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Life cycle assessment (LCA) of a battery home storage system based on primary data

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ABSTRACT

While the market for battery home storage systems (HSS) is growing rapidly, there are still few well-modelled life cycle assessment (LCA) studies available for quantifying their potential environmental benefits and impacts. Existing studies mainly rely on data for electric vehicles and often lack a thorough modelling approach, especially regarding the peripheral components. This paper presents a full cradle to grave LCA of a Lithium iron phosphate (LFP) battery HSS based on primary data obtained by part-to-part dismantling of an existing commercial system with a focus on the impact of the peripheral components. Additionally, alternative battery chemistries (Sodium ion battery (SIB) and two lithium nickel manganese cobalt oxides, (NMC^{811},and NMC^{622}) are investigated under the consideration of the same periphery. This approach allows a comprehensive comparison between present and emerging cell chemistries that can be potentially considered for an HSS.

The total greenhouse gas emissions of the HSS are 84 g CO_2eq/KWh of electricity delivered over its lifetime in a residential PV application, or 31 g CO_2eq/KWh over lifetime when excluding the use-phase impact. The peripheral components contribute between 37% and 85% to the total gross manufacturing impacts of the HSS, depending on the considered cell chemistry and the impact category. Especially the inverter plays an important role, and its impacts are significantly higher than those obtained when using the standard ecoinvent dataset, indicating that the contribution of power electronics might often be underestimated when using this dataset. In terms of cell chemistries, the considered SIB turns out to be not yet competitive with LIB chemistries due to its lower energy density and lifetime, but might become so when reaching similar lifetimes.

1. Introduction

1.1. Background

The ongoing shift towards renewable energies poses a number of challenges, most importantly the fluctuating generation from wind and solar energy. One possibility for overcoming this intermittency are stationary battery storage systems (SBSSs). Especially Lithium-Ion battery (LIB) systems are seen as promising, as they have quick response times, high efficiency and a high modularity (Balakrishnan et al., 2018). SBSSs can either be applied on grid scale, most frequently as container storage systems (CSS), or on residential scale as a home storage system (HSS). HSSs are mostly used in combination with rooftop photovoltaic (PV) systems, storing the self-generated electricity when generation surpasses demand and providing it in absence of solar irradiation, thus increasing self-consumption and grid autonomy.

In consequence, governments promote HSS with numerous incentives. For instance, in Germany a sharp increase in annually installed systems has been observed in the recent years (Enkhardt, 2021; Kairies et al., 2019). At the same time also raised concerns about the environmental impacts related to the entire life cycle of these systems are expressed. While there are numerous publications analysing the impacts related to battery cell production and use (Emilsson and Dahllöf, 2019; Peters et al., 2017), or entire PV-storage systems (Krebs et al., 2020; Stolz et al., 2019), little attention has yet been given explicitly to the

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List of abbreviations

AC	Alternating current
APOS	Allocation at the point of substitution
BMS	Battery management system
CSS	Container storage system
DoD	Depth of discharge
EOL	End-of-life
ETox	Freshwater ecotoxicity
FU	Functional unit
GWP	Global warming potential
HSS	Home storage system
LCA	Life cycle assessment
LCI	Life cycle inventory
LFP	Lithium iron phosphate
Li-Ion	Lithium-Ion
LIB	Lithium-Ion battery
NaNMMT	Sodium nickel manganese magnesium titanate
NMC	Nickel mangan cobalt
PV	Photovoltaic
ResD	Mineral, fossil & renewable resource depletion
SBSS	Stationary battery storage system
SI	Online Supplementary Information
SIB	Sodium ion battery
STL	Steel

periphery and the end of life phase of such systems (Mohr et al., 2020). Typically, peripheral components include the battery management system, power electronics and cooling i.e., everything that is not battery cells and housing. While these are often also summarized as balance of system (BoS) or balance of plant (BoP), the term peripheral components is used throughout this manuscript. These components are usually not well defined, only superficially modelled and add substantial uncertainty to the corresponding assessments (Abbas et al., 2013; Phelps and Nilsson, 2017). The same applies to the end-of-life (EOL) stage (i.e., recycling), disregarded in the majority of available studies on HSS (c.f. Table 1). While there is increasing evidence about the importance of including also the EOL stage for a meaningful assessment, existing studies focus mostly on EV batteries and, again, put little attention on peripheral components (Ellingsen et al., 2014; Pellow et al., 2019; Peters et al., 2019).

1.2. Literature review of LCAs of HSSs

A literature review was conducted to get a detailed overview of the current LCA oriented research in HSS, especially the works dealing with the battery and the peripheral components as management system (BMS), the power electronics and the corresponding EOL treatment. Google Scholar and Science Direct have been used for the literature research. The main keywords were “life cycle assessment”, “LCA”, “environmental impacts”, “stationary battery systems”, “stationary batteries”, “home storage system” and “HSS”. Additionally, the studies had to fulfil specific prerequisites in order to be included in the review: 2015 was considered as the earliest publication year and the studies had to deal with the environmental impacts of SBSSs with LIB.

Table 1 provides an overview of the literature review results. Most studies are based on secondary life cycle inventory (LCI) data, especially for the peripheral components. Only Stenzel et al. (2016) included primary data from a 5 MW/5 MWh battery storage system for primary

Table 1
Evaluation of end-of-life (EOL) consideration in studies with life cycle assessments (LCAs) on Stationary Battery Systems (SBSS).

