Deionized water	EU-28	Water deionized	Sphera	2018	-
Tap water	EU-28	Tap water from ground water	Sphera	2018	-
Process related					
Hydrochloric acid (WWT)	DE	Hydrochloric acid 32%	Sphera	2018	-
Hazardous waste treatment	DE	Hazardous waste (statistic average) (no C, worst case scenario incl. landfill)	Sphera	2018	-
Ferric chloride (WWT)	DE	Ferric chloride 37%	Sphera	2018	-
Limestone (WWT)	DE	Limestone flour	Sphera	2018	-
Waste water treatment	DE	Municipal waste water treatment (mix)	Sphera	2018	-
Injection molding	GLO	Plastic injection moulding (parameterized)	Sphera	2018	-
Soda (WWT)	DE	Sodium hydroxide (caustic soda) mix (100%)	Sphera	2018	-
Water	EU-28	Tap water from groundwater	Sphera	2018	-

3.4.3. 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 3-6.

Table 3-6: Transportation and road fuel datasets

Mode / fuels	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Class EU 4 truck	GLO	Truck-trailer, Euro 4, 28 - 34t gross weight / 22t payload capacity	Sphera	2018	-
Diesel	EU-28	Diesel mix at refinery	Sphera	2016	-
Gasoline	EU-28	Gasoline mix (regular) at refinery	Sphera	2016	-

3.5. 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 table below 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 3-7: LCI results of System A, by battery type (units in kg unless otherwise noted)

Type	Flow	Standard	Improved	Advanced
Resources	Crude oil (resource) [MJ]	75.80	75.85	66.81
	Hard coal (resource) [MJ]	102.05	102.24	108.40
	Lignite (resource) [MJ]	9.51	9.54	23.36
	Natural gas (resource) [MJ]	142.66	142.83	171.57
	Uranium (resource) [MJ]	67.35	67.43	93.03
	Renewable energy resources [MJ]	68.68	68.74	67.53
	Non-renewable elements	0.70	0.70	0.90
	Non-renewable resources	104.21	104.51	143.19
	Renewable resources	2.98E+04	2.99E+04	5.08E+04
	Fresh water	4.67E-03	4.67E-03	5.30E-03
	Ground water	171.31	1.72E+02	2.12E+02
	Lake water	1.14	1.18	7.68
	Rain water	120.47	120.72	199.28
	River water	167.46	168.56	312.61
	Sea water	205.86	206.04	243.96
Emissions to air	Carbon dioxide	28.32	28.37	31.76
	Dust (> PM10)	3.65E-03	3.66E-03	3.48E-03
	Dust (PM10)	2.80E-05	2.80E-05	3.21E-05
	Dust (PM2.5 - PM10)	1.93E-03	1.94E-03	2.06E-03
	Dust (PM2.5)	2.91E-02	2.91E-02	2.91E-02
	Formaldehyde (methanal)	6.83E-05	6.84E-05	7.81E-05
	Hexane (isomers)	1.43E-05	1.43E-05	1.39E-05
	Lead	1.01E-04	1.01E-04	9.07E-05

Type	Flow	Standard	Improved	Advanced
	Methane	5.12E-02	2.85E-02	5.46E-02
	Methane (biotic)	9.19E-04	1.04E-03	1.76E-03
	Nitrogen oxides	5.00E-02	5.01E-02	5.88E-02
	Phenol (hydroxy benzene)	1.56E-05	4.16E-07	1.40E-05
	Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD)	9.25E-11	9.27E-11	9.08E-11
	Polychlorinated dibenzo-p-furans (2,3,7,8 - TCDD)	1.03E-10	1.03E-10	9.83E-11
	Sulphur dioxide	1.64E-01	1.64E-01	1.76E-01
	Xylene (dimethyl benzene)	9.42E-05	9.43E-05	1.14E-04
Emissions to water	Biological oxygen demand (BOD)	7.99E-04	8.00E-04	1.02E-03
	Chemical oxygen demand (COD)	1.07E-02	1.40E-02	1.49E-02
	Nitrate	1.42E-03	1.43E-03	2.36E-03
	Nitrogen organic bound	2.39E-04	2.39E-04	4.75E-04
	Phenol (hydroxy benzene)	1.94E-05	1.56E-05	1.98E-05
	Phosphorus	1.76E-05	1.76E-05	3.25E-05
	Collected rainwater to river	4.71E+00	4.72E+00	5.26E+00
	Cooling water to river	1.19E+02	1.20E+02	2.30E+02
	Processed water to groundwater	-1.15E-01	-1.09E-01	7.59E-01
	Processed water to river	9.16E+01	9.22E+01	1.65E+02
	Turbined water to river	2.75E+02	2.75E+02	3.55E+02

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 2.6. 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. System A – Cradle to Gate

System A comprises only the production of the lead-based battery. It has a cradle to gate scope that does not include end-of-life impacts or potential credits/burdens resulting from reuse/recycling.

4.1.1. Standard Batteries

Total results for the cradle-to-gate production of standard batteries can be seen in Table 4-1, while Figure 4-1 presents relative results broken down by category.

Table 4-1: LCIA for System A of standard batteries

Impact / Indicator	Value	Unit
GWP	21	kg CO_2-eq
AP	0.14	kg SO_2-eq
EP	7.61E-03	kg Phosphate eq.
POCP	7.18E-03	kg Ethene eq.
PED	390	MJ (LHV)
PED, non-renewable	328	MJ (LHV)
PED, renewable	61.4	MJ (LHV)
Water	1.03E+03	kg

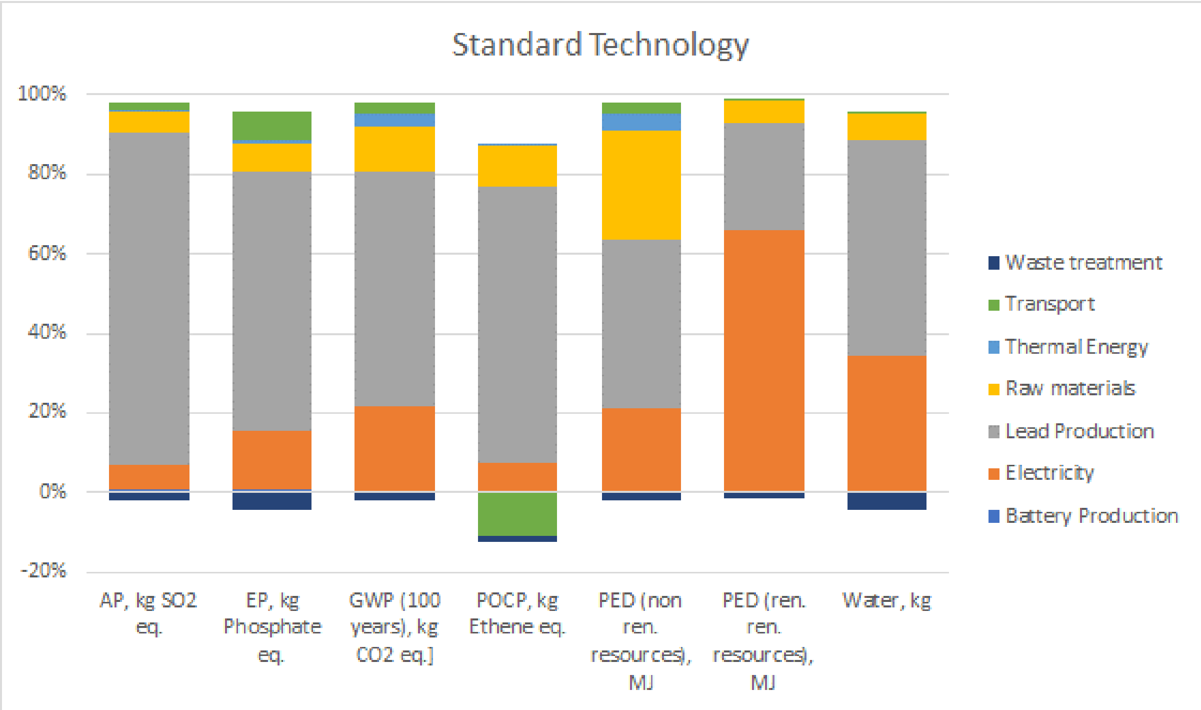

Figure 4-1: Cradle-to-gate results for manufacturing of Standard batteries

GWP In System A of standard battery production, 60% of GWP stems from the upstream production of lead, 22% from onsite electricity consumption, and 13% from the production of other raw materials used. Among the raw materials, it is the production of the plastic parts that is of greatest relevance to GWP impacts. Carbon dioxide is the single largest contributor to GWP (94%).

AP The maximum contribution for standard battery production comes from the production of the lead required (83%). The production of raw materials has a share of 7%, due to the production of plastic parts and sulfuric acid. Electricity production also contributes 9% of impacts, stemming from sulphur content of fuels burned for power generation. Most of the AP is due to sulphur dioxide emissions (89%), followed by impacts from nitrogen oxides (11%).

EP The greatest contributor to EP in System A is the production of lead, at 68%, while the production of the electricity used on-site contributes 17% of impacts. Raw material production contributes 9%. The greatest impact contributions for EP over the entire life cycle stem from nitrogen oxides emissions (77%).

