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Full life cycle assessment of an industrial lead–acid battery based on primary data†

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Although lead–acid batteries (LABs) often act as a reference system to environmentally assess existing and emerging storage technologies, no study on the environmental impact of LABs based on primary data from Europe or North America since 2010 could be found. All available studies assessing LABs in Europe rely on literature values from the same few outdated sources, further decreasing reliability. To close this research gap, this work provides a cradle-to-grave life cycle assessment (LCA) of an industrial LAB based on up-to-date primary data provided by the German manufacturer Hoppecke Batterien GmbH. The analysis of potential environmental impacts includes all three phases: production, use and end-of-life (EOL), and analyses potential environmental impacts. The impacts are compared to those of a state-of-the-art lithium iron phosphate (LFP) battery in two different use cases: data centre and home storage system (HSS), in order to highlight the influence of selected use cases on overall results. The results show that the combination of the production and EOL phases of the LAB have a lower environmental impact in the majority of categories than the same two phases of the LFP battery. Including the use phase, the results diverge strongly depending on the use case. From an LCA point of view, while the LAB is potentially the better environmental choice for a data centre (with few charge/discharge cycles), an LFP battery should be used in applications with many charge/discharge cycles, like in an HSS. This indicates that batteries always need to be investigated and compared on an application-specific basis.

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1 Introduction

1.1 Background

The environmental assessment of batteries has recently become increasingly important in the European Union, as the European commission envisages a "mandatory carbon footprint declaration for industrial and EV batteries" in its current "proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries".[1] Additionally, in the battery directive, the European Parliament will presumably oblige battery manufacturers to comply with "carbon footprint rules" or specifications on "minimum recycled content", among other requirements.[2,3]

This regulatory pressure will have a significant impact on future battery markets. Next to the mobile applications we know from everyday life, and their use in electric vehicles (EV), batteries are also widely used in the stationary sector, which is experiencing increasing demand due to the shift towards renewable energies.[4–7] In the global market of stationary batteries of about 3.4 billion US dollars, use in data centres accounts for the largest share, with approx. 37%, followed by the telecommunication sector (25%).[8] Furthermore, although batteries are already used as energy storage in the public energy grid, it is expected that with the transition towards renewable energies, an increasing number of battery storage systems will be installed in the energy grid in the future.[9,10] The market for batteries acting as uninterruptible power supply (UPS) is not only the largest in the stationary sector, but is expected to grow further. According to precedence research the UPS market is expected to grow significantly, from approximately 9 billion US dollars in 2023 to around 14 billion US dollars in 2034.[11]

Although the European chemicals agency (ECHA) has discussed a ban on the use of lead in batteries,[3,12] lead–acid batteries (LABs), as the most mature battery technology, still have certain technical advantages compared to other technologies, making them attractive in some use cases: a stable voltage, high safety, reliability, low price, the absence of scarce and critical metals and above all the high recycling rate.[13] The high collection and recycling rate of LABs, however, is

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necessary due to the high toxicity of lead; a final disposal of lead would dominate the environmental performance in a significantly negative way, making a high recycling rate of lead inevitable. Additionally, the LAB is one of the two battery types with the biggest market share, together with the lithium-ion battery.[14] LAB, the oldest rechargeable battery technology, often acts as a reference system to environmentally assess existing and emerging technologies.[15] A major problem emerges when such comparisons are carried out using the same life cycle inventory (LCI) of a single LAB type (or any other cell chemistry) for several applications. This becomes even more critical when outdated and very aggregated data is used for modelling. With regard to the battery directive, it is therefore crucial that the environmental assessment of LABs available in the literature is based on up-to-date process data. Furthermore, it has to be assured that comparisons are based on real world application cases to allow purpose driven decision support, which might be very different when using generic used cases.

The aim of this work is to give decision-makers an up to date basis for the environmental assessment of the LAB storage technology produced in Europe. An additional goal is to investigate the ''design by purpose'' concept from an environmental impact perspective and to determine whether the selection of a battery with a lower impact depends on the specific use case or can be addressed more generally. To do so, a full LCA of an LAB is carried out as the focus of this work, with a lithium iron phosphate (LFP) battery as a comparison, for two selected use cases. The cooperation with a leading German battery manufacturer, Hoppecke Batterien GmbH, and the resulting availability of primary up-to-date process data has enabled us to provide new insights into the LAB. However, it needs to be highlighted that the processes of only one manufacturer were investigated.

1.2 Literature review of LCAs of lead–acid batteries

A literature review was conducted to get a detailed overview of all studies quantifying the environmental footprint of an LAB. Google scholar and science direct were used with the keywords ''life cycle assessment'', ''LCA'', ''carbon footprint'', ''environmental footprint'', ''environmental impact'', ''GWP'', ''CO_2'', combined with ''lead–acid battery'', ''PbA'', ''valve regulated lead–acid battery'' or ''VRLA''.

Table 1 shows all studies quantifying the environmental footprint of an LAB since 2010. The total of 44 studies were examined in the categories: origin of life cycle inventory (LCI) data, life cycle phases considered, use case in which the battery was examined, regional context and functional unit. Additionally, all studies working with primary data were marked with marked with footnote *a*.

The review shows that most studies are based on secondary LCI data, while only six of the 44 studies use primary data for the assessment. Five of those studies rely on data from regional Chinese manufacturers[13,16–19] and one study on data from a Bangladesh manufacturer.[20] Outside of the Asian continent, no work was found on the environmental footprint of LABs, based on the assessment of processes and corresponding primary data, since 2010. For the rest of the studies, the most often-used source for the LCI data is the study by Spanos *et al.*[21] This in turn is based on data sheets from an American manufacturer from 2010, which does not consider details of the production processes, but only the composition of the battery, posing certain limitations.

In terms of considered life cycle phases, only 21 out of 44 studies include all three phases of the life cycle (production, use and end-of-life (EOL)), although it is crucial to examine the full life cycle to be able to compare different batteries. For comparability, especially with regard to all storage technologies, the choice of functional unit is also crucial. Of the 20 papers including all lifecycle phases, only 9 use the functional unit kW h to MW h of energy delivered, which is the most suitable functional unit as it represents the core function of a battery, storing energy, and enables straightforward comparison with all kinds of energy storage systems.

The papers presented examine the LAB in very different applications. Most frequently, stationary storage is considered, whereby both the grid level (9) and the utility scale (7) are almost equally represented. LABs are also regularly investigated explicitly in combination with a PV system (9), in a hybrid micro grid (5) or in EVs (6). The investigation of applications in a data centre, a ship, a radio base station or as starting-lighting-ignition (SLI) battery are individual cases. The low number of studies on data centres, where the battery functions as a UPS, is surprising, as lead batteries are still used to a large extent as UPS.[22] Four papers did not consider any application, as they exclude the use phase. However, multiple authors use the same LCI for an LAB, and apply it to several applications, which has potential implications on the practical value of results. In essence, they use the material bill for a LAB designed for standby services related to *e.g.* data centres or power supply. As such, this type of batteries is not suitable and not applied in cycling intensive applications (*e.g.*, Bilich *et al.*[23]).

The final criterion according to which the studies were examined is the regional context. This varies widely between the studies examined and covers large parts of the world. However, it should be noted that Europe, China and the USA are the most frequently considered areas, although, as already mentioned, no study based on primary data in Europe and North America since 2010 has been found. It should be mentioned that the study Rahman *et al.*,[24] which conducted a review on LCAs of energy storage systems, represents an important source for this literature review. However, the focus of Rahman *et al.*[24] is not on LABs; it covers all energy storage systems and does not include the latest studies on LCA of LABs.

2 Methodology

This section provides a detailed overview of the assessment framework, including the system boundaries and the functional unit (FU), and the collection of primary data. Additionally, the characteristics of the analysed batteries, processes and use cases are described.

Table 1 Literature review of studies conducting an LCA of lead–acid-batteries (LABs) since 2010