Study	LCI data	BMS	Power Electronics	EOL consideration
Carvalho et al. (2021)	Own (primary) for cells, Ellingsen et al. (2014) for pack,	Ellingsen et al. (2014)	Not considered	Recycling of cells and electronics. Based on Mohr et al. (2020) and ecoinvent
Krebs et al. (2020)	Majeau-Bettez et al. (2011); Ellingsen et al. (2014);	Ellingsen et al. (2014);	inverter 2.5 kW (ecoinvent)	Not considered
Raugei et al. (2020)	Frischknecht et al. (2015)	Frischknecht et al. (2015)	Frischknecht et al. (2015)	Not considered
Chowdhury et al. (2020)	Pforzheim University, Immendoerfer et al. (2017)	Based on Immendoerfer et al. (2017)	Based on Immendoerfer et al. (2017)	Not considered
Rossi et al. (2020)	Ecoinvent 3.4	Ecoinvent 3.4	Ecoinvent 3.4	Recycling of HSS with PV-System
Le Varlet et al. (2020)	Ellingsen et al. (2014); Tschümperlin et al. (2016)	Based on Ellingsen et al. (2014)	Inverter by Tschümperlin et al. (2016),	Not considered
Schmidt et al. (2019)	Majeau-Bettez et al. (2011); Ellingsen et al. (2014); Bielitz (2016)	Based on Ellingsen et al. (2014); 0.3805 kg BMS/kWh	For application SC: inverter 2.5 kW; for other applications: inverter 500 kW (ecoinvent)	Not considered
Vandepaer et al. (2018)	Vandepaer et al. (2017); Peters and Weil (2017)	Based on Ellingsen et al. (2014);	Not discussed	Recycling of CSS (battery and steel case only)
Ryan et al. (2018)	BatPac, GREET	Dunn et al. (2012): Electronics have 1.1% of battery mass Impacts/mass based on GREET	Based on Mason et al. (2006), linear scaling; Input/mass based on GREET	Recycling of CSS (battery, steel and aluminium only)
Immendoerfer et al. (2017)	Notter et al. (2010); Stenzel et al. (2016)	Ecoinvent 3.2.	Ecoinvent 3.2.	Recycling of CSS
Baumann et al. (2017)	Secondary (based on various LCA studies)	Based on Ellingsen et al. (2014)	Inverter production 500 kW	Not considered
Peters and Weil (2017)	Zackrisson et al. (2010); Bauer (2010)	Based on Ellingsen et al. (2014)	Inverter production 500 kW	Not considered
Vandepaer et al. (2017)	Majeau-Bettez et al. (2011); Batt DB database	Part of ancillary components	Not discussed	Recycling of battery only
Stenzel et al. (2016)	Primary data from Younicos AG, database GaBi 6.0	Electronics, fuses, relays, cable, steel frame 26 kg	8 × 750 kW Inverter	Not considered
Hiremath et al. (2015)	Majeau-Bettez et al. (2011)	Based on Majeau-Bettez et al. (2011) (mobile application)	Inverter taken into account in collar scenario only	Not considered

regulation services in Germany, Carvalho et al. (2021) rely on data from an Italian cell manufacturer, but use secondary data from an electric vehicle battery pack for the peripheral components. While most studies include peripheral components in their LCI, they rely on very different approaches. Six studies (Baumann et al., 2017; Krebs et al., 2020; Le Varlet et al., 2020; Peters and Weil, 2017; Schmidt et al., 2019; Vandepaer et al., 2018) base their assessment on the BMS model by Ellingsen et al. (2014), which is LCI data of a battery for mobile application and might thus not apply for stationary systems. In Stenzel et al. (2016) the BMS is not mentioned separately, but seems to be a part of the included electronics. This is the same for Ryan et al. (2018), where a gross 1.1% of the total battery mass is assumed as the corresponding mass of the electronics, and for Vandepaer et al. (2017) who account them as part of ancillary components. Apart from the BMS, the power electronics are also in the focus of this review. Four studies used secondary data from other studies for the modelling (Chowdhury et al., 2020; Le Varlet et al., 2020; Raugei et al., 2020; Ryan et al., 2018). Another five studies (Baumann et al., 2017; Immendoerfer et al., 2017; Krebs et al., 2020; Peters and Weil, 2017; Schmidt et al., 2019) used the inverter of the ecoinvent database in different versions (Moreno Ruiz et al., 2020). Of the three inverters available in ecoinvent (0.5 kW, 2.5 kW and 500 kW), most works use the 500 kW version, except Krebs et al. (2020) where 2,5 kW version is used. Again, Stenzel et al. (2016) is the only study where primary data has been used for modelling the power electronics. The inclusion of the inverter is not clear in the remaining three publications (Rossi et al., 2020; Vandepaer et al. 2017, 2018). Although thermal regulation is an important aspect of battery storage, it plays a minor role in an LCA of an HSS. This is due to the fact that the thermal regulation in HSS usually consist only of fans and aluminium cooling fins. For this reason, it was not examined separately in this literature review.

The majority of the analysed studies did not integrate an EOL assessment, mostly because of a lack of data availability (Baumann et al., 2017; Chowdhury et al., 2020; Hiremath et al., 2015; Krebs et al., 2020; Le Varlet et al., 2020; Peters and Weil, 2017; Raugei et al., 2020; Schmidt et al., 2019; Stenzel et al., 2016). Rossi et al. (2020) and Carvalho et al. (2021) are the only two studies that considered the recycling of a HSS. The EOL treatment of a CSS is included in three studies (Immendoerfer et al., 2017; Ryan et al., 2018; Vandepaer et al., 2018). Moreover, Vandepaer et al. (2017) assessed the relevance of the EOL treatment of the battery, finding that LFP batteries have very low recycling potential due to the absence of rare metals and therefore require policy regulations for avoiding improper EOL handling. It is also worth mentioning that in some studies the cell type is not clearly stated (e.g., pouch, cylindrical or prismatic), though it might be relevant for the overall environmental performance (Peters and Weil, 2018).