POCP The contribution breakdown for POCP is: 81% from lead production, 11% from the production of electricity used onsite, and 15% from the production of raw materials. Among raw materials, it is the production of sulfuric acid that is of greatest dominance. Transport and waste treatment contribute with a credit of -9% and -1% respectively, for transport this is due to the negative contribution to the POCP as a result of NO emissions which have a negative characterisation factor in the CML methodology, in the case of waste treatment the credit is given to the lead recovered from it. Sulphur dioxide (66%) and NMVOC (19%) are the largest emission contributors to POCP.

PED Lead production is the most energy intensive module using 36% of total PED (renewable and non-renewable). The onsite electricity consumption contributes with 31% and raw materials production with 28%. Separately, renewable and non-renewable both follow the same results trends as total PED.

Water The primary contributor to the water used during the production of standard batteries is lead production (58%) and 35% from Electricity production. A negative value in waste treatment due to the lead recovered and the inclusion of waste water treatment in this category, which accounts for the water released to the environment.

4.1.2. Improved Batteries

Total results for the cradle-to-gate production of improved batteries can be seen in Table 4-3, while Figure 4-2 presents relative results broken down by category.

Table 4-2: LCIA for System A of improved batteries

Impact / Indicator	Value	Unit
GWP	17.8	kg CO_2-eq
AP	0.11	kg SO_2-eq
EP	6.40E-03	kg Phosphate eq.
POCP	5.50E-03	kg Ethene eq.
PED	297.3	MJ (LHV)
PED, non-renewable	252	MJ (LHV)
PED, renewable	45.3	MJ (LHV)
Water	871	kg

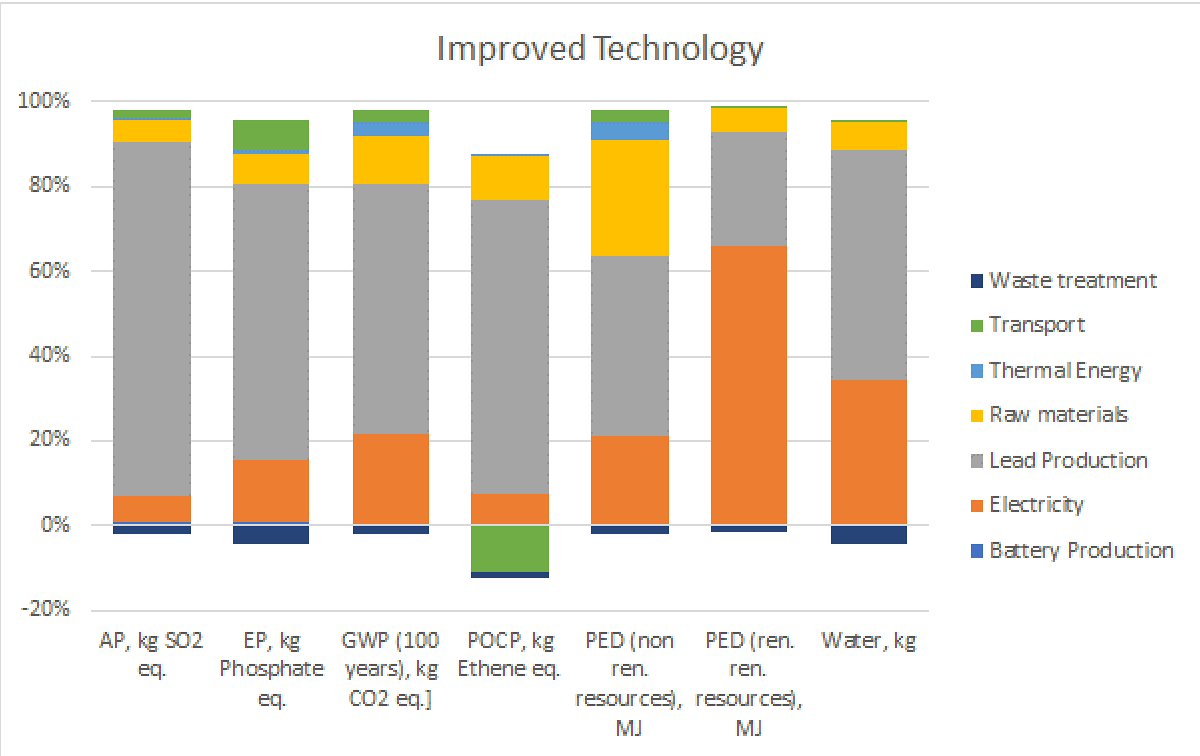

Figure 4-2: Cradle-to-gate results for manufacturing of improved batteries

GWP In System A of improved battery production, 62% of GWP stems from the upstream production of lead, 22% from onsite electricity consumption, and 12% from the production of other raw materials used. Among the raw materials, it is the production of the plastic parts that is of greatest relevance to GWP impacts. Carbon dioxide is the single largest contributor to GWP (96%).

AP The maximum contribution for improved battery production comes from the production of the lead required (87%). The production of raw materials has a share of 6%, due to the production of plastic parts and sulfuric acid. Electricity production also contributes 7% of impacts, stemming from sulphur content of fuels burned for power generation. Most of the AP is due to sulphur dioxide emissions (91%), followed by impacts from nitrogen oxides (9%).

EP The greatest contributor to EP in System A is the production of lead, at 71%. Production of the electricity used on-site contributes 16% of impacts. Raw material production contributes 8%. The greatest impact contributions for EP over the entire life cycle stem from nitrogen oxides emissions to air (72%).

POCP The contribution breakdown for POCP is: 92% from lead production, 9% from the production of electricity used onsite, and 14% from the production of raw materials. Among raw materials, it is the production of sulfuric acid that is of greatest dominance. Transport and waste treatment contribute with a credit of -14% and -2% respectively, for transport this is due to the negative contribution to the POCP as a result of NO emissions which have a negative characterisation factor in the CML methodology, in the case of waste treatment the credit is given to the lead recovered from it. The largest emission contributors to POCP are the emissions of Sulphur dioxide (68%) and NMVOC (19%).

PED Lead production is the most energy intensive module using 41% of total PED (renewable and non-renewable). The onsite electricity consumption contributes with 29% and raw materials production with 25%. Separately, renewable and non-renewable both follow the same results trends as total PED.

Water The primary contributor to the water used during the production of improved batteries is lead production (60%) and 38% from Electricity production. A negative value in waste treatment due to the lead recovered and the inclusion of waste water treatment in this category, which accounts for the water released to the environment.

4.1.3. Advanced Batteries

Total results for the cradle-to-gate production of advanced batteries can be seen in Table 4-3, while Figure 4-3 presents relative results broken down by category.

Table 4-3: LCIA for System A of advanced batteries

Impact / Indicator	Value	Unit
GWP	27	kg CO_2-eq
AP	0.17	kg SO_2-eq
EP	9.67E-03	kg Phosphate eq.
POCP	8.73E-03	kg Ethene eq.
PED	464	MJ (LHV)
PED, non-renewable	398	MJ (LHV)
PED, renewable	66,8	MJ (LHV)
Water	1.42E+03	kg

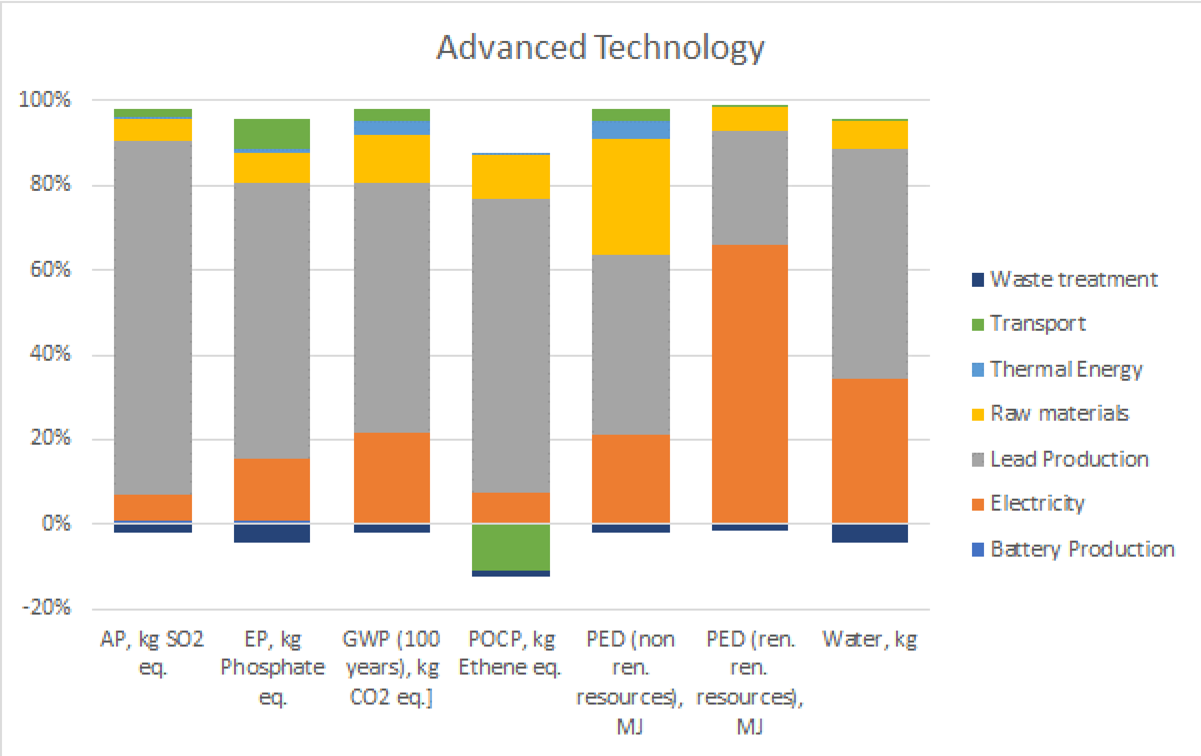

Figure 4-3: Cradle-to-gate results for manufacturing of advanced batteries

GWP In System A of advanced Technology battery production, 61% of GWP stems from the upstream production of lead, 22% from onsite electricity consumption and 11% from the production of other raw materials used. Among the raw materials, it is the production of the plastic parts that is of greatest relevance to GWP impacts. Carbon dioxide is the single largest contributor to GWP (94%).