Study	LCI data	Life cycle phases considered	Battery application use case	Regional context	Functional unit	Comment
Jiao and Mansson[25]	Wang *et al.*, Neiström	Production	Grid-scale energy storage	Sweden	1 kW h storage capacity	
Bhosale *et al.*[26]	Not disclosed	Production, use and EOL	Electric scooter	India	1 kW h storage capacity	
Das[27]	Based on Das *et al.*[28]	Production, use and EOL	Combined with a PV system	India	1 kW h energy generated	
Perčić *et al.*[29]	GREET 2020 database	Production and use	All-electric ships	Croatia	Lifetime of a ship	LCI data was collected before 2011
Yudhistira *et al.*[30]	Based on Spanos *et al.*[21]	Production, use and EOL	Grid-scale energy storage	Use in USA	1 kW h energy delivered	LAB functions as reference system
Gao *et al.*[13 a]	Primary data, China life cycle basic database	Production	None	Production in China	1 t battery	
Rahman *et al.*[31]	Based on Torell[32]	Production, use and EOL	Utility-scale energy storage, together with flywheel energy storage	Production in Canada	1 MW h energy delivered	
Rahman *et al.*[33]	Based on Spanos *et al.*[21]	Production, use and EOL	Utility-scale energy storage	Production in USA	1 MW h energy delivered	
Baumann *et al.*[34]	Based on Spanos *et al.*,[21] Kim *et al.*[35]	Production, use and EOL	Utility-scale energy storage	Use in Germany	1 kW h energy delivered	
Charles *et al.*[36]	Based on Baumann *et al.*[37]	Production	Solar home system	South Africa	1 kW h storage capacity	
Lewerenz[38]	Based on Spanos *et al.*[21]	Production and use	Energy storage system in neighbourhood power networks	Production in Europe	1 MW h electricity delivered	
Marcelino *et al.*[39]	Based on Baumann *et al.*[40]	Production and use	Hybrid microgrid system	Brazil	1 kW h storage capacity	
Rahman *et al.*[41]	Based on García-Valverde *et al.*[42]	Production	Combined with a PV system	Bangladesh	1 kW h storage capacity	No full LCA, only energy required for production converted into CO_2 eq.
Schmidt *et al.*[43]	Based on Bielitz[44]	Production and use	Grid-scale energy storage	Production in the EU, use in Switzerland, Germany and Poland	1 kW h storage capacity	
Stougie *et al.*[45]	Based on Liu *et al.*[18]	Production, use and EOL	Grid-scale energy storage	Production in China, use in the Netherlands	10 kW h energy stored	Absorbent glass matt LAB
Terlouw *et al.*[46]	Swiss times energy system model (STEM), Ecoinvent	Production and use	Hybrid micro-grid system	Use in Switzerland, production not disclosed	1 pack with a capacity of 165 kW h	
Terlouw *et al.*[47]	Based on Schmidt *et al.*[43]	Production and use	Utility-scale energy storage	None	1 kW h energy delivered	
Hasan and Mustafi[20 a]	Primary data (local battery manufacturer)	Production, use and EOL	Electric vehicle (3 wheelers)	Bangladesh	1 kW h storage capacity	
Ma *et al.*[16 a]	Primary data	Production	Starting-lighting-ignition	China	1 kV A h storage capacity	
Mostert *et al.*[48]	Based on undisclosed literature, data sheets, Ecoinvent 3.1	Production and use	Grid-scale energy storage	None	14 600 MW h efficiency of EEST[a]	
Muha and Peroša[49]	Based on Ishihara *et al.*[50]	Production, use and EOL	Electric vehicle	Slovenia	1 electric vehicle	
Baumann *et al.*[40]	Based on Spanos *et al.*[21]	Production and use	Hybrid micro-grid system	Use in Germany	1 kW h energy consumed within the HMGS along the year	
Baumann *et al.*[37]	Based on Spanos *et al.*[21]	Production and use	Grid-scale energy storage	Use in the EU	1 kg battery, 1 kW h storage capacity	

Table 1 (*continued*)

Study	LCI data	Life cycle phases considered	Battery application use case	Regional context	Functional unit	Comment
Bilich *et al.*[23]	Based on Spanos *et al.*[21]	Production, use and EOL	PV application	Kenya	1 kW h energy delivered	
Chen *et al.*[19a]	Primary data	Production and EOL	None	China	1 kV A h storage capacity	Only lead considered, other materials of LAB excluded
Richa *et al.*[51]	Based on Sullivan and Gaines,[52] Rantik,[53] Rydh[54]	Production, use and EOL	Grid-scale energy storage	USA	1 kW h energy delivered	LAB as reference system
Wang *et al.*[17a]	Primary data	Production	None	China	1000 kW h discharge power	
Das *et al.*[55]	Based on Newnham and Baldsing[56]	Production and EOL	PV application	India	1 kg battery	Energy requirement calculated
Davidson *et al.*[57]	European life cycle database (ELCD)	Production, use and EOL	Electric vehicle	None	1 battery with the capacity 70 A h	
Saenz *et al.*[58]	Based on Sullivan and Gaines[59]	Production, use and EOL	Electric tricycles	USA	1 kg battery	
Unterreiner *et al.*[60]	Based on Sullivan and Gaines,[59] Jülch *et al.*[61]	Production, use and EOL	PV system	None	1 kW h storage capacity	
Hiremath *et al.*[62]	Based on Spanos *et al.*[21]	Production and use	Stationary applications	Use in Germany	1 MW h electricity delivered	Cumulative energy demand calculated
Jülch *et al.*[61]	Based on Ashby and Polybank,[63] Sullivan and Gaines[52]	Production	PV system	Germany	1 kW h electricity delivered	
Lansburg and Siret[64]	GaBi 4 software system	Production, use and EOL	Data centre	None	Provision of 80 A h batteries	
Liz *et al.*[18]	Primary data	Production, use and EOL	e-bikes	China	1 kW h captivity	
Oliveira *et al.*[65]	Based on van den Bossche *et al.*[66]	Production, use and EOL	Large scale energy storage	Belgium	1 kW h energy delivered	
Kabakian *et al.*[67]	Based on McManus[68]	Production and use	PV application	Lebanon	1 kW h energy delivered	
Spanos *et al.*[21]	Based on datasheet of exide absolytes GX V-0 by Jantech Services, Inc. from 2010	Production, use and EOL	Stationary application	USA	1 kW h energy delivered	Lead–calcium–tin alloys for positive electrode grids and lead–calcium for negative grids
McKenna *et al.*[69]	Based on a datasheet of a BP solar 'PVstor' valve regulated lead–acid battery from 2001	Production and use	Utility-scale energy storage	UK	1 kg of battery	
McManus[68]	Based on Rantik[53]	Production	Small scale micro-generation system	None	1 kg of battery	
Sullivan and Gaines[52]	Based on a datasheet of MSDS, East Penn Manufacturing, Inc. From 2010	Production	None	None	1 kg of battery	
Bianco *et al.*[70]	Not disclosed	Production, use and EOL	Radio base station	Italy	1 kW h energy delivered	
Bonnin *et al.*[71]	Based on Rantik[53]	Production, use and EOL	Electric vehicle	None	Car lifetime of 200 000 km	
Mousazadeh *et al.*[72]	Based on Köhler *et al.*[73]	Production, use and EOL	Hybrid electric tractor	None	1 kg of battery	

[a] indicates the use of primary data, comments are only made where necessary.

2.1 Assessment framework

In this study, a cradle to grave life cycle assessment (LCA) of an industrial LAB is carried out according to the international standards ISO 14040: 2006 and ISO 14044: 2006 + Amd 1: 2017. Considering the whole life cycle, a product is followed from its ''cradle'' where raw materials are extracted from natural resources, through production, use, EOL treatment, and recycling to its ''grave'', the final disposal.[74]

The goal of this work is to provide a full LCA of an LAB based on primary data from current industrial production and EOL processes. As can be seen from the literature review, despite the high diversity of assessment levels, there are only a very limited number of studies based on primary data – and there are no studies available for the European and North American regions since 2010. The provision of up-to-date primary data in the area can be especially important for the evaluation of other, newer storage technologies, as the LAB often serves as a reference battery, especially for the production and EOL phases.

The environmental impacts are calculated per one kW h of energy delivered by the battery over its lifetime (the FU). This represents the basic function of any battery and enables straightforward comparison with the results of not only other batteries, but also other energy storage systems. It considers the type and frequency of use, efficiency losses and the corresponding impacts on battery degradation over its lifetime.[21] Fig. 1 shows the system boundaries of the conducted LCA, including the EOL phase, the production phase and the use phase. The EOL phase consists of the recycling processes and the final disposal of waste. This phase is illustrated here at the beginning of the life cycle to emphasise its importance, as the recycling process of LABs is well-developed and widely spread in Europe. It is intended to show that every production process of an LAB has a recycling process upstream, from which the recovered lead is almost fully reused and covers the major part of the lead required for the production. The production phase then addresses the energy and material required to extract and process the resources. The subsequent use phase includes the impacts related to charge–discharge losses, the stand-by consumption and replacement considering the aging of the battery. Within the scope of this work, it was not possible to carry out onsite measurements of direct emissions from the production and recycling processes. However, the majority of the emissions are already taken into account through the use of the Ecoinvent processes, such as the onsite combustion of gas and oil as energy sources. No further process-specific emissions are to be expected that would greatly change the picture, as the highest occupational health and safety guidelines apply at the production site, which make filter systems, exhaust air purification *etc.*, mandatory. Furthermore, no data on the external recycling of the electrolyte in a company in Germany were available. Also, in this case, noteworthy emissions are not to be expected for the reasons mentioned above. In order to take the efforts of the recycling process of the electrolyte into account, only 80% of the recycled electrolyte was credited as a lower-value neutralising agent in the second lifecycle. In addition, due to the use of the cut-off approach, the recycled lead used in the battery enters the system burden-free and bears only the impacts of the recycling process.

The underlying model of the study is based on the database Ecoinvent 3.8, with the well-known cut-off approach. According to the cut-off allocation approach, burdens originating from the material extraction are only allocated to the primary user. Therefore it allows the use of recycled materials burden-free so that secondary materials bear only the impacts of the recycling process.[75]

The EOL phase is modelled in a closed-loop. Materials recovered in the recycling process are assumed to be fully reused for production, which in the case of LABs reflects reality well. The collection and recycling processes for lead in Europe have progressed to the point where approximately 99% of the lead included in LABs is collected and reused.[57] The high recycling rate of 99% is consistent with the primary data the

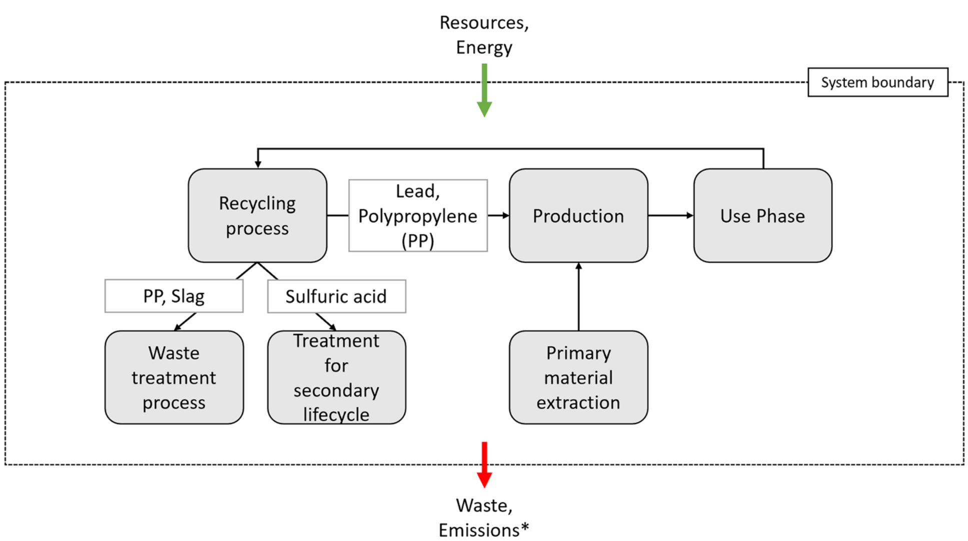

Fig. 1 System boundaries of the conducted LCA. *Excluding process-specific direct emissions.

authors obtained from the manufacturer Hoppecke GmbH. In this light it is interesting that the EU battery directive aims for a share of 85% recycled material used in industrial batteries in 2031. These advanced lead recycling processes are therefore taken account of by the combination of the closed-loop and the cut-off approaches.