1.3. Aim and scope

The literature review shows the diversity of assessment levels and also the very limited amount of primary data available for stationary home storage systems, especially for the related peripheral components and recycling. For these, almost all studies rely on data for electric vehicle batteries and focus modelling efforts on the battery cells, despite the relevant contribution of the peripheral components to the total environmental impacts of these systems. Being the availability of detailed and reliable primary data one of the principal concerns of any LCA study and a fundamental factor for its meaningfulness, there seems to be need for improving modelling efforts for these secondary components and for assessing their contribution to the potential impacts of stationary battery systems.

Therefore, this work provides a detailed study of the impact of the peripheral components for the overall environmental impacts of a HSS under a full life-cycle perspective (including the EOL phase) based on primary data for the system composition. A commercial HSS has been disassembled to gather first-hand primary data about peripheral components, which, as revealed in the literature review, have been modelled majorly based on assumptions. The obtained inventory data are used for a cradle to grave life cycle assessment (LCA) of an HSS in three different configurations: Equipped with the default Lithium iron phosphate (LFP) battery cells, and two hypothetical modifications where these are substituted by lithium nickel manganese cobalt (NMC) Li-Ion and by sodium nickel manganese magnesium titanate (NaNMMT) type Sodium Ion battery (SIB) cells.

2. Methodology

This section provides a brief introduction to HSS and a detailed overview of the overall approach and the collection of primary data. It also outlines the system boundaries and defines the functional unit (FU) and the considered peripheral components.

2.1. Assessment framework

2.1.1. Scope and system boundaries

As mentioned before, the aim of this work is the quantification of the potential environmental impacts of the peripheral components on the overall environmental impacts of a typical HSS under a full life-cycle perspective, based primary data for the system composition. It considers the whole life cycle including the end-of-life of the product (cradle to grave assessment). Fig. 1 shows the system boundaries of the conducted LCA, including primary material extraction, the production phase, the use phase and the EOL phase. The EOL phase consists of the recycling processes and the final disposal of waste. The materials recovered in the recycling processes are assumed to be fully re-used for production of new HSS ('closed loop'). The bill of material for the HSS is obtained from the dismantling of a commercial system, while data related with the cell layout and use-phase (efficiency, auxiliary consumption etc.) are taken from literature. The manufacturing of battery cells and modules is assumed to take place in China, while the modules are assembled into the final HSS in Germany. Whenever available, the corresponding country-specific datasets are used e.g., the Chinese electricity mix for cell manufacturing and related processes, and the German one for system manufacture and -assembly. More details on the used background data can be found in the specific inventory tables provided for each process in the Online Supplementary Information (SI). Background data for material production and upstream processes are taken from the ecoinvent 3.7 database (Moreno Ruiz et al., 2020).

2.1.2. Impact assessment and functional unit

The study was conducted using the open source software openLCA 1.10.2. In combination with the ecoinvent 3.7 database, the Allocation at the point of Substitution (APOS) approach is applied in this study. APOS is an allocation approach that uses expansion of product systems to avoid allocating within treatment systems. In this approach burdens are attributed proportionally to specific processes leading to the inclusion of the environmental impacts of by-products (Moreno Ruiz et al., 2020).

The environmental impacts are calculated per one kWh of energy delivered by the considered systems over their lifetime (the functional unit). This represents the basic function of any HSS and enables straightforward comparison with the results for other energy storage systems. Furthermore, it considers the type and frequency of use and the corresponding impacts on battery degradation.

For quantifying environmental impacts the ILCD methodology is used (JRC European Commission, 2017), applying the following midpoint indicators: global warming potential with a 100-year time horizon (GWP), mineral, fossil & renewable resource depletion (ResD) and freshwater ecotoxicity (ETox). The former two are the impact categories most frequently assessed by LCA studies on Lithium-Ion battery (LIB) and post LIB and also most present in the public debate, while toxic impacts are relevant especially in the upstream processes like mining (Emilsson and Dahllöf, 2019; Hund et al., 2017; Peters et al., 2017).

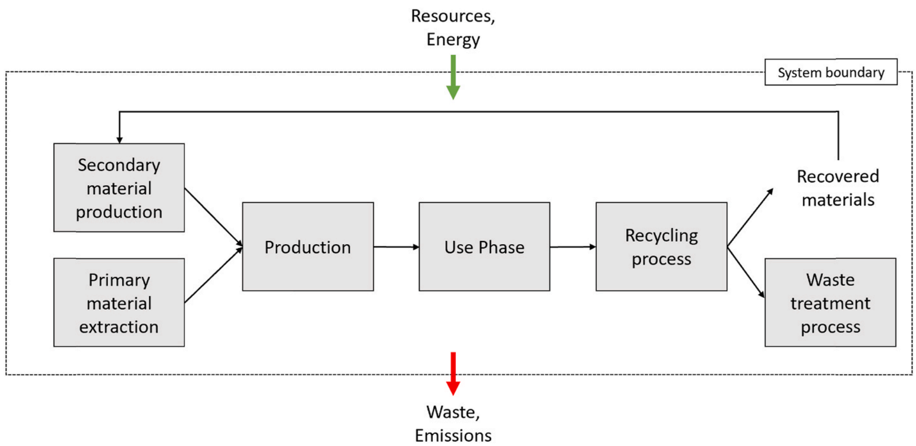

Fig. 1. System boundaries of the presented study. Included: primary material extraction, production, use phase and recycling. The recovered materials are computational used in the production.