AP The maximum contribution for advanced Technology battery production comes from the production of the lead required (88%). The production of raw materials has a share of 6%, due to the production of plastic parts and sulfuric acid. Electricity production also contributes 6% of impacts, stemming from sulphur content of fuels burned for power generation. Most of the AP is due to sulphur dioxide emissions (88%), followed by impacts from nitrogen oxides (12%).

EP The greatest contributor to EP in System A is the production of lead, at 71%. The production of the electricity used on-site contributes 16% of impacts. Raw material production contributes 8%. The greatest impact contributions for EP over the entire life cycle stem from nitrogen oxides emissions 79%.

POCP The contribution breakdown for POCP is: 88% from lead production, 7% from the production of electricity used onsite, and 13% from the production of raw materials. Among raw materials, it is the production of sulfuric acid that is of greatest dominance. Transport and waste treatment contribute with a credit of -9% and -0.2% respectively, for transport this is due to the negative contribution to the POCP as a result of NO emissions which have a negative characterisation factor in the CML methodology, in the case of waste treatment the credit is given to the lead recovered from it. The largest emission contributors to POCP are the emissions of Sulphur dioxide (68%) and NMVOC (19%).

PED Lead production is the most energy intensive module using 40% of total PED (renewable and non-renewable). The onsite electricity consumption contributes with 30% and raw materials production with 24%. Separately, renewable and non-renewable both follow the same results trends as total PED.

Water The primary contributor to the water used during the production of Advanced batteries is lead production (56%) and 39% from electricity production. A negative value in waste treatment due to the lead recovered and the inclusion of waste water treatment in this category, which accounts for the water released to the environment.

4.2. System B – Cradle to Gate and Use

In the evaluation of System B, the climate change impacts, and savings have been represented by the global warming potential (GWP) indicator, expressed in kg CO_2 eq. GWP has been selected due to the wide-spread relevance of the indicator as a measure of climate change potential and because the emissions from the combustion of fuel in vehicle engines are highly relevant to this category.

The charts in Figure 4-4 show the relative savings of CO_2 eq. stemming from the use of start-stop technology, of which Improved Technology batteries are an integral part. The chart accounts for the manufacturing impacts of the batteries as well as the manufacture of replacement batteries required over the lifetime of the vehicle. It considers the savings in CO_2 eq. emissions associated with the production of fuel as well as those from the exhaust of the vehicle, when the fuel is burned.

Figure 4-4 displays the environmental impacts incurred and credits obtained due to fuel savings when the two battery types are used in their respective applications/systems, for a vehicle lifetime of 150,000 km (see section 2.2 for more details). The Standard Technology battery and its associated fuel consumption (see Table 2-2) are considered as a baseline scenario and the savings of the Improved Technology battery over the course of the vehicle's lifetime are calculated relative to it. Figure 4-4 presents how these fuel savings translate to credits/reduction in environmental impact, as measured by the GWP indicator. The 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 section 2.2, represent a best case assumption for the battery as the benefit is not exclusively due to the merit of the batteries, but the batteries do enable this engine technology use.The reference lifetime of 150,000 km is a standard used by the automotive industry for Small MPVs. The manufacturing impacts of the batteries (including the battery in the vehicle and its replacements) are accounted for in the chart and appear as small 'steps' at the start of vehicle lifespan and at the points where the battery life runs out. A magnified view of the manufacturing impacts has been included in a window below the chart to illustrate the small scale of the impact relative to the savings (as visible from the impact values) and the relative comparability of manufacturing impacts of the two battery types.

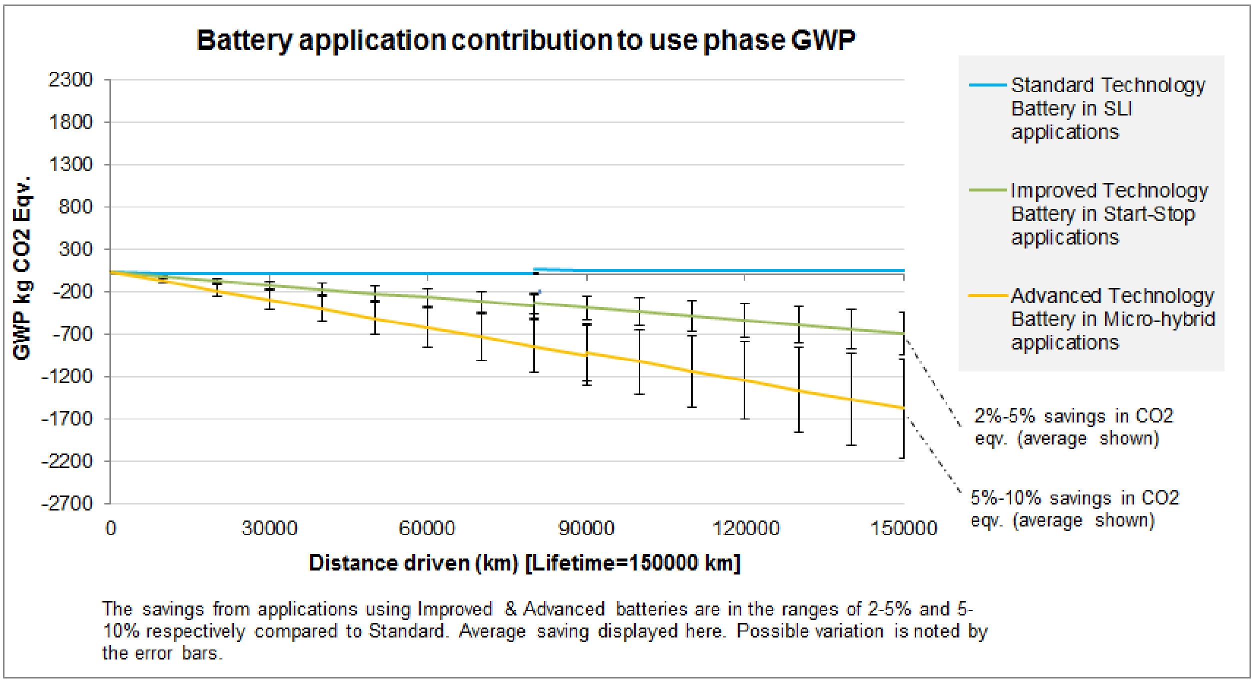

Figure 4-4: System B results – battery use phase according to application

As a result, it can be seen that, over the vehicle's lifetime (excluding end of life) the GWP from the start-stop system has an average value of -695 kg CO_2 eq. The negative value implies that 695 kg CO_2 eq. are avoided due to the use of the start-stop application, containing the improved technology battery. This saving is far greater in magnitude than the environmental impact of the production of the battery alone which is approximately 32.5 kg CO_2 eq.

Net values over the lifetime are also alternatively illustrated in the bar chart in Figure 4-5.