For the quantification of the environmental impacts, the international life cycle data system (ILCD) methodology is used,[76] applying the midpoint indicators of global warming potential (GWP), mineral, fossil & renewable resource depletion (ADP), acidification potential (AP) and freshwater ecotoxicity (ETox). The consideration of GWP quantifying the CO_2 equivalents is inevitable due to the fact mentioned above, that the European commission will most likely oblige the manufacturers of batteries to make a ''mandatory carbon footprint declaration for industrial and EV batteries''.[1] In addition, resource depletion is a widely-discussed category when environmentally assessing batteries, as scarce metals are usually the central component of a battery. The two concluding categories of acidification and ecotoxicity are considered as lead toxicity is a highly important environmental issue. The results of all remaining ILCD midpoint indicators can be found in the ESI.†

2.2 Battery characteristics

The LAB examined in this study is a stationary sealed lead–acid battery of type OGi bloc grid|power V H 6-200 by the manufacturer Hoppecke Batterien GmbH (Fig. 2).

The battery consists of lead grids covered with lead paste forming the positive and negative electrodes in the shape of plates. These plates, separated by pocket separators around the positive electrode, are assembled into three individual cells that are connected in series. In combination with the liquid electrolyte, which is diluted sulfuric acid, and a polypropylene (PP) housing, the battery is formed. The battery has PP valves at the upper end, which enable occasional gas exchange with the environment as overpressure regulation in case of overcharging. Consequently, although the battery is sealed, it may require refilling with water.

The OGi Bloc 200 consists of three single cells with a voltage of 2 V each. It has an energy efficiency of 0.77 and a resulting charge factor of 1.3. In terms of aging, the manufacturer states that the battery must be replaced after it has lost 20% of its total capacity. Calendrically, a replacement is necessary after an average of 12 years.[78] Further technical details can be found in the ESI.†

As a reference for the assessment of the LAB, a conventional lithium-ion battery is used. The two battery technologies are investigated with the same assumptions in relation to the different use cases and their environmental impacts are compared. The lithium cell chemistry used here is a lithium iron phosphate (LFP) battery. The LFP battery is chosen as a reference because of its high thermal stability and long cycle and calendar life, categories in which the LFP battery has even more favourable properties than the nickel–manganese–cobalt (NMC) battery widely-used in consumer appliances.[79] Thus, this battery convinces with different properties than the LAB and makes a comparison particularly interesting, as both batteries are used in similar application areas. The LFP battery used for the LCA in this study originates from Peters *et al.*[80] Here, an energy density of 197.4 W h per kilogram at cell level, and an energy efficiency of 0.93 is assumed. Further details can be found in Peters *et al.*[80]

2.3 Process characteristics

In the course of this work, the entire industrial processes that are part of the life cycle of the LAB under investigation were analysed. Starting with recycling, this includes the shredding and separation of used batteries. The recovered materials are reused on site in the case of lead, and by external service providers in the cases of electrolyte, plastic and remaining metal. The lead, both from the grids and from the lead paste, can be recovered at a rate of almost 99% and subsequently also has the necessary material properties to be used again in an LAB. The sulfuric acid used is further processed into neutralising agents, and most of the polypropylene is recycled back into the cycle.

Production begins by processing the lead in two different ways: first, it is melted and cast into the required grid shape. Secondly, a lead dust is created, which is the main component of the active mass. In the next steps, the electrode plates are

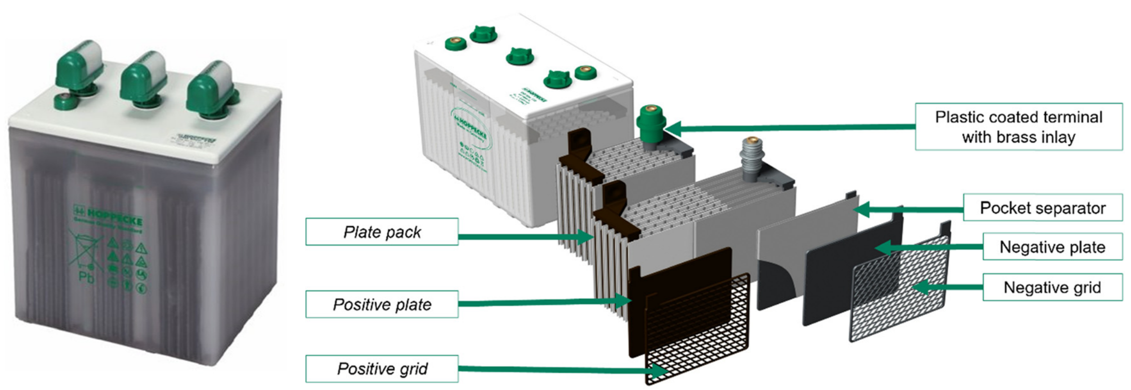

Fig. 2 The examined LAB OGi Bloc 200. The pocket separator encases the positive plate. Source: Hoppecke Batterien GmbH.[77]

formed by combining the grids with the active mass, forming these into cells and assembling them inside a PP housing. After the battery is filled with electrolyte, closed and tested, it is charged and shipped. A detailed description of the individual process steps, as well as detailed diagrams, can be found in the ESI.†

The energy mix usually plays a central role in an LCA. In this case, a mix was assumed that was provided by the manufacturer, and roughly consists of 40% electric power, 50% natural gas and 10% mineral oil. The details of the energy consumption as well as the material composition of the OGi Bloc 200 can be found in the ESI.†

The process steps could not be reproduced in the model due to the lack of information on the mass and energy flows in the various steps. For this reason, the battery is modelled and assessed on the basis of the composition. The recycling of the three main components of the battery – the PP housing, the electrolyte and the lead – can be summarised as follows: in the recycling process of PP, about 55% of the mass is successfully recycled and can be reused in all applications, while 45% of the quantity is thermally utilised. Sulfuric acid is made usable again as a neutralising agent in a second life cycle, as reuse as an electrolyte in a battery is not possible due to process specifications. From an environmental point of view, however, lead recovery is particularly important. In this case, 99% of the lead used can be reused in the next battery, whereby only 1% is not recoverable and is treated finally.

2.4 Use case characteristics

It is important that battery technologies are studied and compared in a specific use case, as the use phases are usually decisive about the magnitude of the results. In order to take this into account, two use cases are examined in this work: firstly, the UPS use case data centre, and secondly the cyclical use case home storage system (HSS). The investigation of two such different use cases should provide information on whether the environmentally best choice of a battery cell type depends on the application. This is also known as ''design by purpose'', and the analysed LAB has been specifically developed for UPS. It should be noted that no balance of system components were included in the study for in either use case. Table 2 provides an overview on the key assumptions of the two use cases:

LABs are widely used in data centres to provide an uninterruptible power supply. In the event of a power failure, the batteries are used to bridge the time until a diesel generator or other emergency generator provides power. The following are brief explanations of the assumptions in the data centre use case, exceeding the information provided by the manufacturer: the number of two assumed cycles per year in this use case originates from a required test once a year and an actual interruption of power, which in Germany is an average time of around 8 minutes per year according to Statista.[81] The 8 minutes of downtime mentioned would thus be completely covered by the assumed 10 minutes of maximum system runtime. However, it is important to note that the mentioned 10 minutes reflect the maximum start-up time of an emergency power generator in a data centre.[82] The number of batteries connected in series results from the required supply voltage of 324 V and the individual voltage of 6 V per battery. The use phase of the LAB is modelled and calculated according to the following standards of the international electrotechnical commission (IEC): IEC 60896-11, -21, -22; IEC 61427; IEC 62485-2[83] and the ZVEI.[78] The LFP reference battery has been modelled to match the LAB. However, a simplified approach is taken here as the focus of the study is on the LAB. The resulting size of 81.56 kW h for the LAB based system when 54 cells are connected in series was also chosen for the LFP battery system. It is further assumed that the same self-discharge rate of 0.1% per day and no replacement is required for the use case specifications.

The second, rather hypothetical, use case considered in this work is an HSS as an electrochemical energy storage located in a conventional household storing the energy obtained by a PV system. This case intentionally represents a very different application of the battery compared to the application in the data centre, as it runs through 3650 cycles over the total lifetime. The additional investigation in an application with many cycles should represent a contrast to the first use case, increase the interpretation possibilities of the results. This demonstrates how inappropriate application field comparisons can lead to misleading conclusions. The HSS examined here is taken from Jasper *et al.*,[84] where a system consisting of LFP batteries with a total capacity of 14.4 kW h was disassembled. The authors assumed a system lifetime of 20 years and that the HSS runs on average half a cycle per day, in other words one cycle every two days, at a discharge depth of 0.9. It should be

Table 2 Key assumptions of the use cases investigated

Characteristic	Data centre	HSS
Service life	10 years	20 years
Number of cycles per year	2	182.5
Number of LABs in series	54	9
Power supply voltage (LAB)	324 V (DC)	54 V (DC)
Self-discharge per day at 20 °C	0.1% of the nominal capacity	0.1% of the nominal capacity
Maximum supply duration	10 minutes	—
Discharge current for 10 minutes for 1.65 V	445.5 A	—
Average charge retention voltage	2.23 V	—
Average charge retention current	50 mA/100 A h	—
Total capacity	—	14.1 kW h
Depth of discharge (DOD)	—	0.9

noted that the LAB OGi Bloc 200 investigated here was not designed for such an application. However, for comparison purposes, it is theoretically installed in the investigated HSS in such a way that a similar capacity is achieved (14.1 kW h). The approach taken to the HSS use case is to use the same system design with an identical storage capacity for both cell types, as well as the same usage profile. Therefore, the LFP battery system is also assumed to have the size of 14.1 kW h and an identical self-discharge rate of 0.1% per day.