2.1.3. Sensitivity analysis

Being many parameters used for the assessment based on assumptions or providing literature a range of possible values, the most important assumptions are subjected to a sensitivity analysis. For this purpose, parameters that have a relevant impact on the results and that are associated with significant uncertainty are varied in order to assess their relevance on the total outcome of the study. The following parameters are subjected to the sensitivity analysis:

- Number of cycles per day
- energy density
- standby electricity
- discharge round-trip efficiency of the system
- lifetime in years and cycles
- recycling rates

However, to limit the number of results graphs the analysis is limited to the impact category global warming potential. Results for the other impact categories are provided in the SI.

2.2. Data acquisition

There are several designs of HSSs from various manufacturers consisting of different components. Usually, AC coupled HSS systems as the one considered here have an own inverter, whilst DC coupled HSS use the same inverter as the PV system (Munzke et al., 2021; Sandelic et al., 2019; Weniger et al., 2014). AC coupled battery systems are easy to add to an existing PV installation and therefore especially suitable as retrofit solutions. In contrast, DC-coupled HSS avoid the need for a second inverter (and the corresponding environmental impacts and efficiency losses). In any case, all battery storage systems include (Hiremath et al., 2015; Le Varlet et al., 2020; Ryan et al., 2018).

1. Battery modules (composed of battery cells, a module housing, some control electronics and optionally an active or passive cooling system),
2. A system control unit (mainly active electronic components such as printed wiring board, microprocessors and display),
3. Power electronics (composed of printed wiring boards, contactors and passive electronic components),
4. Thermal regulation (fans or other forced cooling)
5. Housing and cabling

The largest share of data used in this study is measured at Battery Technology Center (BATEC), KIT. A modular HSS, build in 2015, was disassembled over one week and its components were measured in weight in kg and size in cm^3. The HSS consists of up to 6 battery modules containing LFP pouch cells with a capacity of 2.4 kWh per module and a maximum capacity of 14.4 kWh Two scales were used for weight measuring. The larger one has a maximum capacity of 300 kg and shows 100 g steps and the smaller one has a maximum capacity of 5 kg showing the weight in 1 g steps. The size of the components was measured with a measuring tape. Components such as coils, capacitors and fans were separated from wiring boards via soldering irons and were weighted separately as far as possible. The data obtained was subsequently normalised to 1 kg of component. A detailed description of the measuring including photos is provided in the SI. The battery cells were weighed and then modelled by adjusting the inventory data provided by Mohr et al. (2020) to the obtained cell mass. The HSS includes a bidirectional inverter, an ampere power charger (charge and discharge regulation), a system controller (including the energy manager), and battery modules. Additionally, each module contains a BMS. A schematical and real representation of the layout of the HSS is shown in Figs. 2 and 3.

The components of the HSS are assembled in a steel cabinet, which can be placed in a residential building. It has a height of 1600 mm, a width of 600 mm and a depth of 600 mm. The total weight is 268 kg, when six modules are built in. As the system includes an inverter, it can directly be alternating current (AC) connected with the building and the grid. The power electronics consisting of the inverter and the ampere charger, seen on the top left-hand side in Fig. 2, have a charging and

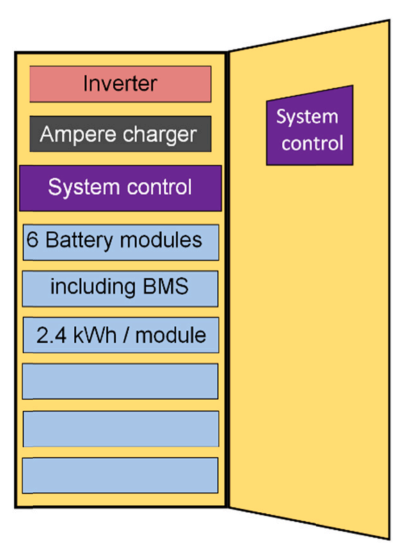

Fig. 2. Schematic representation of the measured HSS.

Fig. 3. Photo of the measured HSS – battery modules already disassembled.

discharging power of 7.2 kW. The expected number of cycles for the LFP cells is 6000 with maximum 80% depth of discharge (DoD). Small fans and aluminium heatsinks are used for cooling of the components (accounted for as part of the corresponding system component).

The inventory data collected in this way (mass and number of the components) is combined with data from the ecoinvent 3.7 database, used for the background processes, electricity mixes and materials.

The production of the main components (modules, inverter, ampere charger) is assumed to be in China and the assembling in southern Germany. As in Pettinger and Dong (2017), it is assumed that the components are transported 8000 km by sea freight from China to Hamburg and then 1000 km on the road by lorry to southern Germany. After assembling the final product is assumed to be transported 300 km by lorry. According to these assumptions the Chinese electricity mix is considered for the production of the components and the German electricity mix for the assembling of the HSS.

2.3. Analysed cell types

By default, the analysed HSS is equipped with LFP pouch cells. However, to provide a broader picture of potential environmental impacts of different types of HSS, three more cell types are examined: (i) NMC^{622} i.e., lithium nickel manganese cobalt oxide with stoichiometric shares of 60% nickel, 20% manganese and 20% cobalt; (ii) NMC^{811} and (iii) sodium ion battery (SIB) cells (NaNMMT; using Sodium Nickel Magnesium Manganese Titanium Oxide cathode in combination with a hard carbon anode). Due to their electrochemical similarities, all three cell types are considered suitable for HSS application within the same periphery. The named chemistries differ in terms of energy density, cycle and calendric life time, which are relevant parameters for the use phase impacts (Le Varlet et al., 2020; Peters et al., 2017). (Preger et al., 2020). While LIBs are an established technology, it is difficult to find robust performance data for the SIB, which are still on a lower technology readiness level. Depending on the SIB chemistry, a wide range of values is provided in the literature for their cycle life, varying between 1.000 and 10.000 cycles (Liu et al., 2019). However, due to its structural similarity, the NaNMMT chemistry can be expected to achieve maximum cycle life rather in the range of current NMC cells than those of LFP cells. With SIB and LIB having comparable coulombic efficiencies, their round trip efficiency can be assumed to be comparable (Peters et al., 2016; Peters and Weil, 2016). It has to be mentioned here, that there are several SIB types available that similarly to LIBs have very different characteristics depending on their specific chemistry (Peters et al., 2021). The main characteristics of the different cell types can be seen in the following table:

2.4. Use phase

An HSS is typically used at end-consumer level in a residential building to increase the self-consumption of the electricity produced with a rooftop photovoltaic (PV) plant. While the electricity production peaks during the day, the consumption peaks usually in the evening. Therefore, the battery is charged during the day and discharged during the night, resulting (on average) in one full cycle per day, or 7300 cycles over the lifetime of the HSS (20 years). This represents a conservative estimate of project life time of a residential PV-system, in which the PV-Cells can technically achieve life times over 25 years (Sandelic et al., 2019). PV electricity (low voltage) from monocrystalline PV panels on a slanted roof installation in Germany is assumed as sole electricity source for charging the HSS (based on ecoinvent data).

However, not all components of the HSS reach the lifetime of 20 years or 7300 cycles. The peripheral components for example almost all reach their end of life before 20 years have passed. For instance, the warranty time of the inverter installed in the HSS is five years. However, literature sources indicate values of 15 years or below (energie-experten.org, 2016, Sangwongwanich et al., 2018). Therefore, in this work 8 and 15 years are considered as minimum and maximum values. The corresponding replacement factors are 1.33 (15 years) and 2.5 (8 years), with a mean value of 1.92. Additionally, also the components lifetime in terms of cycles is examined. For the inverter, the mentioned literature sources indicate a lifetime of minimum 5000 cycles and maximum 10000 cycles, resulting in replacement factors of 1.46 (5000 cycles) and 0.73 (10000 cycles). As the minimum number of years is reached before the minimum number of cycles, calendric lifetime determines the total lifetime and results in the larger replacement factor. For all components, the replacement factors are determined based on cycle life and calendar life information and the larger value is used as replacement factor for each component. As default, the mean value between the minimum and maximum replacement factor is used for the following calculations. The replacement factor is then multiplied with the environmental impacts of the different components, in order to include the additional impacts due to replacements into the calculation.

Table 3 shows the replacement factors used for the following calculations. All these values are the mean values between the replacement factors for the minimum and maximum lifetime. The detailed assumptions regarding the lifetimes of the components and the corresponding factors can be found in the SI.

In addition to the replacement of the components, the electricity consumption during the use phase needs to be accounted for i.e., the energy losses during charge-discharge and during the standby mode. For the time the system remains in standby mode, it is important to consider the state of charge of the batteries, as the required energy can either be covered by the stored solar power or by electricity from the grid, leading to different environmental impacts per kWh (Munzke et al., 2021). It is assumed that the HSS is in standby mode 68% of the time (approximately 6000 h per year), half of the time in a charged state and the other half discharged, not being able to cover the consumption with stored electricity (Munzke et al., 2017; Weniger et al., 2019). Therefore, the system uses electricity from the grid for 3000 h per year and stored solar power for another 3000 h in order to cover its own electricity consumption in standby mode. In order to determine the amount of energy consumed, Weniger et al. (2019) investigated the efficiency of 16 HSSs giving a range of values for the standby consumption of 5 W–42 W. As this is a large range, a mean value of 22.5 W between the two extremes of 5 W and 40 W are assumed for the standby consumption.

Regarding the losses during charge-discharge, the manufacturer datasheet of the assessed BESS mentions a maximum round-trip efficiency of 97.6%, a very high value. In contrast, Munzke et al. (2017) investigated nine different HSSs quantifying the amount of energy lost per cycle and found an average maximum round-trip efficiency of 81.5%

on system level, excluding standby demand and self-consumption. Considering that the value provided in the manufacturer datasheet is the 'maximum efficiency', and that such an efficiency would be already significantly above the average of existing LIB on cell level i.e., without accounting for all further system losses, the measured values are considered to be more meaningful for a BESS under real life operation conditions. In fact, the efficiencies reported by Munzke et al. (2017) represent values for different systems using 10 so called type days for PV following standard measurement procedures according to normative VDI 4655 (VDI-Gesellschaft Energie und Umwelt, 2021).The corresponding load profiles are varying with power demand strongly affecting the HSS total efficiency. High values of over 90% (with a maximum of 94%) are achieved only in case of optimum operation conditions with low power output below 40% of the net power output of the system (Munzke et al., 2021). An average value of 81.5% is therefore used for the total system efficiency, and the influence of varying charge-discharge efficiency further evaluated in the sensitivity analysis.

2.5. Recycling

End-of life processes are modelled following a product substitution approach, where materials recovered from recycling processes are assumed to avoid the use of the equivalent amount of materials from primary sources in the production phase (closed loop recycling; materials circulate within the product system). Hence, the environmental impacts of the avoided primary inputs are subtracted from the investigating system, generally leading to a reduction of the total environmental impacts due to recycling. However, the impacts resulting from the recycling processes themselves, such as the energy consumption, emissions or waste generation, are added to the investigated system and can also result in a net increase of impacts.

In the whole production process of secondary material only a part of the collected waste material can be reprocessed into useable material, while a certain amount is lost in the process (e.g., dissipated, retained in the slags or similar). The amount of recovered material per amount of scrap material fed into the recycling process is defined as the recycling rate, and the proportion lost in the process is its reciprocal value (1-recycling rate). This waste is mainly treated finally through municipal incineration.