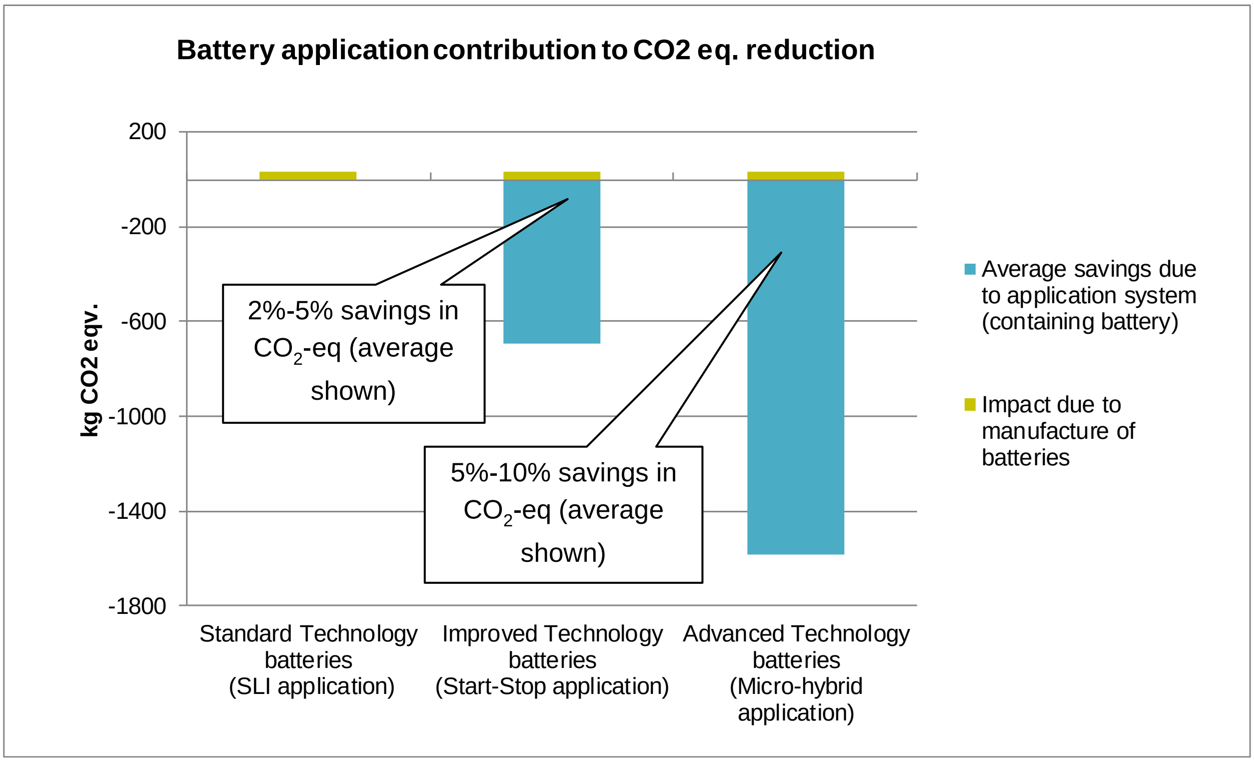

Figure 4-5: Net impacts and savings associated with batteries required over vehicle-lifetime

4.3. System C – Cradle to Gate and EoL

The System C comprises the impacts from the production of the battery and also includes the impacts associated with recycling the lead based battery.

A take back rate of 99% has been considered in this study. While all old lead batteries on the market are taken back and recycled by manufacturers, this figure provides a conservative estimate, accounting for any batteries not received after being used (due to the 'hoarding effect'). These used batteries proceed to a recycling facility where the useful materials are recovered. According to the ILA battery recycling dataset used, around 0.65 kg of lead is recovered per 1 kg of battery input to the process.

The following two approaches were used to assess the impacts associated with the EoL of the batteries after its collection:

- <u>Cut-off approach:</u> This approach neglects the burdens associated with the scrap and also the benefits of reusable lead once it is recycled.
- <u>Substitution approach:</u> This approach connects the amount of scrap generated by the process to the amount of scrap demanded and compensates for any difference with additional lead production. Only the difference in lead leads to an impact or credit from secondary lead in the production stage. The burden of processing the secondary lead falls in the recycling stage.

System C – Cut-off approach

Figure 4-6 shows the cut-off approach whereby the upstream burdens and impacts associated with the scrap input are neglected and so are the downstream benefits of the lead from the batteries that is recycled at the end of its useful life.

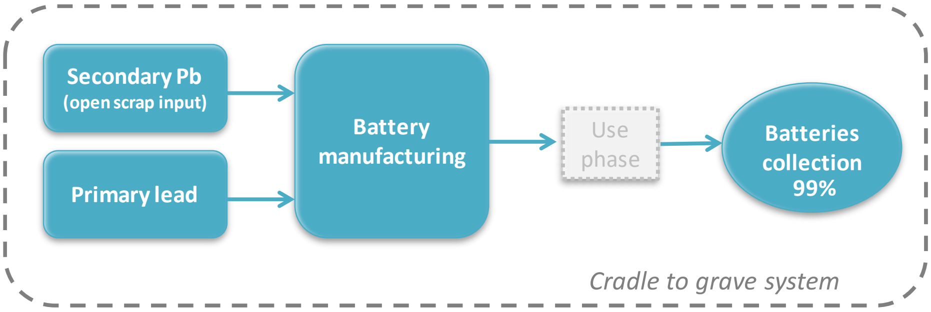

Figure 4-6: System C – Cut-off approach

System C – Substitution approach

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 falls in the recycling stage.

The lead used in the manufacturing of the batteries comes from two main routes, 75% secondary and 25% primary. The secondary lead dataset has open 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. Figure 4-7 and Figure 4-8 depict the approach applied.

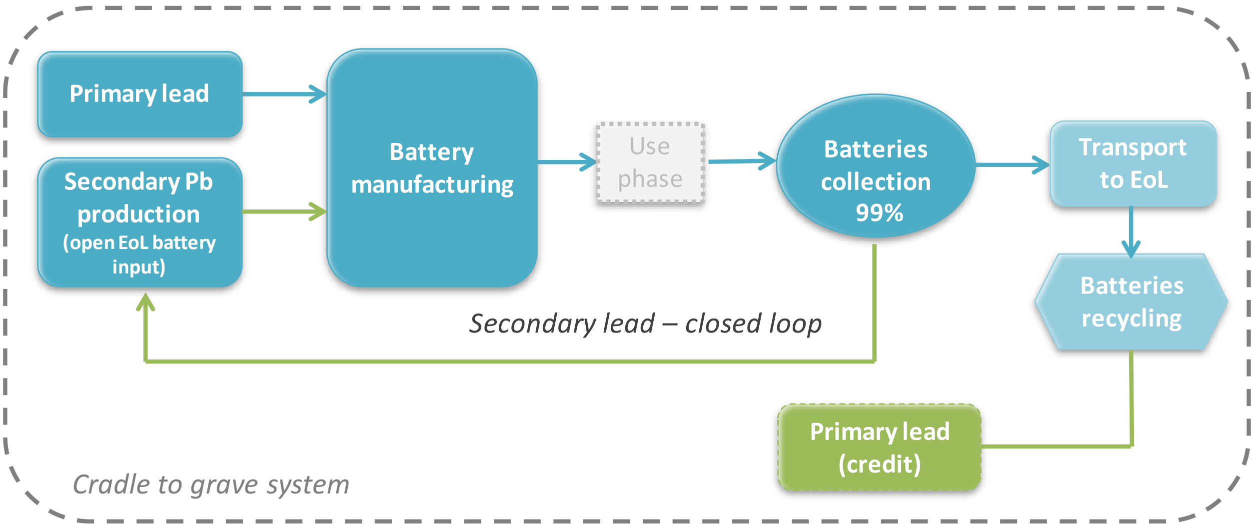

Figure 4-7: System C – Substitution approach

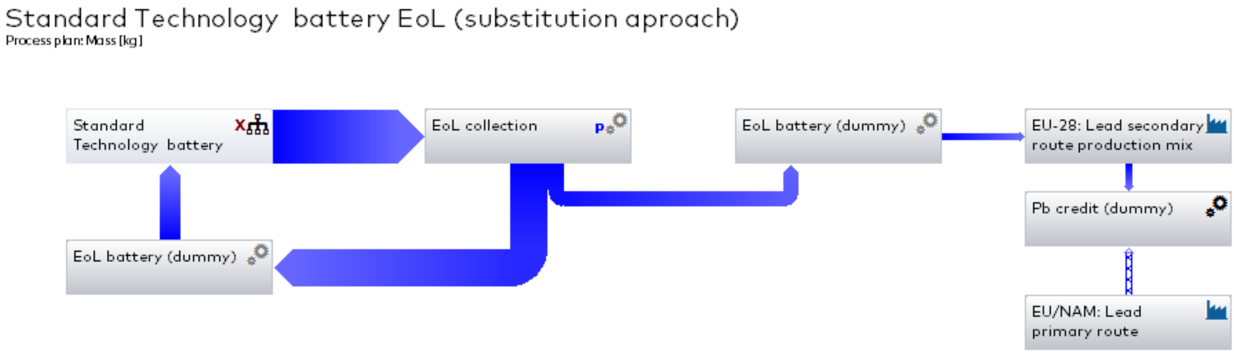

Figure 4-8: GaBi model screenshot of system C – Substitution approach

Figure 4-9 to Figure 4-14 illustrate net environmental impacts of the cradle to grave assessment. Two different EoL approaches have been analysed, being the substitution approach the most commonly used by metal industry.