For both use cases three use phase impacts are investigated: the environmental impact in the context of the battery's self-consumption, charging and discharging losses and finally, ageing and the resulting replacement. Formula (1) and (2) show the calculation of the electricity losses due self-discharge and charge–discharge, respectively. Consequently formula (3) displays the calculation of the impact in the considered categories. The impacts due to ageing and replacement are calculated based on the calendric and cyclical lifetime, depending on which type of ageing reaches its limits first.

$$\text{Self-discharge}_{\text{lifetime}}\ [\text{kW h}] = \text{capacity}\ [\text{kW h}] \times \text{self-discharge}_{\text{per day}}\ [\%] \times \text{operating days}_{\text{lifetime}} \quad (1)$$

$$\text{Charge}-\text{discharge losses}_{\text{lifetime}}\ [\text{kW h}] = \left(\frac{\text{electric work}_{\text{cycle}}}{\text{efficiency}} - \text{electric work}_{\text{cycle}}\right) \times \text{cycles}_{\text{lifetime}} \quad (2)$$

$$\text{Impact}_{\text{category per kW h}} = \frac{\text{Losses in category}_{\text{lifetime}}\ [\text{kW h}] \times \text{impact factor}_{\text{per kW h}}}{\text{Energy delivered}_{\text{lifetime}}\ [\text{kW h}]} \quad (3)$$

2.5 Data acquisition

This work is based on primary data. The LAB manufacturer Hoppecke GmbH provided data on its current processes and material compositions for the LAB investigated. The mass flows of the model are primarily determined using the bill of material of the battery. However, the incomprehensibility as well as the inconsistency of the data posed the main challenges for the authors. These were resolved through close communication with the manufacturer, as experts from the company in the affected areas were consulted on more complex issues, with the exchange partners either providing the necessary information, if available, or carrying out measurements for individual process steps to obtain the missing data. In addition, the availability of data was an issue, as some disposal operations are carried out by external service providers, making it difficult to obtain process details. Here, the advantage should be highlighted that lead recycling takes place on the production site and therefore detailed information on energy consumption and the like is available. Furthermore, some data is not available in the level of detail that might be desirable. A key example is energy consumption, where only information on the total consumption of the company within a year is available, when it would have been desirable to obtain the energy consumption per process step. This data would have made it possible to model the battery at the process level rather than on a compositional level, and subsequently identify optimisation and savings potential.

Table 3 Calculation of the water and energy demand for the production and EOL phases for LAB

Category	Demand per kW h produced capacity	Demand OGi Bloc 200-6 V (1.566 kW h)
Water (m^3)	0.18	0.28
Electricity (kW h)	23.91	37.45
Natural gas (kW h)	30.38	47.57
Heating oil (kW h)	6.46	10.12

As energy and water consumption data were only available on company level, the demands of the investigated battery are calculated according to the top-down approach:

$$\frac{\text{Total demand}_{\text{year}}}{\text{Battery output}_{\text{year}}\ [\text{kW h}]} = \text{Demand}_{\text{per kW h produced capacity}} \quad (4)$$

$$\text{Demand}_{\text{per kW h produced capacity}} \times \text{capacity}_{\text{OGi Bloc}} = \text{demand}_{\text{OGi Bloc}} \quad (5)$$

In this approach, an average of all the year-related data (electricity, natural gas, oil and water consumption) is divided by the storage capacity produced in batteries during the year, so that the figures for the production and EOL phases of one kW h of storage capacity is obtained (see formula (4)). This figure is then multiplied by the nominal capacity of the battery studied (1.566 kW h) to reach the demand of the OGi Bloc 200 (see formula (5)).

It is clear that the figures calculated in this way are only an approximation, as different batteries require different amounts of energy to produce. Furthermore, it is not possible to distinguish between the energy used in production and that used in recycling. However, this approximation remains more accurate than the data used in the reviewed literature. The process is carried out in the same way with the water demand in production and recycling and results are shown in Table 3. The energy demand for the battery cell manufacturing of the LFP battery is provided in the ESI.† Detailed information on the all assumptions regarding the LFP cell manufacturing can be found in the work by Peters *et al.*[80] and the corresponding ESI.†

3 Results

3.1 Production and EOL phases

In Fig. 3 the results are displayed of the life cycle phases of production and EOL of an OGi Bloc 200 on GWP, ADP, ETox and AP per kW h storage capacity. As already noted, the two phases cannot be separated as the energy data is only available for both combined phases.

It can be seen that in terms of GWP the majority of the impacts that occur during the production and EOL phases of

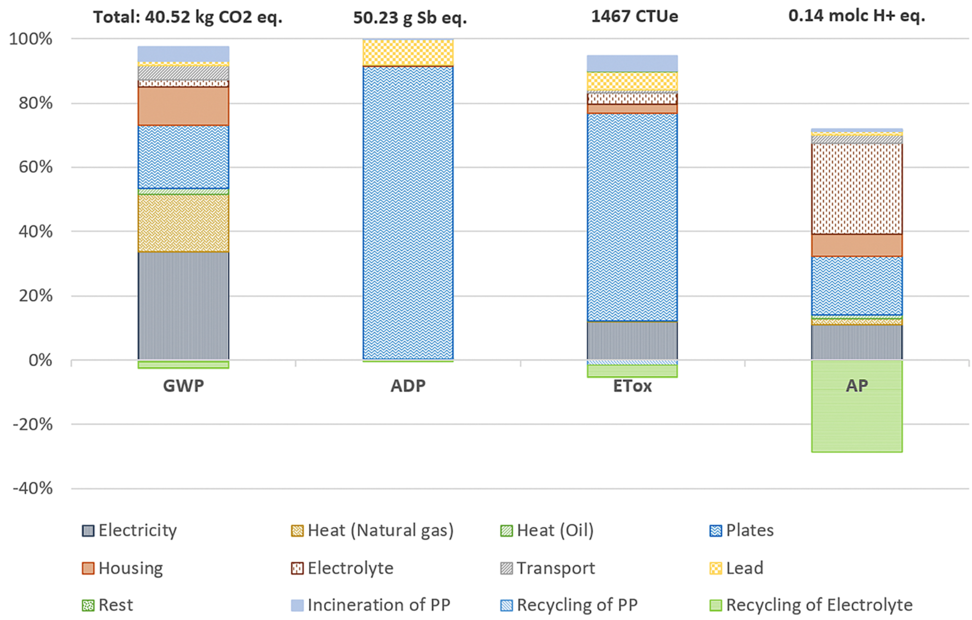

Fig. 3 Impact of the production and EOL phases of LAB on global warming potential (GWP), mineral, fossil & renewable resource depletion (ADP), freshwater ecotoxicity (ETox) and acidification potential (AP). Total values are given per kW h of storage capacity (OGi Bloc 200: 1.556 kW h).

the battery are due to the energy demand (55%), while the plates, representing the anode and cathode of the battery, only make up approximately 22%. It is noted in this context that no energy demand is included on the component level as it is already covered by the total demand, excluding the housing, which is produced from primary PP by a supplier. The low impacts accounted to the lead can additionally be explained by the fact that it enters the process 99% burden-free and only the remaining 1% and the additives are factored in. The only two items that reduce the impact in terms of GWP are the recycling of the PP (−0.29 kg CO_2 eq.) and the electrolyte (−1.43 kg CO_2 eq.). In both cases, the "avoided product" methodology is used. This methodology calculates how much greenhouse gas would be emitted in the production of the material that can be replaced by the recovered material. The savings from lead recycling cannot be listed separately, as these are obtained at the production site and no detailed data is available on the energy consumption per process.

With regard to the two categories ADP and ETox, a different picture can be drawn. Here, the plates are considered the main contributors to the environmental impacts (92% and 72%, respectively). This is mainly due to the use of antimony and barium. In the AP category, the environmental impacts are fairly evenly distributed among the components, with the plates accounting for 43%. It should also be noted that recycling of the electrolyte brings high benefits in terms of acidification, reducing the impact by about 40%. The numerical results can be found in the ESI.†

It must be mentioned how the impacts of the reference LFP battery are composed. The impact factors per kW h battery capacity for the LFP production (GWP: 49.59 kg CO_2 eq., ADP: 0.0308 kg Sb eq., ETox: 7955 CTUe, AP: 0.34 molc H+ eq.) from the latest publication by Peters *et al.*[80] are combined with the current state of recycling from Mohr *et al.*[85] and related environmental burdens or credits (GWP: 0.45 kg CO_2 eq. ADP: −0.0033 kg Sb eq., ETox: −1590 CTUe, AP: −0.193 molc H+ eq.). The current state of recycling of LFP batteries is limited to the recovery of aluminium, copper and steel components obtained from mechanical recycling. The active material is usually discarded.[80] The combination of the two values result in the impact factors for production and EOL phases used in this study and shown in Table 4. The total results of the production and EOL phase of the LFP battery is a result of the impact factors per kW h battery capacity multiplied with the respective system size (data centre: 14.1 kW h; HSS: 81.56 kW h).