In consequence, recycled material can never cover the total material demand, and primary material must be added in order to close the material life cycle. The share of primary material added is exactly the share that was lost in the recycling process (1-recycling rate). Table 4 provides the recycling rates assumed for the four main components of the periphery Steel, Aluminium, Iron and Copper and the two high-impact metals Silver and Tin together, obtained as average values from the corresponding literature sources.

Regarding the recycling of the battery cells, an advanced hydrometallurgical recycling process is assumed, based on the model published by Mohr et al. (2020). This represents the latest state of technology with advanced recycling processes recovering also graphite and electrolyte from the battery cells. The individual processes will not be further examined in this study as this is not the focus of this work. A detailed description including an LCA of the different processes can be found in Mohr et al. (2020) and Peters et al. (2021).

3. Results & discussion

3.1. Environmental impact per delivered kWh

3.1.1. Production phase

The environmental impacts of the HSS production phase (cradle-to-gate; per kWh of electricity delivered over lifetime) are provided in Fig. 4 for the three considered impact categories.

Under global warming (GWP) aspects, the best results are obtained by the NMC^{622}, closely followed by the NMC^{811} and the LFP system. The contribution of the peripheral components varies for the different cell chemistries, being their environmental impacts divided by different

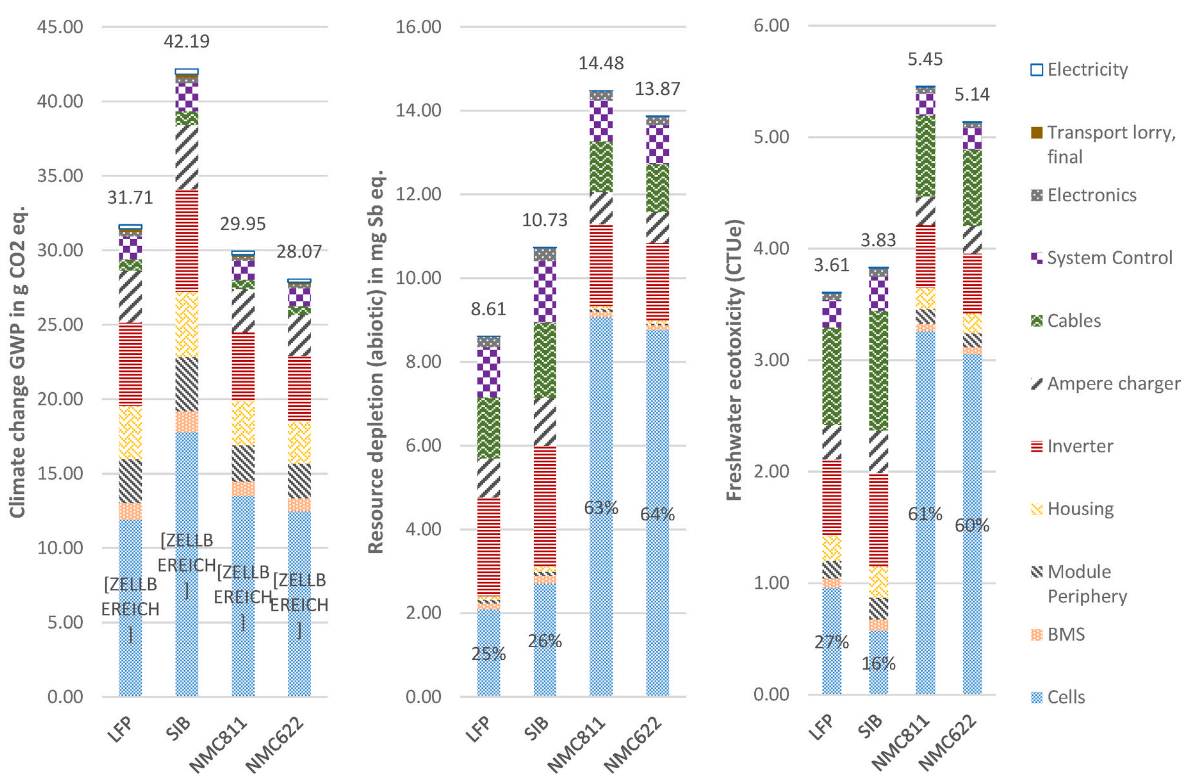

Fig. 4. Impact of production and resource extraction (cradle-to-gate) on climate change (GWP), mineral, fossil & renewable resource depletion (ResD) and Freshwater ecotoxicity (ETox). Values given per kWh of energy delivered over lifetime of the HSS (FU).

amounts of total electricity delivered over lifetime. In turn, the total electricity delivered over lifetime is determined by the total storage capacity of the HSS, since for all HSS the same total system lifetime of 20 years is assumed. Therefore, NMC^{622}, with the highest energy density cells, also has the highest storage capacity (see Table 2) and thus delivers the highest amount of total energy. This indicates a strong correlation between the energy density of the cell chemistry and the impact of the system on GWP.

The peripheral components are responsible for between 35.5% and 61.2% of the total impacts, with the main contributors being the production of the inverter, the system and module housings, and the ampere charger. Within these, the energy required in the production and upstream processes can be pinpointed as a key driver for GWP impacts. For the battery cells, with between 38 and 45% another important contributor, impacts are driven mainly by the energy demand required for cell manufacturing and the cathode active materials. A detailed break-down of the cell composition and the corresponding contribution of cell components to the total environmental impacts are provided in the underlying publication Mohr et al. (2020) and are therefore not discussed further.