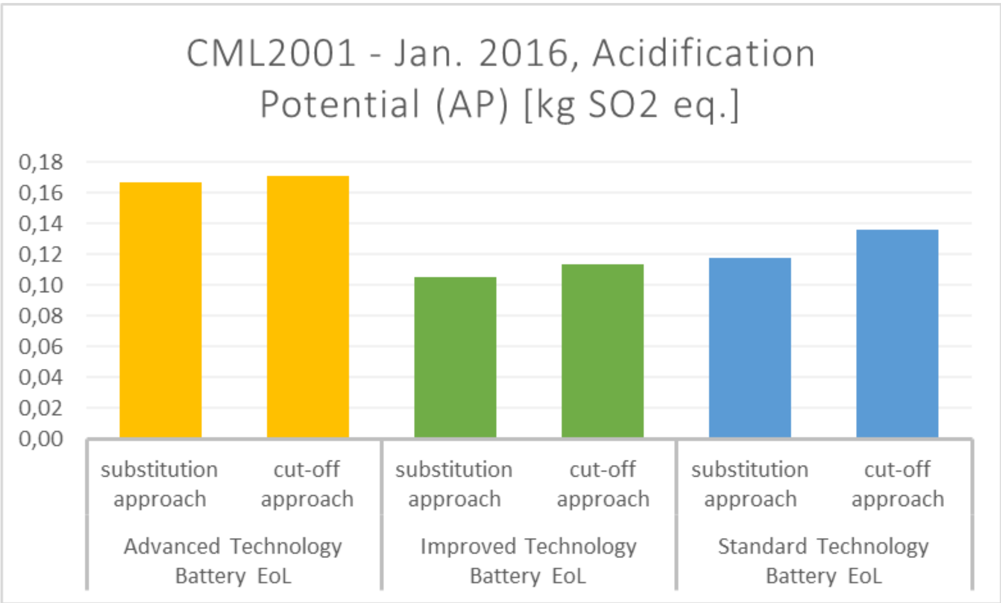

Figure 4-9: Cradle-to-grave results – Acidification Potential

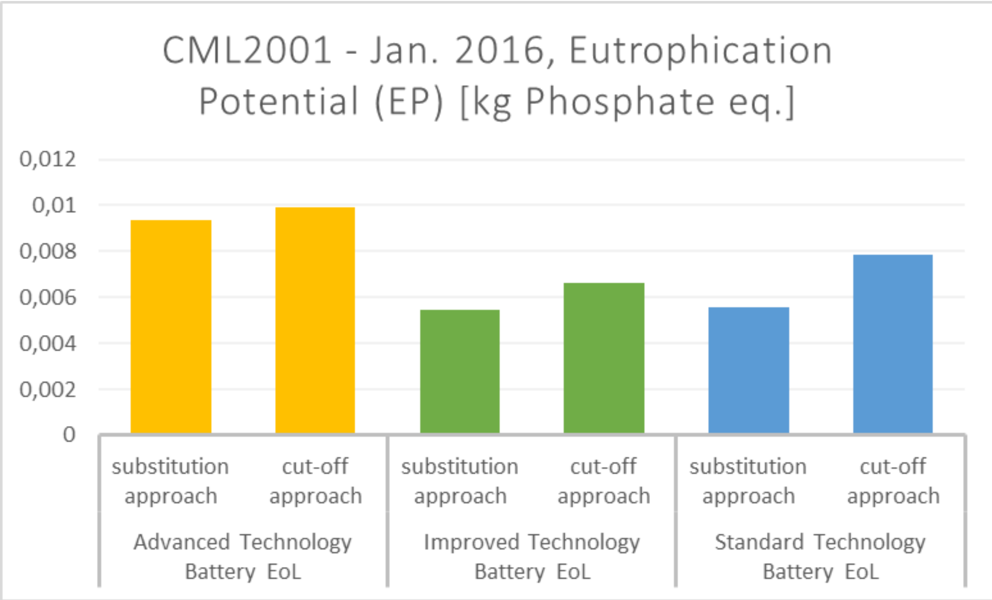

Figure 4-10: Cradle-to-grave results – Eutrophication Potential

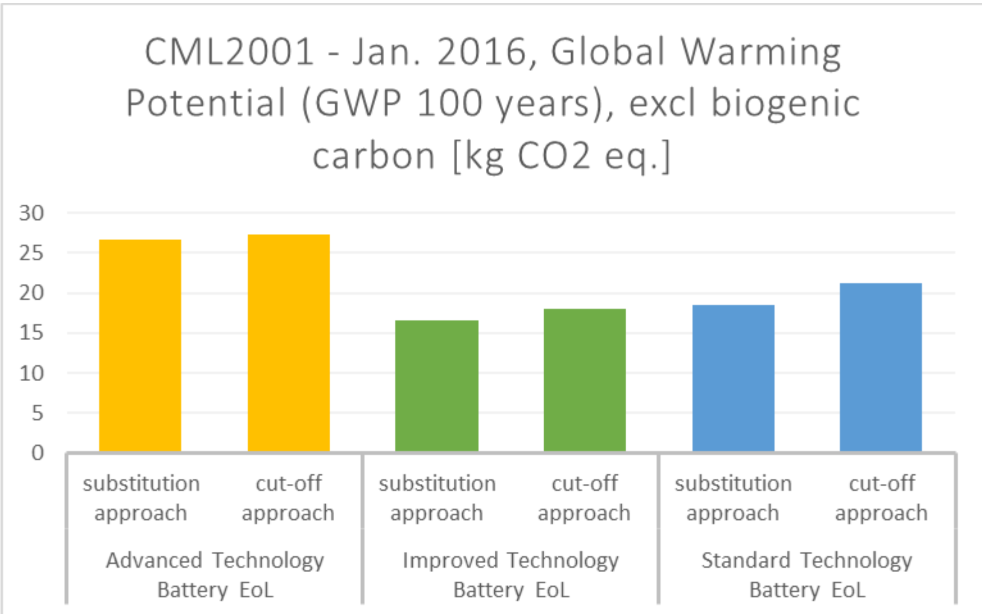

Figure 4-11: Cradle-to-grave results – Global Warming Potential

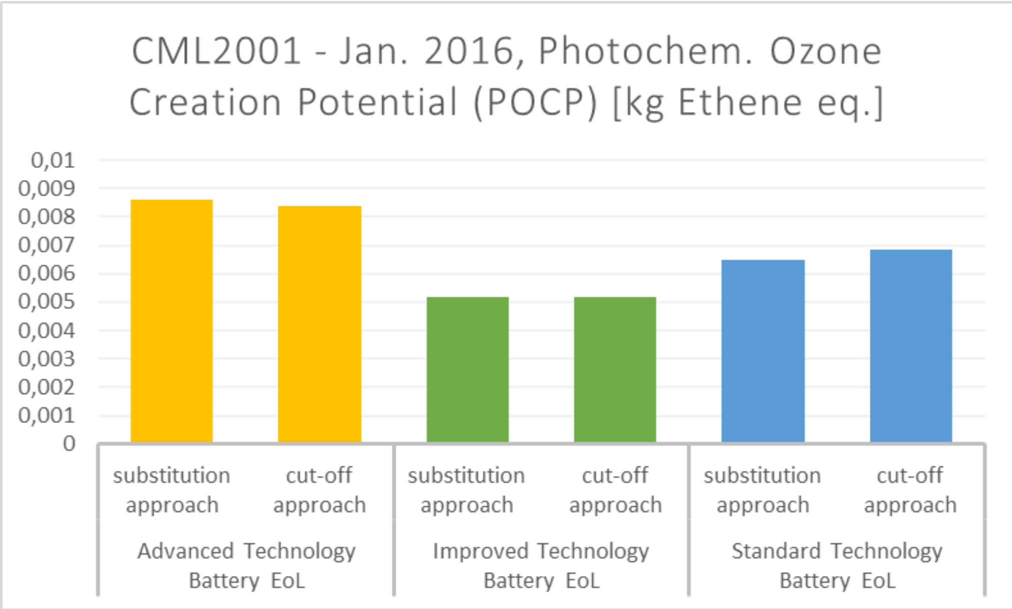

Figure 4-12: Cradle-to-grave results – Photochem. Ozone Creation Potential

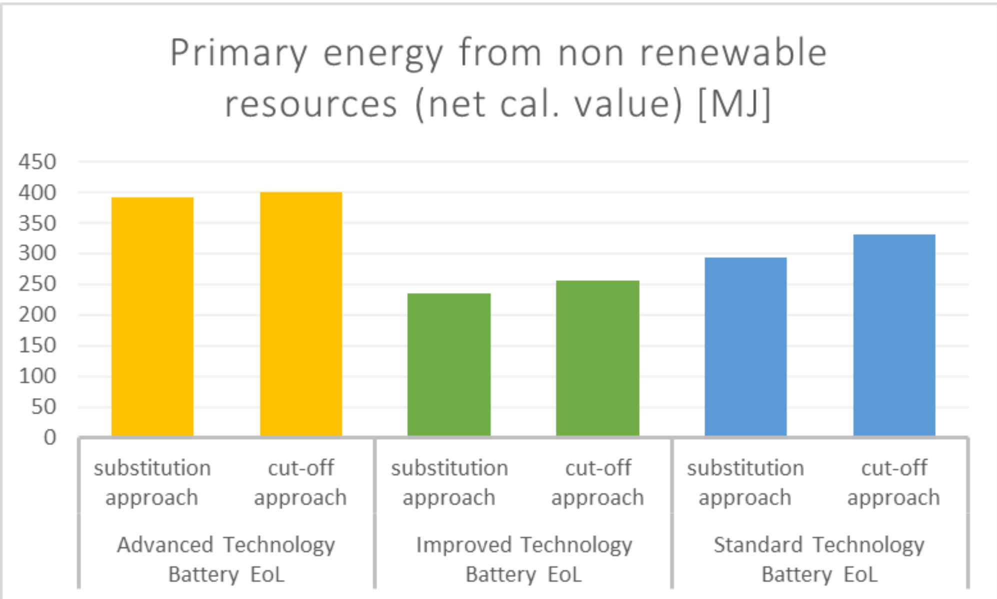

Figure 4-13: Cradle-to-grave results – Primary Energy Demand (non-renewable resources)