3.2 Use case data centre

For the investigation of the use phase, three categories are considered: the environmental impact in the context of the battery's self-consumption, charging and discharging losses and finally, ageing and the resulting need for replacement. The impacts are calculated according to the formulas (1)–(3), presented in 2.4. Fig. 4 shows the resulting impacts of the use phase per kW h of energy delivered.

The environmental impact of the use phase per kW h of energy delivered is greater for the LAB (*e.g.*: 462 g CO_2 eq. per kW h) than for the LFP battery (*e.g.*: 338 g CO_2 eq. per kW h)

Table 4 Impact factors for the production and EOL phases of the LAB and LFP battery for presented impact categories per kW h battery capacity

	Global warming potential [kg CO_2 eq.]	Resource depletion [kg Sb eq.]	Ecotoxicity [CTUe]	Acidification [molc H+ eq.]
LAB	40.52	0.0502	1469	0.1405
LFP	50.04	0.0274	6364	0.1425

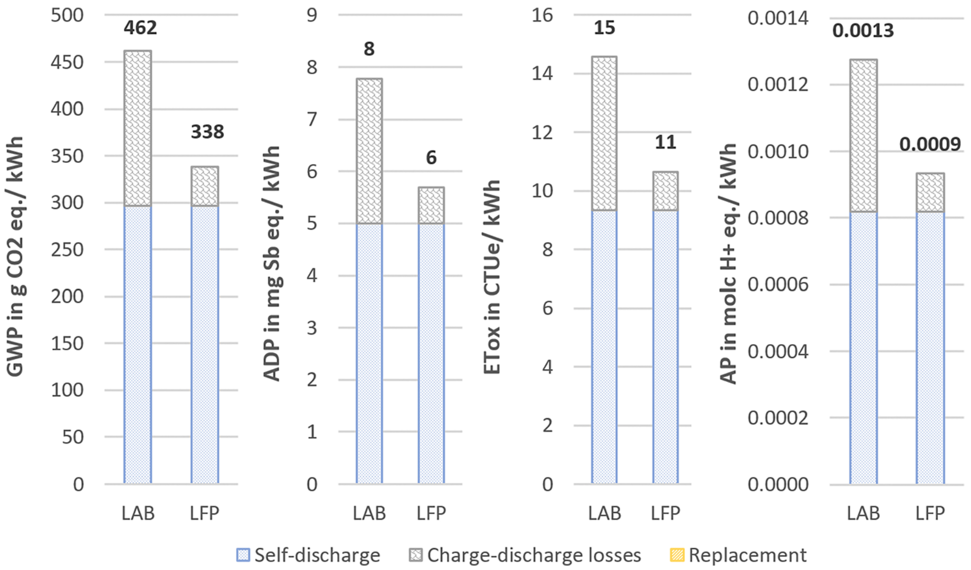

Fig. 4 Impacts of the use phase of the UPS use case on global warming potential (GWP), mineral, fossil & renewable resource depletion (ADP), freshwater ecotoxicity (ETox) and acidification potential (AP). Values are given per kW h of energy delivered over lifetime (FU).

for all four impact categories analysed. It should be noted that the results are given per kW h delivered, considering only two cycles per year with a continuous charge retention. The results in terms of the self-discharge losses are equally large for both battery types. This is due to the fact that a self-discharge rate of 0.1% of the total capacity per day is assumed for both. As a basis for calculating the environmental impacts, the electricity mix from Germany was used, which is available in the Ecoinvent 3.8 database. This results in a factor of 0.55 kg CO_2 eq. per kW h energy delivered for GWP, for example. Regarding the charging and discharging losses, also known as efficiency losses, the energy efficiency plays a central role. This, and the amount of energy to be supplied by the system, determine how much electrical energy is lost over the lifetime of the system. Since the LAB with 0.77 has a significantly lower energy efficiency than the LFP battery with 0.9, the results in this category for the LAB are significantly higher than for the LFP battery. In this use case, no replacement is needed and therefore no impact can be attributed to it. This is due to the fact that both the LAB and the LFP battery have at least a calendrical lifetime of 10 years and at least a cycle lifetime of 20 cycles (10 years of operation × 2 cycles per year) and therefore do not need to be replaced during the period of use.

Overall, it can be stated that the minimally lower environmental impact of the LFP battery in the use phase is due to lower efficiency losses and the higher energy efficiency.

Fig. 5 shows the environmental impact on GWP per kW h of energy delivered in all three phases: production, use and EOL. Replacement, which is normally assigned to the use phase, is shown separately, as the effects arising there are normally repeated production.

It can be clearly seen that the impact of the LAB is significantly lower than the impact of the LFP battery for the impact categories GWP and ETox. It is also evident that the production and EOL phases play the decisive role. In terms of ADP the impacts of the LAB are notably higher than of the LFP battery, attributable to the high ADP of the lead-electrodes. Both batteries show equally high impacts in the category of AP.

3.3 Use case home storage system (HSS)

The results for the use case HSS are also being calculated according to formulas (1)–(3) presented in 2.4, but are significantly less alike for the two battery types than in the use case data centre, as many more cycles are run through in the lifetime. Here, the use phase of the LAB with 357 g CO_2 eq. per kW h energy delivered has a significantly higher impact than that of the LFP battery with 47 g CO_2 eq. per kW h energy delivered (Fig. 6).

The self-discharge losses almost lose relevance in the use case HSS, when the results are given per kW h of energy delivered. This is mainly due to the significantly higher amount of energy delivered over the lifetime: 39 611 kW h for the LAB and 47 842 kW h for the LFP battery. These figures result on the one hand from the design-approach taken here, after which both battery systems have the same capacity of 14.1 kW h and the same total number of cycles of 3650 cycles over the lifetime, and on the other hand from the energy efficiencies of the systems. The efficiencies are 0.77 for the LAB and 0.9 for the LFP battery, which results in a higher amount of energy delivered for the LFP battery. The efficiency losses of the two systems in charging and discharging are just as high per kW h of energy delivered as in the use case data centre.

Replacement takes on a much more important role in the HSS use case. The LAB needs to be replaced 14 times over the considered lifetime due the fact that at a discharge depth of 90%, the LAB has a lifetime of only 257 cycles. With an average of 0.5 cycles per day (182.5 cycles per year), the battery would only last 1.41 years until it reached the minimum capacity of

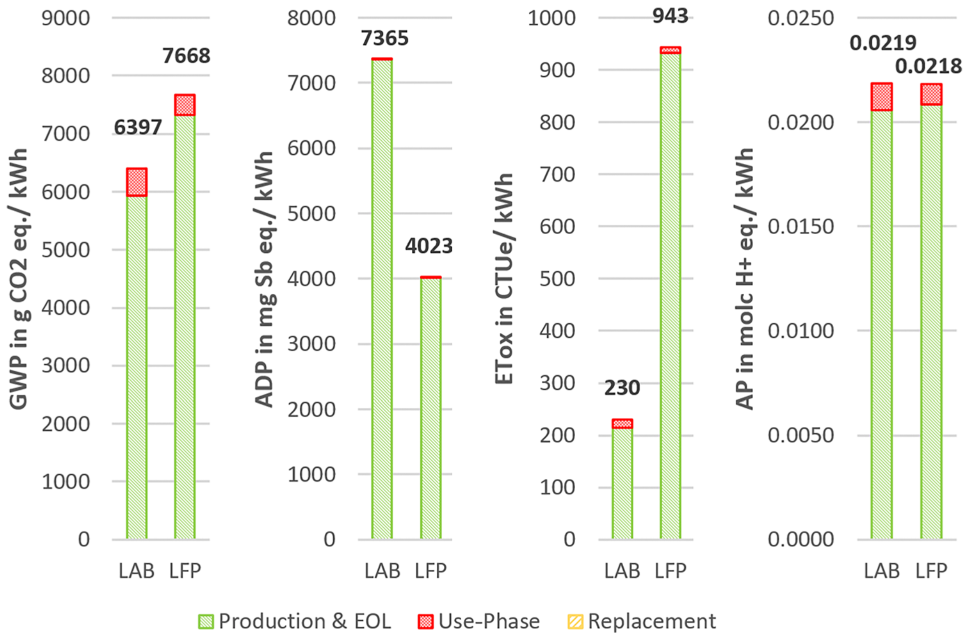

Fig. 5 Total impact of the full life cycle in the UPS use case on global warming potential (GWP), mineral, fossil & renewable resource depletion (ADP), freshwater ecotoxicity (ETox) and acidification potential (AP). Values are given per kW h of energy delivered over lifetime (FU).

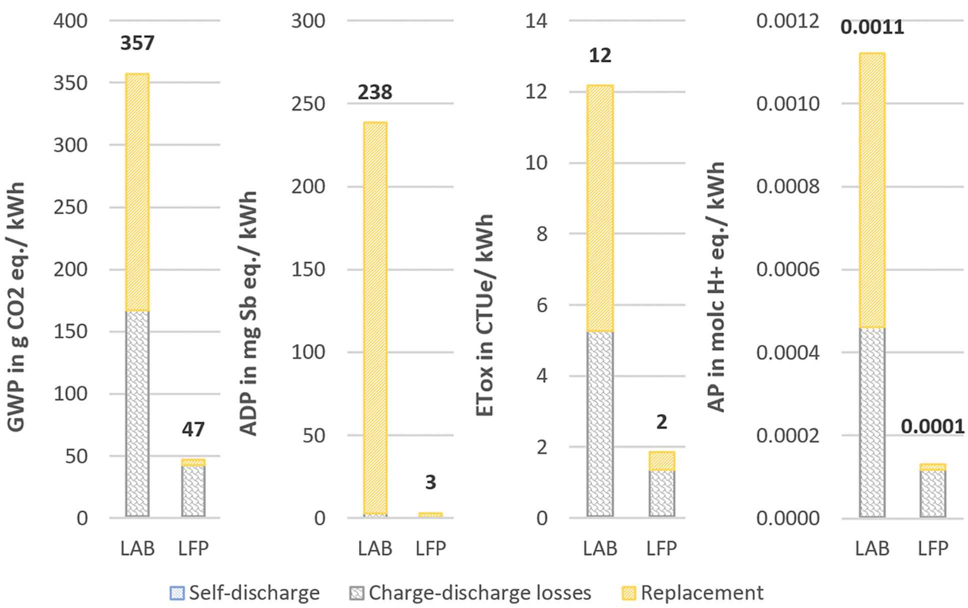

Fig. 6 Impacts of the use phase of the HSS use case on global warming potential (GWP), mineral, fossil & renewable resource depletion (ADP), freshwater ecotoxicity (ETox) and acidification potential (AP). Values are given per kW h of energy delivered over lifetime (FU).