For resource depletion (ResD), the NMC-based HSS shows by far the highest impact, mainly driven by the battery cells and the corresponding content of nickel and cobalt, but also the higher content of copper in the anodes (Mohr et al., 2020). LFP and SIB show significantly better results despite their lower energy density, relying on more abundant metals. The housing of the HSS, despite its high contributions to the global warming potential, has only a marginal impact on resource depletion, being majorly made of abundant material i.e., steel. However, the remaining peripheral components, especially the power electronics, cables and system control contribute between 36.7% and 76% of the total impact for the NMC^{622} and the LFP HSS, converting them into one of the key drivers of resource demand, mainly due to their content of copper, silver and tin.

ETox impacts show a very similar profile to ResD, indicating the importance of the materials and their mining also for toxic impacts associated with HSS production. Again, the main drivers are the use of copper (current collectors for the battery cells and electronic components) and other metals such as silver and tin (electronic components), and, in case of the two NMC type battery systems, the mining of cobalt and nickel required for the cathode active material.

3.1.2. *Use phase*

The use-phase impacts for the three considered impact categories are shown in Fig. 5.

In terms of GWP, all LIB systems show a similar picture for the use phase, with cell replacements and internal losses (charge-discharge losses and standby consumption) making up about half of the total impacts. Only the SIB system obtains significantly higher values. The main driver is the replacement, as the difference in impacts in the production phase between the systems is multiplied by the replacement factor, causing the difference due to energy density to be even more significant. It is worth mentioning that the replacement of cells is heavily dependent on the definition of the use phase, e. g. the equivalent full cycles that are assumed in a given business case. Under real world operation conditions, also other factors such as c-rates, temperature and state of charge of the battery can influence the replacement factors, though these are out of the scope of this work.

For ResD and ETox, the results are very similar to GWP, though with a higher share attributable to the charge-discharge losses (efficiency), while the standby consumption plays a minor role, attributable to the different sources of electricity assumed for both. Standby consumption is covered to a high share by grid electricity, with higher GWP but lower material intensity (ResD). Again, the SIB system shows a slightly higher environmental impact attributable to the replacement due to their lower energy density.

3.1.3. *End-of-life*

The environmental impacts of the HSS EOL phase (per kWh of electricity delivered over lifetime) are provided in Fig. 6 for the three considered impact categories.

For GWP, environmental benefits are obtained from recycling for all components of the HSS except the cables (with copper already containing a high share of secondary material and therefore low marginal benefits from recycling in combination with the high energy demand in the recycling process of copper). Except the LFP, all HSS show significant GWP benefits from recycling, saving between 8% and 16% of the original impact caused by the production of the system. The recycling of the battery modules, and within those of the battery cells, makes up the main share (>85%) of these benefits for the NMC and the SIB cells. For the LFP battery, only a marginal GWP benefit is obtained from recycling the housing of the system, giving a comparably low overall benefit in this category. This is due to the low recycling potentials of LFP batteries compared to NMC or NMMT-type SIB batteries (Mohr et al., 2020; Peters et al., 2021; Vandepaer et al., 2017). Electronic components, among the principal drivers of manufacturing impacts, also achieve only small benefits from recycling, being only the most valuable metals effectively recovered with current recycling technologies while major parts, including the printed circuit board itself, are typically being incinerated. Furthermore, the reprocessing of the materials requires a similar amount of energy as the production of the primary materials. Since the energy demand of the production process is the main driver in GWP, only minor effects can be observed in this impact category. Under ResD aspects, again the highest recycling benefit can be attributed to the battery cells. The best results are obtained for the NMC cells, as approximately 90% of the environmental impact of the production of the cells on ResD can be compensated by the recycling credits. The use of the rare metals cobalt and nickel plays the central role here. Despite the lower impact of the EOL phase of LFP and SIB modules compared to the NMC modules, in both cases a high share of the impact of the production phase of the modules can be equalized through recycling (95% for LFP and 53% for SIB). Regarding the peripheral components, again the benefit from their recycling is significantly lower than their manufacturing impacts, so that only a relatively share of their impacts can be mitigated by recycling.

The results for ETox are comparable to the results for ResD. All peripheral components show a negative environmental impact for the EOL phase reducing the overall impacts of the system. The modules again have alternating negative impacts with the best results for the NMC systems, followed by the LFP system and the SIB system.

Table 2
Main characteristics of the considered battery cell types and underlying literature source. a) Harlow et al. (2019); b) Preger et al. (2020); c) Liu et al. (2019) d) Peters et al. (2016) e) Mohr et al. (2020).

Cell type	Energy density in Wh/kg	Cycle lifetime	Calendar lifetime in years	Efficiency in %	Development stage	Storage Capacity of the HSS in kWh	Cell model
LFP[a]	140	2500-10,000	13–20	93	Mature	14.4	e)
SIB [c, d]	128[d]	2000–10,000	13–20	93	Under development	13.17	d)
NMC^{811} [a, b]	190	2000–6000	13–17	93	Introduction into market	19.54	e)
NMC^{622} [a, b]	200	2000–6000	13–17	93	Mature	20.57	e)

Table 3
Replacement factors for the lifetime of 20 years and 7300 cycles.