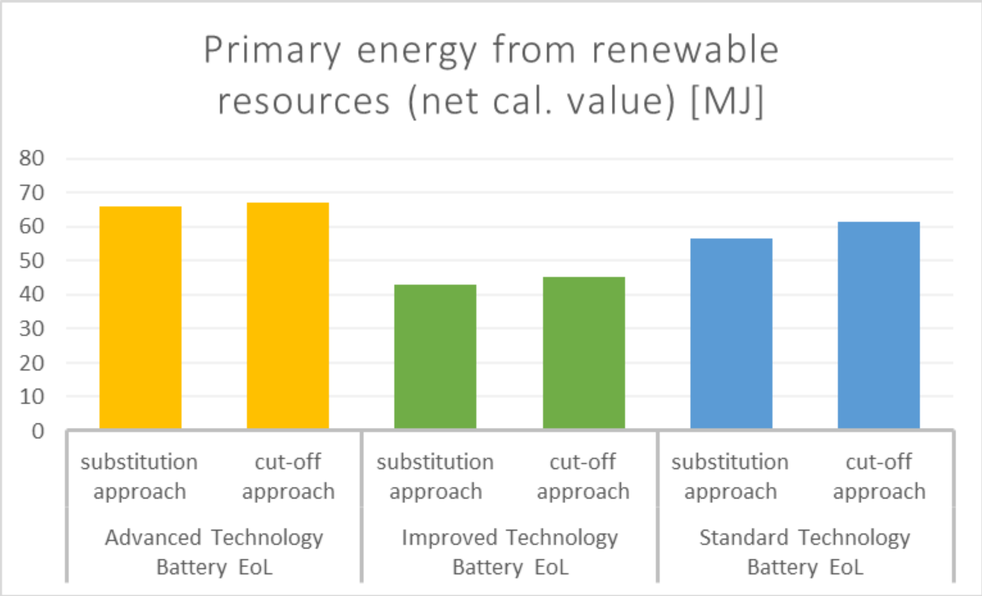

Figure 4-14: Cradle-to-grave results – Primary Energy Demand (renewable resources)

5. Interpretation

5.1. Identification of Relevant Findings

Within System A, lead production and electricity use are most often the primary drivers of impacts. Raw materials like sulfuric acid and plastic parts can also have a noticeable contribution. Lead production contributes anywhere from 36% to 83% of total impacts, while the range for electricity was 9%-35% and raw materials was 7%-28% (ranges exclude toxicity results due to the previously mentioned uncertainty associated with these impact categories). All other production categories each contributed less than 10% to the impact categories assessed. Although the weight of the improved batteries is higher than the standard batteries, their environmental impacts are lower due to the fact that the total net lead use is lower. I.e Lower lead input and higher lead scrap output in the manufacturing side (and therefore higher credit) (see Table 3-2). It was expected that the results for improved batteries would be higher than the standard, following the pattern more battery weight, more impact. The production data of the specific manufacture that leads to these results have been confirmed and are consistent. Table 5-1 summarizes the most relevant findings.

Table 5-1: Most relevant findings

Impact category	Most relevant findings	Standard	Improved	Advanced
GWP	Main contributor to manufacturing results	60% lead production / 22% electricity / 13% raw materials (plastic)	62% lead production / 22% electricity / 12% raw materials (plastic)	61% lead production / 22% electricity / 11% raw materials (plastics)
	Main input/output contributing to overall results	carbon dioxide (94%).	carbon dioxide (96%).	carbon dioxide (94%).
AP	Main contributor to manufacturing results	83% lead production / 7% raw materials (plastic, acid sulfuric)	87% lead production / 6% raw materials (plastic, acid sulfuric / 7% electricity	88% lead production / 6% raw materials (plastic, acid sulfuric) / electricity (6%)
	Main input/output contributing to overall results	sulfur dioxide (89%) / nitrogen oxides (11%)	sulfur dioxide (91%) / nitrogen oxides (9%)	sulfur dioxide (88%) / nitrogen oxides (12%)
EP	Main contributor to manufacturing results	68% lead production / 17% electricity	71% lead production / 16% electricity / 8% raw materials	71% lead production / 8% raw materials / electricity (16%)
	Main input/output contributing to overall results	nitrogen oxides (77%)	nitrogen oxides (72%)	nitrogen oxides (79%)
POCP	Main contributor to manufacturing results	81% lead production	92% lead production	88% lead production

Impact category	Most relevant findings	Standard	Improved	Advanced
	Main input/output contributing to overall results	NMVOC (19%) / sulfur dioxide (66%)	NMVOC (19%) / sulfur dioxide (68%)	NMVOC (19%) / sulfur dioxide (68%)
PED	Main contributor to manufacturing results	36% lead production / 31 % electricity / 28% raw materials	41% lead production / 29% electricity / 25% raw materials	40% lead production / 30% electricity / 24% raw materials
water	Main contributor to manufacturing results	58% lead production / 35% electricity	60% lead production / 38% electricity	56% lead production / 39% electricity

The batteries assessed in this study are required in conventional and start-stop, and micro-hybrid vehicles. Within System B, the start-stop and micro-hybrid applications lead to a reduced fuel consumptions and emissions when compared to conventional applications. Although the improved technology and advanced technology batteries contain more lead (6 to 16% respectively more than standard it was demonstrated that the start-stop and micro-hybrid technology, using advanced and improved technology batteries, lead to reduced fuel consumptions and emissions when compared to conventional applications. Although the improved technology batteries contain more lead (15% more than standard technology batteries), they have a lower impact in the production phase (15% lower GWP), these batteries contribute also to fuel savings in the vehicle they are used in. Improved and advanced technology lead-based batteries bring GWP benefits through reduction of fuel consumption by the total system of 2-10% in the use phase. Used in the start-stop application, improved technology batteries lead to GWP savings of 695 kg CO_2 eq., and 1586 kg CO2 eq. for advanced technology assuming the total benefit is allocated to the battery. As highlighted by the results, these fuel savings more than amortize for all GWP caused due to their production (chapter 4.2). It is also found that the battery's GWP during manufacturing is in the range of 1% that of the manufacture of the overall vehicle.[16]

Within System C, two methods were assessed for the end of life of lead batteries. Applying the cut-off approach, the cradle to grave system stops in the collection step so no recycling process is used, this is because the input scrap and battery materials are coming burden free and so the burden of recycling belongs to the subsequent life cycle. In the substitution approach the EoL lead batteries are recycled in the production of secondary lead in the input of the production, since there is a 25% of primary lead used, the surplus of EoL battery is then send to recycling and the lead produced is credited. In the closed loop scenario, the recycled lead from batteries is assumed to all recirculate through the identical production processes to be made into new lead batteries. In this case, no consideration of avoided burden is necessary. In the closed loop scenario, the burden for the production of secondary lead (i.e., recycling) falls under the same production stage, while it falls under recycling in the open loop scenario. Owing to the high take back rates (99%) of lead-batteries by manufacturers, the closed loop modelling approach most closely mirrors the real-world material flow, though ultimately the total results are the same for both scenarios.

[16] A comparison was made with between the manufacturing impacts of the battery and that of a complete car (Volkswagen, 2010) and it was found that the impacts (GWP kg CO2-eq.) from the manufacture of the battery is less than 1% of those manufacture of a complete car.

5.2. Assumptions and Limitations

The following emissions to air, if not reported by a company, were approximated using the average of all other reporting companies: sulfuric acid vapor, 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 dataset. For emissions to water, sulphate was approximated using an average of other companies if not reported by a site.

The emissions related to the combustion of natural gas to provide thermal energy, have been accounted for by the GaBi 6 dataset for thermal energy (See: Table 4 5). In case the reported emissions of CO2, CO, NOx, NMVOC or SO2 were higher than the average emissions from the GaBi 6 thermal energy dataset, the difference was added to supplement the data. Thereby, the emission profile of the GaBi 6 thermal energy dataset (based on the thermal energy requirement by the companies in MWh) was maintained as a lower threshold. This ensures that at least all the emissions stemming from the thermal energy production are accounted for.

Of the companies participating, none provided auxiliary batteries data, therefore these batteries were estimated by scaling down the automotive batteries.

Where the reported outputs of water were less than the inputs, it was assumed that the remainder evaporated.

For system B, the emission profile of the vehicle from the combustion of fuel only considers the contribution of the CO2 to the GWP. While other contributing emissions might exist, CO2 is predominant and hence provides a representative picture of the contribution of the burning of fuel in the engine to the GWP stemming from use of the vehicle.

For the glass mat, a proxy with glass fibres has been used to avoid data gaps.

For the use of sand in the production of the advanced batteries Limestone flour has been used as a proxy. The total amount used is very low and so its contribution in the results.

5.3. 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 2019 database were used. The LCI datasets from the GaBi 2019 database are widely distributed and used with the GaBi ts 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.

5.3.1. Precision and Completeness

- ✓ **Precision:** As the majority of the relevant foreground data are measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be high. Seasonal variations and variations across different manufacturers were balanced out by using yearly, weighted averages. Most background data are sourced from GaBi databases with the documented precision.

- ✓ **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is considered to be high. Most background data are sourced from GaBi databases with the documented completeness.

5.3.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while most 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.

5.3.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the year 2017. Most secondary data come from the GaBi 2019 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 high.
- ✓ **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 high.
- ✓ **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 high. All primary and secondary data were modeled to be specific to the technologies or technology mixes under study, except for primary data on auxiliary batteries and the proxies documented for the secondary data.

5.4. Model Completeness and Consistency

5.4.1. 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 with regard to the goal and scope of this study. Completeness of foreground unit process data is considered to be high, except for auxiliary batteries. Capital's goods have been excluded in this study since the impact is expected to be negligible.