80%. The LFP battery, on the other hand, has to be replaced on average 1.27 times over its entire service life. This replacement factor is based on the cycle life as well as on the calendar life. Since the minimum replacement factor, which indicates how long the battery provides adequate performance, is calendrically higher than the cyclical one, *i.e.*, under the minimum assumptions, the product would be replaced due to calendar aging. However, since the 13 years assumed for the LFP battery as minimum durability represents the worst case, this is combined with the optimal case of 20 years, and the average value of 1.27 is calculated. Therefore, the use phase of the LAB has a significantly higher impact in all four categories than the use phase of the LFP battery, mainly due to the necessary high replacement efforts and the lower energy efficiency. However, it must be noted that the LAB is not designed for cyclical use.

Regarding the full life cycle, including production, use and EOL, with a separate designation of replacement, the results draw the same picture. The LAB has a significantly higher

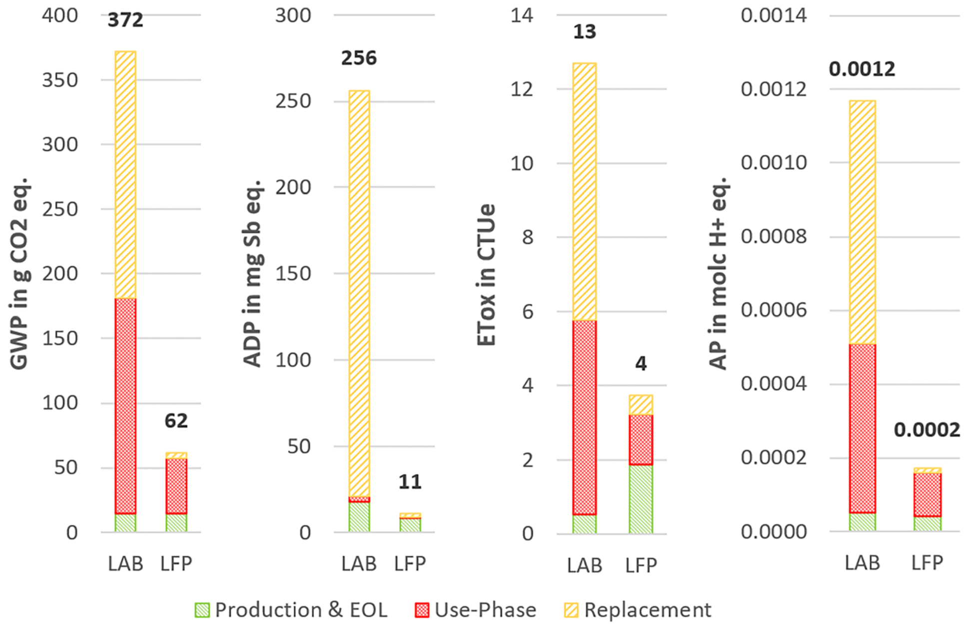

Fig. 7 Total impact of the full life cycle in the HSS use case on global warming potential (GWP), mineral, fossil & renewable resource depletion (ADP), freshwater ecotoxicity (ETox) and acidification potential (AP). Values are given per kW h of energy delivered over lifetime (FU).

impact per kW h of energy delivered than the LFP battery in all four categories. The poorer performance of the LAB can be completely attributed to the use phase, and especially the replacement. The lower impacts of the LAB in the production and EOL phases almost lose relevance because the divisor, the amount of kW h of energy delivered, has become so large. Thus, in a cyclical application, efficiency losses and replacement play the central role, rather than production effort or self-discharge (Fig. 7).

3.4 Sensitivity analysis

Both, in the production and EOL phase of the battery, as well as in the use phase, the impact attributable to electricity consumption represents a major part of the overall environmental impact (*e.g.* for GWP: around 36% in Prod. & EOL, 100% in use phase data centre and 47% in the use phase HSS). Therefore, the sensitivity analysis focuses on this aspect and alternates the source of electricity from the German electricity mix to exclusively renewable energy sources. In addition, the change of electricity supply sources helps also to gather insights of the impacts related to the location of the LAB factory. Due to the large extent of a full sensitivity analysis, only the results regarding GWP are presented in the following, all other numerical results for the other impact categories can be found in the ESI.† In terms of GWP, the emission factor of one kW h of electricity is consequently reduced from approx. 0.55 kg CO_2 eq. per kW h (electricity mix in Germany according to Ecoinvent 3.8) to 0.02 kg kW h^{-1} (electricity mix in Switzerland with exclusively renewable energy sources, according to Ecoinvent 3.8). This conversion is carried out once for the production and EOL phases combined as well as for the use phase.

For the production and EOL phases of the LFP reference battery, a different approach is taken, as the use of literature values made it difficult to adjust the electricity mix. Instead, an advanced type of recycling is included in the assessment to see how progress in this area affects the overall impact. The advanced recycling originates from the study by Peters *et al.*[80] and in addition to the mechanical processes also includes an advanced hydrometallurgical recycling process. It must be noted that the advanced recycling is not yet available on an industrial scale. The sensitivity analysis is first carried out for the use case data centre, as this is a common use case for the OGi Bloc 200.

Fig. 8 shows the results of the LAB on the left-hand side and the results of the LFP battery on the right-hand side.

It can be seen that the total impact of the LAB can be reduced by about 7% through the use of renewable energy in the use phase. If the electricity consumption in the production and EOL phases were to be converted, a saving of up to 32% could be achieved. Both measures combined could reduce the total impact of the LAB by approx. 39%, from 6397 g CO_2 eq. per kW h energy delivered to 3909 g CO_2 eq. per kW h energy delivered.

The use of renewable energies can also reduce the overall impact of the LFP battery. Using a different electricity mix in the use phase can save about 4%. Advanced recycling, however, does not have quite as great an effect on the savings. The use of additional hydrometallurgical recycling processes can save about 13% of the total impact. The combination of advanced recycling and renewable energies in the use phase reduces the total impact by approx. 18% from 7668 g CO_2 eq. per kW h energy delivered to 6318 g CO_2 eq. per kW h energy delivered. A detailed breakdown of the impacts with the modified assumptions in the sensitivity analysis can be found in the ESI.†

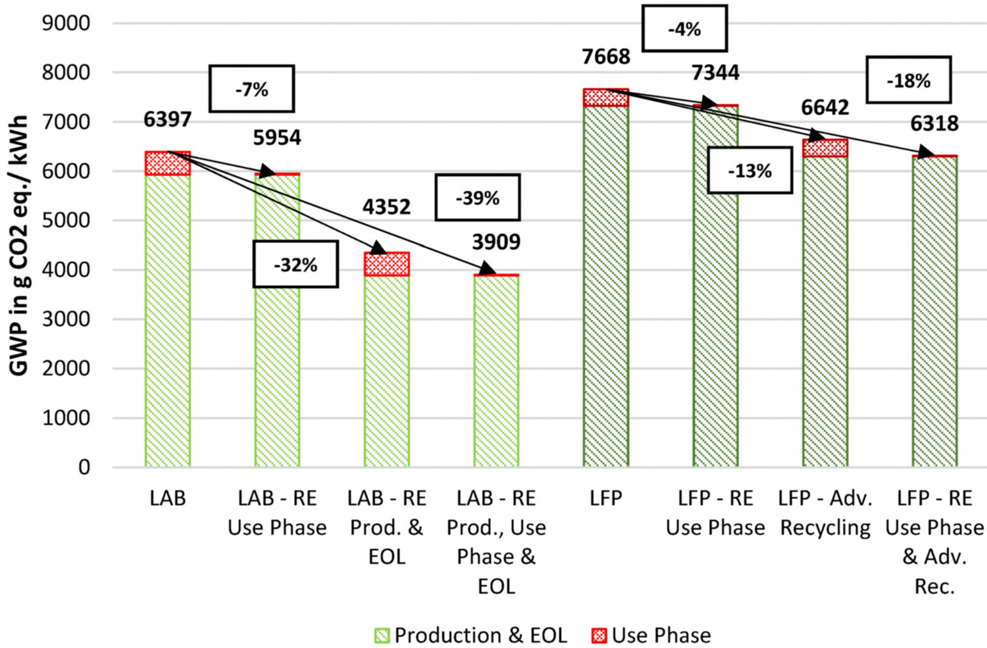

Fig. 8 Sensitivity analysis alternating the electricity mix and recycling method for the use case data centre. Impacts on GWP considering the full life cycle. RE: renewable energies, Prod.: production, Adv. Rec.: advanced recycling. Values are given per kW h of energy delivered over lifetime (FU).

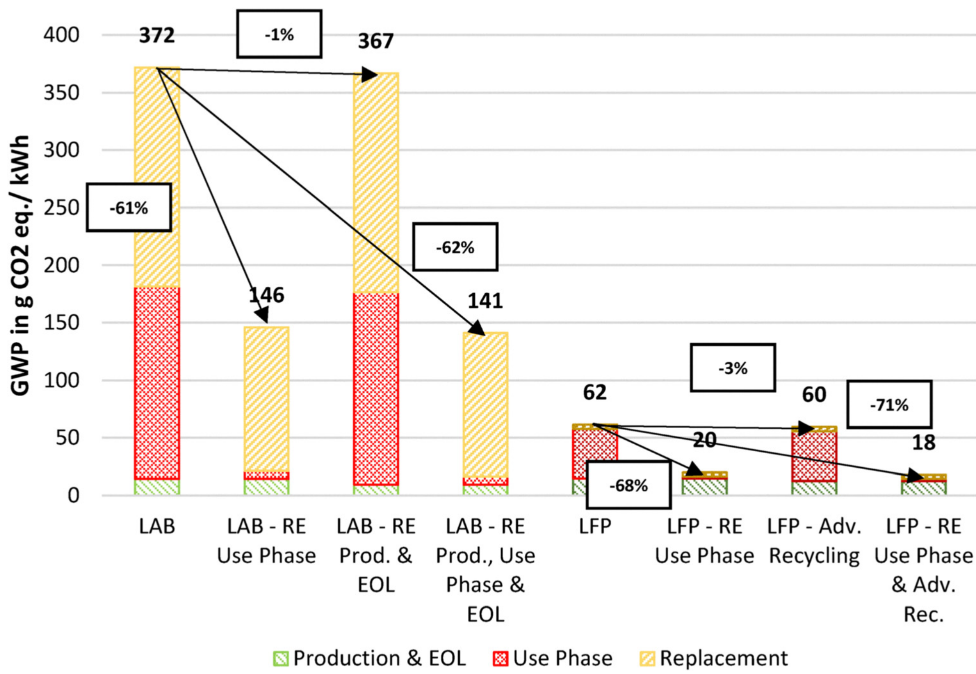

Fig. 9 Sensitivity analysis alternating the electricity mix and recycling method for the use case home storage system. Impacts on GWP considering the full life cycle. RE: renewable energies, Prod.: production, Adv. Rec.: advanced recycling. Values are given per kW h of energy delivered over lifetime (FU).

Further, the same sensitivity analysis is carried out for the use case HSS. Fig. 9 shows the results for the LAB and LFP battery in the same manner as for the use case data centre.

In the previous presentation of the results for the full life cycle, it was shown that the production and EOL phase in the HSS use case does not play a major role in the environmental impact of the batteries. This can also be seen in the sensitivity analysis, where a change in the electricity mix for the production and EOL phase for the LAB, or a change in recycling for the LFP battery, results in only a small reduction in impact (1% and

3% respectively). However, for an application with many cycles, such as the HSS, the use phase plays a central role. Changing the electricity mix can therefore lead to a reduction of more than 60% for both battery types. The detailed breakdown of the impact of the sensitivity analysis for the HSS use case can also be found in the ESI.†

4 Discussion

4.1 Interpretation of results

The production and EOL phases of the LAB are environmentally more favourable than that of the LFP battery. In the assessment of current industrial processes, the impact of the LFP battery on GWP is 25% higher than that of the LAB (50 kg CO_2 eq. per kW h battery capacity and 40 kg CO_2 eq. per kW h battery capacity respectively). However, these results are not yet embedded in suitable application cases. By examining the batteries in their use cases, it becomes apparent which aspects and phases are decisive for the environmental impact.

The first use case, data centre, is one for which the LAB was designed. Its results can be summarised by stating that the overall impacts of the LAB are significantly lower than those of the LFP battery for GWP and ETox. While the impacts in the category of AP are equally high, the LAB has higher impacts in terms of ADP. With the exception of AP, the production and EOL phases dominate when considering the entire life cycle, while the use phase is not very influential. The results of the midpoint indicator human toxicity is included only in the ESI,† as the majority of lead is kept within a closed loop and the remaining 1% managed carefully alongside process slag. Here, according to the manufacturer, all measures following the high German waste disposal standards are taken, which ensure no uncontrolled direct emissions of lead. Therefore, the potential for lead exposure to the environment is markedly diminished, leading to a lowered concern when compared to other more pressing impact categories.

For the second use case HSS, where the battery is used cyclically, it must be noted that the LAB was not designed for such use. With its low cycle lifetime, the LAB considered here is not designed to run through many cycles in its lifetime and must be replaced approximately every 1.4 years with the assumptions made here. But there are also LABs that are suitable for HSS. LABs made for cyclic applications, for example, have a much better cyclic lifetime and thus lower impact due to replacement. ‘‘Design by purpose’’ is therefore not only limited to the choice of cell chemistry, but also within a battery technology the batteries are made for different requirements and applications.[86] In order to consider a use case whose characteristics differ from the first case data centre and thus increase the possibilities for interpretation, the batteries are nevertheless compared in the application of an HSS. The environmental performance of the LAB for both the use phase and the entire life cycle is correspondingly poor in comparison to the LFP battery, which is predestined for cyclical applications. The LAB has significantly higher impacts in the use phase, which is due to both the high replacement impacts and the higher efficiency losses. Even an LAB with the same cyclic life as the LFP battery, ceteris paribus, would have a significantly higher environmental impact than the LFP battery due to its low energy efficiency. Therefore, both the cyclic life and the energy efficiency of this particular LAB would have to be improved simultaneously to be competitive with the LFP battery. The same result can be seen with regard to the entire life cycle, while the production and EOL phases are not particularly significant.

The modelling approach taken for the HSS use case, where the systems are designed with the same storage capacity for both cell types, together with the assumption of the same number of cycles in a lifetime, but different energy efficiencies, results in different amounts of energy delivered over the lifetime. A different approach that could be taken is to assume the same energy delivered for both battery systems and adjust the size of the systems according to the number of cycles and the energy efficiency of the cell types. However, this would lead to identical results as a change in system size will lead to a parallel change in the amount of energy delivered. These two effects on the overall impacts will cancelling cancel each other out.

Consequently, the environmental impacts of the LAB and LFP battery are very different in the two considered use cases. In conclusion, from a purely environmental point of view, the LAB should be preferentially used in the application case data centre (or similar applications with comparable load profiles), while the LFP battery is preferred in the case of HSS. One central factor for the different results of the two use cases is the divisor, the functional unit, which is the number of kW h of energy delivered. On the one hand, the larger the divisor, *i.e.*, the more energy is delivered by the system and the more cycles are run through, the more important are the effects that occur in each cycle. Efficiency losses in particular should be emphasised here. In addition, cycle lifetime and thus the resulting replacement impacts play a greater role. Effects such as those of the production and EOL phases become less important. All this applies to the second use case, HSS. On the other hand, in applications with a low amount of energy delivered, the absolute losses and effects such as self-discharge and the production and EOL phases effects are decisive – applicable to the first use case, data centre.

In the sensitivity analysis, the extent of the influence of the energy demand was checked again by replacing the electricity demand from the conventional electricity mix with a ‘green’ electricity mix that exclusively contains renewable energy sources. The results show that energy demand is not only important for the overall impact, but also central to the savings potential, and therefore to the overall LCA results, especially for the LAB. For the use case data centre, using the ‘green’ electricity mix alone in all three phases of the life cycle, without changing the gas or oil demand, can reduce the impact on GWP by up to 47%.

4.2 Optimisation potentials

The greatest lever for reducing environmental impacts of the LABs investigated lies in the energy demand. In addition to the aforementioned conversion of the power source to purely renewable energy, the energy demand can also be reduced, thus saving a significant amount. One example is the maturing room used in the production of lead plates. The machine during operation is most likely to be energy-intensive and has therefore high potential savings. A different approach to optimise the environmental impact of the production might be to reduce the impact of natural gas by either reducing the required amount or replacing it in certain process steps with a more environmental solution, such as biogas. Two other ways for the manufacturer to reduce its impact on the environment require investment by the company. Firstly, PV systems can be installed on the buildings and on open spaces of the production facility. Thus, there is no need to wait until enough electricity from renewable energy sources is available in the grid, but the electricity would be generated to a certain degree by the company itself. In addition, this would relieve the electricity grid. Secondly, waste heat from the processes can be reused. The heat generated is suitable for covering one's own heating needs or for supplying the surrounding residential buildings with heat. Further optimisation potentials require a further detailed assessment of the product and its processes.

4.3 Comparison to previous studies

The results obtained in this study are here compared with the results from the literature. This helps checking if the corresponding impacts based on the collected primary data are within the bandwidth of other published studies. However, the choice of studies for comparison has to be made carefully, as different assumptions, system boundaries, regional context, system sizes or application areas strongly influence the numerical results strongly.[30] Even in this work, the results of the two use cases differ by a factor of about 20 in terms of GWP. Therefore, seven studies using the FU kW h of energy delivered and including all three phases of the life cycle are taken from the literature review in order to verify the correct order of magnitude of the obtained results.[21,23,31,33,51,65,70] As all these studies examine a cyclical use case, the results obtained from the use case HSS are used for comparison.

Fig. 10 shows the results of the studies compared to the results obtained here. The studies are additionally marked with the size of the system investigated: HSS – home storage system corresponds to a small system, MG – microgrid to a medium-sized system and GSS – grid-scale system to a large system.

It can be seen that all studies show results of the same order of magnitude. The results vary between 0.11 kg CO_2 eq. per kW h energy delivered in the study by Bilich *et al.*[23] and 0.78 kg CO_2 eq. per kW h energy delivered in that of Rahman *et al.*,[33] with the result of this work of 0.37 kg CO_2 eq. per kW h energy delivered lying fairly in the middle. Furthermore, the result obtained here is very close to the average value of the compared studies of approx. 0.39 kg CO_2 eq. per kW h energy delivered, shown in the graph by the red dashed line. Although the comparison of the battery investigated in this work was carried out in an application for which the battery is not intended, the results are similar to those in the literature, which may have been based on batteries designed for cyclic use. The question of how a battery designed for cyclic use would perform ecologically with current processes from Europe remains open.