5.4.2. 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 2019 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.5. Conclusions, Limitations, and Recommendations

5.5.1. Conclusions

This study represents a comprehensive industry-average LCA of lead-based batteries produced in Europe for vehicle applications. The conclusions drawn here can be extrapolated across the entire industry. The study covers three automotive lead-based battery technologies (Standard, Improved and Advanced), with the contributing industry data representing more than 87% of the production volume for those technologies in Europe.

The study comprehensively evaluates the impacts and benefits associated with automotive lead-based batteries from a cradle-to-grave perspective. These overall conclusions take into account a holistic environmental profile of automotive lead-based batteries, extending beyond their production-related impacts by considering their use, take-back, and recycling.

It is clear, that lead production is the dominant contributor to environmental impacts associated with the production of lead-based batteries. In Europe the lead used in the batteries is sourced mainly from the recycling of spent batteries, lead scrap (lead sheets, pipes, etc.) and the primary route with an average of 25%.

In terms of global warming potential (GWP), the advantage of advanced technology lead-based batteries during the use phase outweighs the additional impacts of its production. This battery features progressively higher cycling performance and charge recoverability and is installed in start-stop and micro-hybrid vehicles to contribute directly to fuel consumption reductions of between 2% to 10% (compared with standard technology batteries used only for starting, lighting and ignition (SLI) in a conventional vehicle). Over the lifetime of the vehicle, this GWP advantage of the whole system is significantly larger than the production impact of the batteries used.

Therefore, Improved and advanced technology lead-based batteries help reduce global warming. This begins to demonstrate their importance as a mass-market technology already being used by car manufacturers to help achieve targets for reduced CO_2 emissions from transport.

The recyclability of lead back to the same technical properties, alongside the closed-loop system in place for take-back and recycling of lead-based batteries within Europe, ensures the return of the lead used in batteries at their end-of-life. The losses of lead along the process routes are minimal and the take-back rates are close to 100% within Europe.

To conclude:

- When considering the full life cycle, the battery manufacturing process itself only plays a small role for the environmental impacts of the batteries under analysis.
- The fuel consumption reductions provided by Improved and advanced technology lead-based batteries in start-stop and micro-hybrid vehicles outweigh the life-cycle global warming potential of their production.
- Overall, the differences between the two EoL allocation approaches are relatively small for the lead batteries studied.
- The reduction in fuel consumption is a result of the application engine technology, of which the battery forms an integral part. As such, the modelled fuel savings represent a best-case assumption for the battery as the benefit is not exclusively due to the merit of the batteries, but the batteries do enable this engine technology use.

5.5.2. Limitations

The results of this study are only applicable to lead-acid batteries produced in Europe. It may not be appropriate to extrapolate these results to other regions, especially if there are significant differences in lead battery recycling rates, production technologies, etc.

Additionally, System B results only look at GWP, but future assessments may want to consider other impact categories.

5.5.3. Recommendations

As with every industry association LCA, increased participation of member companies would improve the representativeness of the results.

Additionally, as technologies, both in batteries and vehicles, continue to evolve, EUROBAT should continue to evaluate LCA impacts.

After lead production, electricity consumption was often the second largest contributor to impacts. A key opportunity for participating companies to further reduce the environmental impact of these products would be by increasing the share of renewable energy used in their production grid mix.

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Annex A Critical Review Statement

Critical Review Statement

LIFE CYCLE ASSESSMENT OF AUTOMOTIVE LEAD BATTERIES - EUROPE

Commissioned by:	International Lead Association, United Kingdom Association of European Automotive and Industrial Battery Manufacturers, Belgium
Prepared by:	Sphera Solutions Inc., Germany
Review panel:	Prof. Dr. Matthias Finkbeiner, Germany
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 reviewer 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 concurrently to the study according to paragraph 6.2 of ISO 14044, because the study is not 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 V6.0 dated 12.05.2022.

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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 International Lead Association (ILA), Association of European Automotive and Industrial Battery Manufacturers, Belgium (EUROBAT), Sphera Solutions (Sphera) and the reviewer. As a first step in the review process, a kick-off call was held on 11.07.2019. In this call, the details of the review process were agreed, and an outline of the goal and scope of the study was presented by Sphera.

The first draft of the goal and scope report was submitted to the reviewer the day after. The reviewer provided 25 comments of general, technical and editorial nature to the commissioner by 16.07.2019. A revised goal and scope text was provided as part of the draft final report.

As a next step, the commissioner provided the first draft of the final report on 19.02.2021. The reviewer provided 37 comments on the draft final report of general, technical and editorial nature and sent them to the commissioner by 25.02.2021. Sphera provided a revised report and documentation on the implementation of the review comments on 05.05.2022. All critical issues and many of the recommendations of the reviewer were addressed in a proper manner. Just four basically editorial issues needed further correction. The final version V6.0 of the report was dated and received on 12.05.2022.

The reviewer acknowledges the unrestricted access to all requested information as well as the open and constructive dialogue during the critical review process.

General evaluation

The study assessed the life cycle environmental profile of different lead-based battery technologies for the automotive sector, produced in Europe. The cradle-to-gate environmental impact of each battery type has been evaluated, based on the production mass weighted-average results from participating manufacturers.

Primary site data have been gathered from EUROBAT's members to ensure that the models used are technologically representative for each stage of the production process. The study covers three automotive lead-based battery technologies (Standard, Improved and Advanced), with the contributing industry data representing an impressive 87% of the production volume for those technologies in Europe.

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The study was 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.

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 is limited to the specific lead battery concepts defined for the use in the European automotive applications described.
- the use phase modelled a reduction in fuel consumption as a result of the application engine technology, of which the battery forms an integral part. As such, the modelled fuel savings represent a best-case assumption for the battery as the benefit is not exclusively due to the merit of the batteries, but the batteries do enable this engine technology performance.

As with every LCA, the outcomes of a specific 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.

16th May 2022

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Annex B Toxicity Results

Table B 1 presents toxicity results for standard, improved, and advanced batteries. Given the high uncertainty associated with toxicity results, the precision of the characterization factors is within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity and should be taken into account when looking at the total values.

Table B-5-2: Toxicity results for System A of standard, improved, and advanced batteries

Impact / Indicator	Standard	Improved	Advanced	Unit
Ecotoxicity	0.0491	0.0321	0.0532	CTUe
Human toxicity, cancer	2.23E-09	1.84E-09	2.68E-09	CTUh
Human toxicity, non-cancer	2.58E-11	2.19E-11	3.41E-11	CTUh

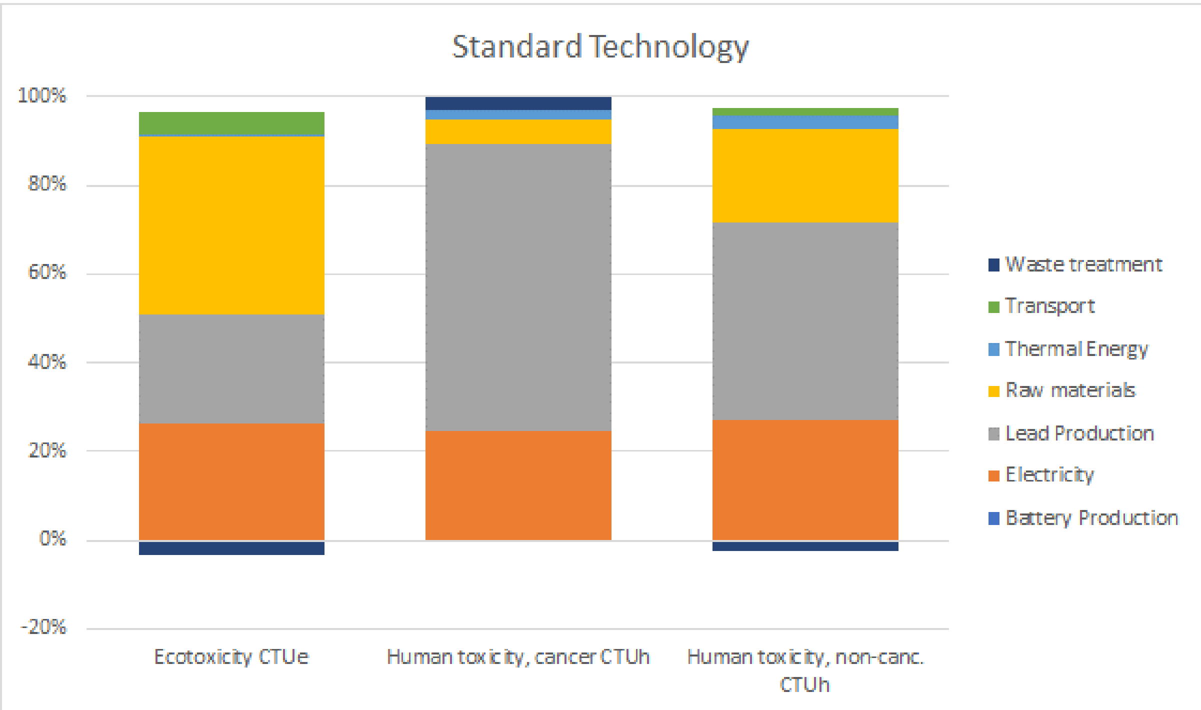

Figure B-1: Cradle-to-gate toxicity results for manufacturing of AGM battery technology

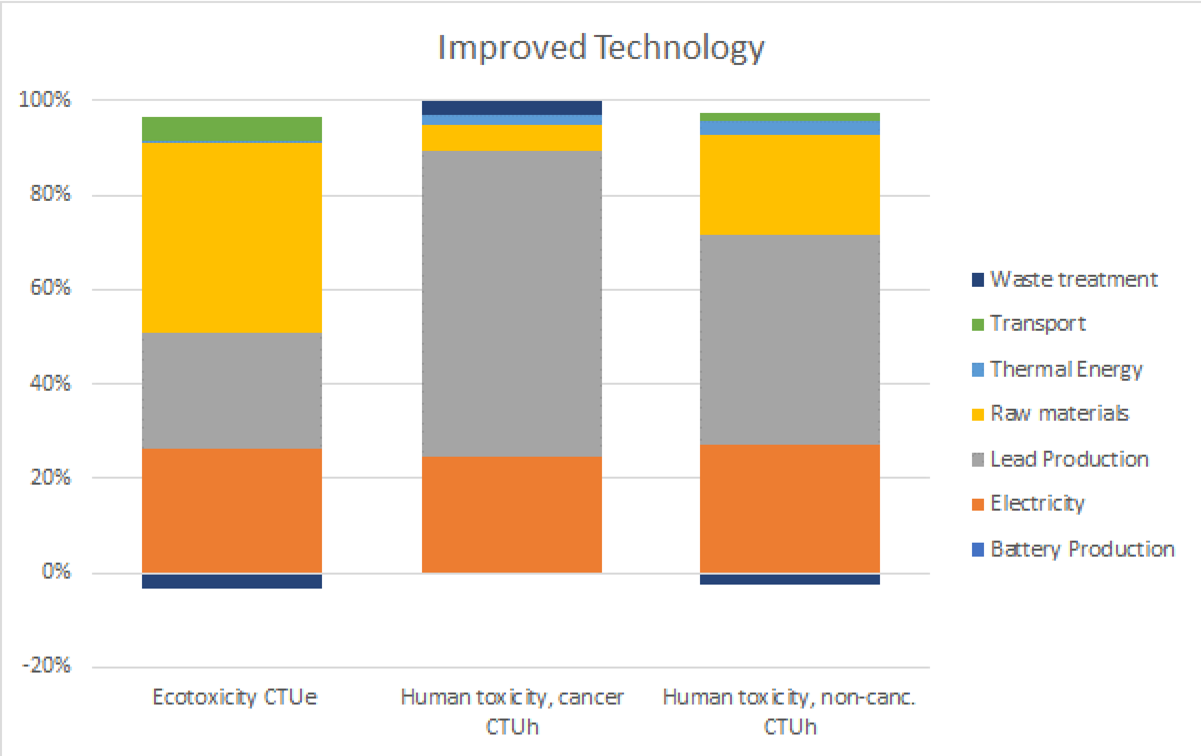

Figure B-2: Cradle-to-gate toxicity results for manufacturing of improved battery technology

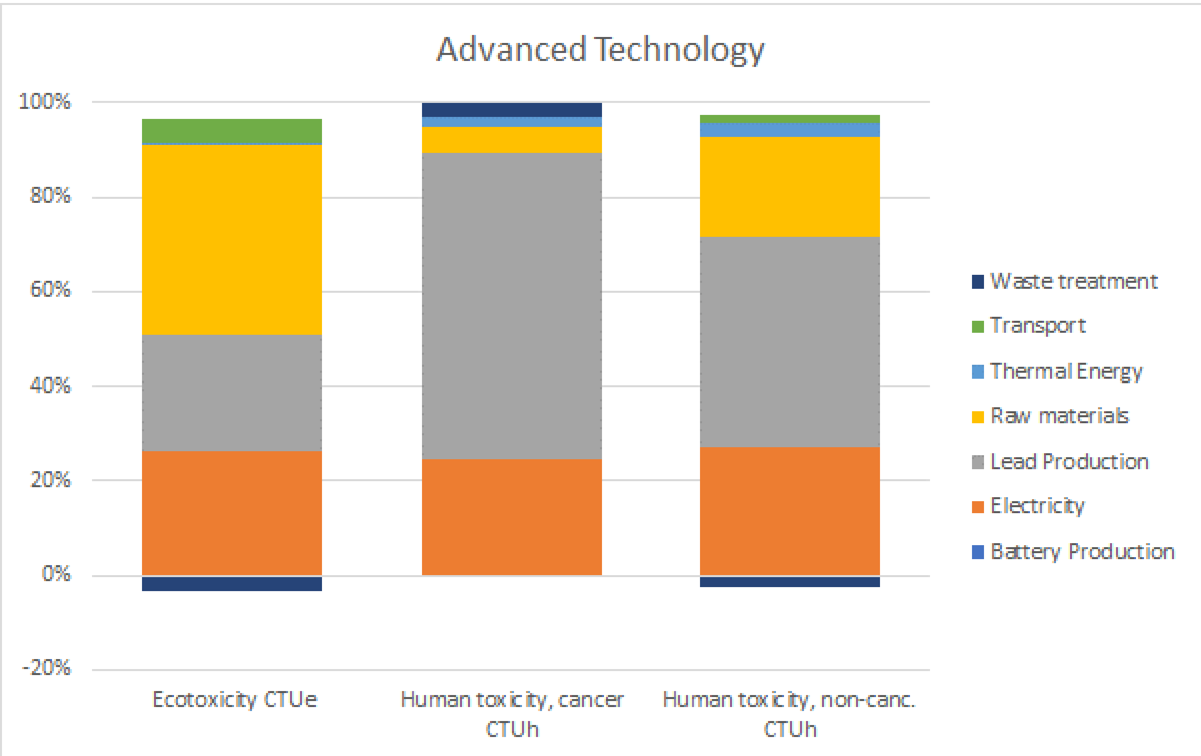

Figure B-3: Cradle-to-gate toxicity results for manufacturing of advanced battery technology

Figure B-1 to Figure B-3 presents results for the improved and advanced technology batteries. The trends for ecotoxicity and human toxicity (non-cancerous) are similar, with lead production and raw materials (plastics, sulfuric acid, and glass wool) contributing the majority of impacts. Lead production is the primary driver for human toxicity (cancerous). Formaldehyde, xylene, and phenol to air are the most significant emissions to human toxicity (non-cancerous). Polychlorinated dibenzo-p-furans (2,3,7,8 – TCDD) and formaldehyde emissions to air contribute to most of the human toxicity (cancerous) impacts. Finally, ecotoxicity impacts are driven by phenol, anthracene, and alachlor emissions to fresh water.

Annex C System A – Auxiliary Batteries

C.1 Product Function and Functional Unit

In the case of the auxiliary batteries, only system A has been analysed and these results have been documented in an annex, for internal use of the study commissioners. The functional units for the auxiliary batteries corresponding to system A, 1 battery and its respective average battery weight, can be found in Table C.1 1.

Table C.1 1: Auxiliary Batteries Technical characteristics – system A

Battery type	Average battery mass (kg)	Capacity (Ah)	Voltage (V)	Life span (years)	Application
Auxiliary L1 Flooded	12.3	50	12	5	BEV
Auxiliary AGM	4.9	12	12	6	Start-stop, hybrid
Auxiliary L1 AGM	14.5	50	12	6	BEV

C.2 Auxiliary L1 Flooded Batteries

Total results for the cradle-to-gate production of auxiliary L1 flooded batteries can be seen in Table C-5-3. As the auxiliary L1 flooded battery is approximated by the flooded battery production, the only difference is the weight of the batteries. See section 0 for details on the relative results broken down by category.

Table C-5-3: LCIA for System A of auxiliary L1 flooded batteries

Impact / Indicator	Value	Unit
GWP	14.4	kg CO2-eq
AP	0.09	kg SO2-eq
EP	5.20E-03	kg Phosphate eq.
POCP	4.90E-03	kg Ethene eq.
PED	266	MJ (LHV)
PED, non-renew	224	MJ (LHV)
PED, renew	41.9	MJ (LHV)
Ecotox.	2.41E-02	CTUe
Human tox., cancer	1.53E-09	CTUh
Human tox, non cancer	1.76E-11	CTUh
Water	703	kg

C.3 Auxiliary AGM and Auxiliary L1 AGM Batteries

Total results for the cradle-to-gate production of auxiliary AGM and auxiliary L1 AGM batteries can be seen in Table C-5-4. As auxiliary L1 AGM batteries are approximated with auxiliary AGM batteries, the difference in results is due only to the difference in weight of the batteries.

Table C-5-4: LCIA for System A of auxiliary AGM batteries

Impact / Indicator	Auxiliary AGM	Auxiliary L1 AGM	Unit
GWP	5.81	21.6	kg CO2-eq
AP	0.04	0.12	kg SO2-eq
EP	2.37E-03	7.01E-03	kg Phosphate eq.
POCP	2.14E-03	6.33E-03	kg Ethene eq.
PED	114	337	MJ (LHV)
PED, non-renew	97.4	288	MJ (LHV)
PED, renew	16.4	48.4	MJ (LHV)
Ecotox.	1.22E-02	3.61E-02	CTUe
Human tox., cancer	6.57E-10	1.95E-09	CTUh
Human tox, non cancer	8.36E-12	2.47E-11	CTUh
Water	348	1.03E+03	kg