Regarding the two marginal values of the comparison, both the study with the lowest and the one with the highest results are based on the LCI data from the same study, by Spanos *et al.*[21] In the study by Bilich *et al.*[23] the battery is examined in the context of a PV microgrid in Kenya. Here, about three quarters of the total impact comes from production, which is a relatively high share compared to the share of 4% obtained in this study. The high share of production is due to very low impact attributed to the use phase, as the electrical energy used in the use phase can be obtained almost burden-free from the connected PV system. Since the use phase usually accounts for a large part of the impact on GWP, the results of Bilich *et al.*[23] are lower than the average of the studies. In the study by

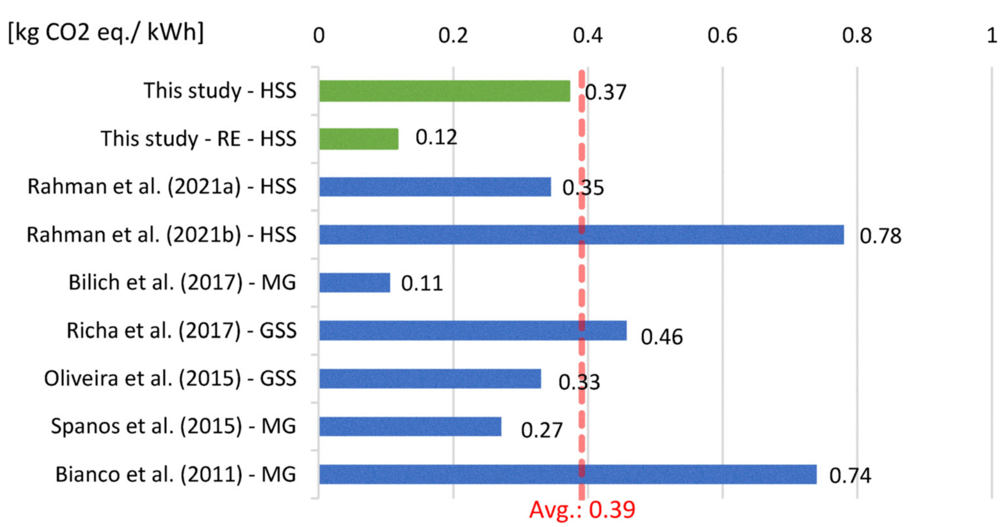

Fig. 10 Comparison of the impacts of the full life cycle on GWP in kg CO_2 eq. per kW h energy delivered. HSS: home storage system; MG: microgrid; GSS: grid-scale storage.

Rahman *et al.*[33] the exact opposite is the case, as the impacts of the use phase play the key role and are the main driver for the high overall impacts in this work.

In the comparison carried out here, it becomes clear that the assumptions made by the respective authors and the application area of the battery are decisive for the level of impact. The hypothesis that batteries must be investigated and compared on a well-defined application-specific basis is further confirmed.

Overall, the results of this work are comparable to the existing results in the literature. But in the area of production and EOL phases, the data presented here are more granular and up-to-date than those from the literature. They allow subsequent studies to base their results on modelling that reflects current industrial processes. In addition, for the first time, the transition from the conventional electricity mix to electricity from renewable technologies is examined in this context. It is shown that such a conversion can reduce the environmental impact in the use case HSS by more than 60%.

4.4 Limitations and future research

This work provides a detailed investigation of an industrial LAB based on up-to-date primary data. As in any study, assumptions and limitations had to be made that will need to be considered when interpreting the results in the future. These, as well as the resulting propositions for future research on the LAB are presented in the following.

Regarding data acquisition, the results acquired are based on the investigation of a specific battery manufactured in a specific production site. The results can be seen as representative, but are not generally valid for every LAB. The calculations made for the use phase regarding battery ageing are tailored to the OGi Bloc 200 battery type and are therefore not generally applicable to all LABs. Furthermore, not every LAB production facility has a recycling plant on-site and in the case of external recycling, the impacts due to additional transport of both the waste lead and the procurement of the secondary lead must also be considered. In a future study of another LAB, it would be interesting to uncover the energy requirements of the individual process steps and thus be able to draw a more accurate picture regarding the impacts attributable to the energy demand. Additionally, a detailed investigation of the recycling of the electrolyte would further improve the accuracy of the data. While the composition and mass balance of the battery are provided in great detail, some assumptions were made for the use phase that require further investigation. These include the number of cycles in both use cases, the respective depth of discharge and the optimal system sizes to limit battery ageing as far as possible. The assumptions regarding self-discharge and energy efficiency, on the other hand, represent reality of LIB and LAB fairly accurately. But it hast to be mentioned again that for the comparison of both battery types, the data of the LFP battery are based only on the literature. No balance of system components such as BMS or housing were included in the assessment for either use case.

Temperature plays a significant role in the use phase, but has been kept constant at 20 degrees celsius in the assumptions, due to a lack of detailed data. A corresponding cooling system is also not included in the scope of the work. In addition to temperature fluctuations, direct emissions from the production site, the exact wastewater treatment and the effects that ageing has on the battery, such as the changing internal resistance or increasing capacity losses, are of particular interest when it comes to future research. Furthermore, both a technical- and a cost analysis, complementary to the environmental assessment carried out here, would add great value for decision-makers.

5 Conclusion

This work fills a research gap by providing a full LCA of an industrial LAB, serving as a reference battery technology in many studies. The presented LCA is based on reliable, up-to-date primary data from a manufacturer based in Germany and carefully considers the targeted application field to address the design by purpose principles, wherein a product is optimized for a certain application as the analysed LAB for uninterruptable power supply. A conducted mass and energy flow analysis led to detailed life cycle inventories which build the important basis of reliable LCAs. The work improves significantly the data situation of the LABs in the literature and provides new insights regarding the environmental performance of LABs produced in the EU. Additionally, it shows which drivers are mainly responsible for the environmental impacts.

In detail, the following key findings are pointed out:

• The production and EOL phases of the LAB combined have a lower environmental impact on GWP, ETox and AP than the same two phases of the LFP battery, while the LFP battery performs more favourably regarding ADP.

• The biggest contributors for the environmental impact of the production and EOL phases of the LAB are the energy demand regarding GWP, the use of antimony and barium in the plates with respect to ADP and ETox, and the use of sulfuric acid and its recycling in terms of AP.

• In the context of the data centre use case, the LAB outperforms the LFP battery across a majority of impact categories. This outcome is attributed to the low number of cycles associated with this use case, which highlights the central role of the production and EOL phases.

• Conversely, when considering the HSS use case, the LFP battery demonstrates more favourable performance in all categories, primarily due to its considerable higher lifetime and energy efficiency compared to LAB.

• The sensitivity analysis shows that changing the source of electricity from the German electricity mix to purely renewable energy sources can reduce the overall environmental impact on GWP up to 39% for the LAB in the use case data centre (7% in the use phase, 32% in production and EOL phases).

From the above key findings, it can be concluded that the environmentally best choice of a battery cell type is directed by the respective application and the different cell performance.

Firstly, the magnitude of results depends on the application, when the results are given per kW h energy delivered, as different amounts of energy are delivered over the lifetime. Thus, no comparisons can be made between them. Secondly, different applications have different drivers of environmental impacts. Thus, for high cyclical applications, for example, the impacts of the use phase, caused by replacement and efficiency losses, play the decisive role, and the production and EOL phases decrease in relevance. In the case of non-cyclical applications, such as UPS, the picture is exactly the opposite and the impacts of the production and EOL phases are most important.

In summary, batteries need to be investigated and compared on an application-specific basis, following the concept of "design by purpose". For the two use cases investigated here, the results show different favourable battery types from an environmental impact perspective. Therefore, using the same LAB and corresponding LCI for a different application field can lead to non-practical, misleading comparisons and recommendations. In the future it would be interesting to compare the results of this work with assessments based on LAB processes and primary data of different manufacturers with different technology specifics and regional context.

Abbreviations

ADP	Mineral, fossil & renewable resource depletion
AP	Acidification potential
DC	Direct current
ECHA	European chemicals agency
EOL	End-of-life
ETox	Freshwater ecotoxicity
EV	Electric vehicle
FU	Functional unit
GSS	Grid-scale system
GWP	Global warming potential
HSS	Home storage system
IEC	International electrotechnical commission
ILCD	International life cycle data system
KVA	Kilo volt ampere
kW	Kilo watt
kW h	Kilo watt hour
LAB	Lead-acid battery
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LFP	Lithium iron phosphate
MG	Microgrid
NMC	Nickel–manganese–cobalt
PbA	Lead-acid
PEF	Product environmental footprints
PP	Polypropylene
RE	Renewable energies
SLI	Starting lighting and ignition
UPS	Uninterruptible power supply
VRLA	Valve-regulated lead-acid battery

Author contributions

Friedrich B. Jasper: investigation, formal analysis, methodology, conceptualization, validation, writing – original draft, visualization. Manuel Baumann: conceptualization, supervision, writing – review & editing, validation, project administration. Milosch Stumpf: investigation, validation, resources. Andreas Husmann: investigation, resources, project administration. Bernhard Riegel: validation, resources, supervision. Stefano Passerini: writing – review & editing, supervision. Marcel Weil: conceptualization, supervision, writing – review & editing, validation, project administration.

Data availability

The data supporting the findings of this study can be found in the ESI† and under **https://doi.org/10.5281/zenodo.14836938**. Please note that the presented data might be in some parts limited due to confidentiality constraints.

Conflicts of interest

The authors declare the following conflicts of interest: Author MS reports a relationship with Hoppecke Batteries Ltd and Co: former employment. Authors AH and BR report a relationship with Hoppecke Batteries Ltd and Co: employment. There are no further conflicts to declare.

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