Component		LFP	SIB	NMC811	NMC622	Housing	Inverter	Ampere Charger	Cable	System Control	Electronics
Lifetime (years)	min	13	13	13	13	20	8	8	10	8	8
	max	20	20	17	17	20	15	15	20	15	15
Lifetime (cycles)	min	2500	2000	2000	2000	10000	5000	5000	10000	10000	10000
	max	10000	10000	6000	6000	10000	10000	10000	10000	10000	10000
Repl. Factor (cal.)	min	1.54	1.54	1.54	1.54	1.00	2.50	2.50	2.00	2.50	2.50
	max	1.00	1.00	1.18	1.18	1.00	1.33	1.33	1.00	1.33	1.33
Repl. Factor (cycl.)	min	2.92	3.65	3.65	3.65	0.73	1.46	1.46	0.73	0.73	0.73
	max	0.73	0.73	1.22	1.22	0.73	0.73	0.73	0.73	0.73	0.73
Replacement Real	min	2.92	3.65	3.65	3.65	1.00	2.50	2.50	2.00	2.50	2.50
	max	1.00	1.00	1.22	1.22	1.00	1.33	1.33	1.00	1.33	1.33
	avg	**1.96**	**2.33**	**2.43**	**2.43**	**1.00**	**1.92**	**1.92**	**1.50**	**1.92**	**1.92**

Source:(Eltamaly and Mohamed, 2018, energie-experten.org, 2016, Peters et al., 2017, SMA Solar Technology AG 2020)

Table 4
Recycling rates for the six key metals Steel, Aluminum, Iron, Copper, Silver and Tin (Kupferinstitut, European Commission, 2017, Garside, 2022, The Aluminium Association, 2013,Graedel et al., 2011).

Material	Worst Case	This work	Best Case
Steel (STL)	0.76	0.8	0.95
Aluminium (Al)	0.74	0.95	0.95
Iron (Fe)	0.39	0.8	0.95
Copper (Cu)	0.55	0.8	0.99
Other Metals (Tin (Sn), Silver (Ag)	0.55	0.8	0.99

3.2. Full life cycle

Combining the results for each stage of the life cycle according to the previous sections provides the net impacts of the HSS over its whole life cycle. The corresponding results are presented in Fig. 7.

The overall picture is similar in all three considered impact categories: under the given assumptions, the SIB system shows the highest environmental impacts over the entire life cycle, mainly due to the lower energy density of SIBs. The LFP system is close to the two NMC systems in all categories, but still with slightly higher total impacts. Lowest overall environmental impacts are obtained for the two NMC systems in all categories, with the NMC^{622} cell chemistry achieving even better results than NMC^{811}, mainly due to its slightly higher energy density.

The favourable results for the NMC systems can be attributed, apart from their high energy density, to their high recycling potential. Here, a major share of the copper, nickel and cobalt are recovered, which are major drivers of production impacts. Recovering these at the EOL correspondingly leads to high recycling benefits and a good overall performance. In consequence, disregarding the last phase of the life cycle would change the results in favour of LFP systems. Furthermore, the use phase turns out to be highly relevant, accounting for the largest share of environmental impacts in most of the cases. This is driven mainly by the replacement of battery cells during the lifetime of the HSS, and less due to internal losses or standby consumption. To illustrate this, a distinction is made in the following diagram between the environmental impacts of the replacement and those of the use phase. As can also be seen in the following sensitivity analysis, the results vary most due to the adjustment of the assumptions of use. A change in cycles per day is shown by the error bars. The lower bound shows a load profile of 2 cycles per day and the upper bound 0.5 cycles. The significant differences are again due to the increasing replacement rates.

3.3. Sensitivity analysis

A sensitivity analysis is carried out to analyse the impact of key parameter variation on the results. More specifically, the sensitivity of

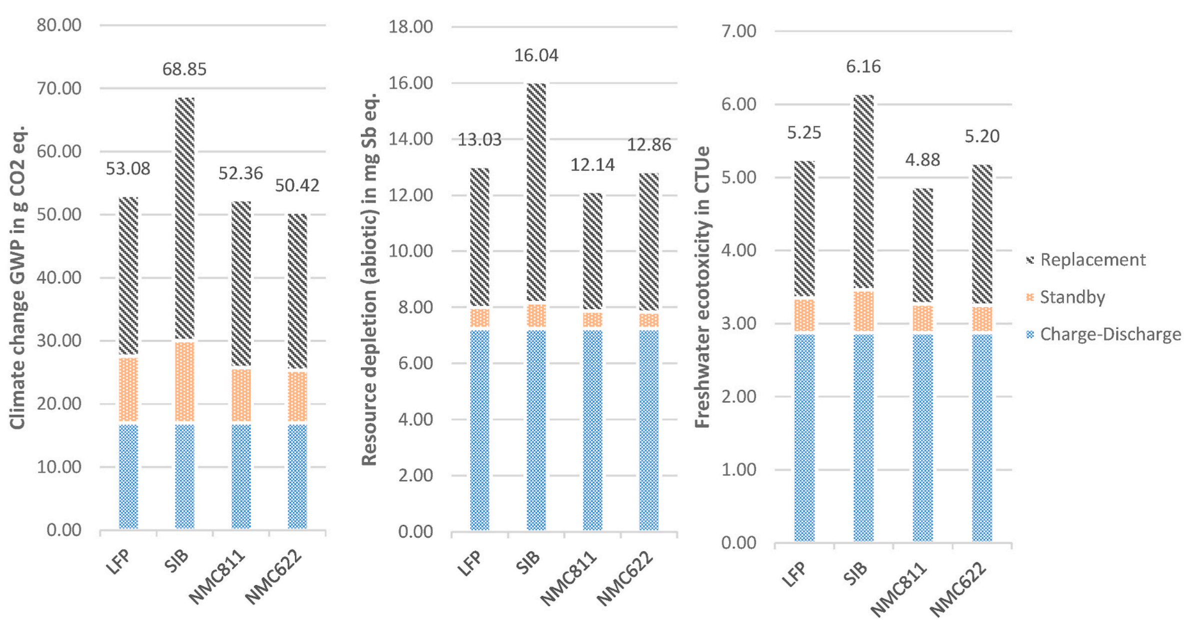

Fig. 5. Impact of the use phase on climate change (GWP), mineral, fossil & renewable resource depletion (ResD) and Freshwater ecotoxicity (ETox). Values given per kWh of energy delivered over lifetime of the HSS (FU).

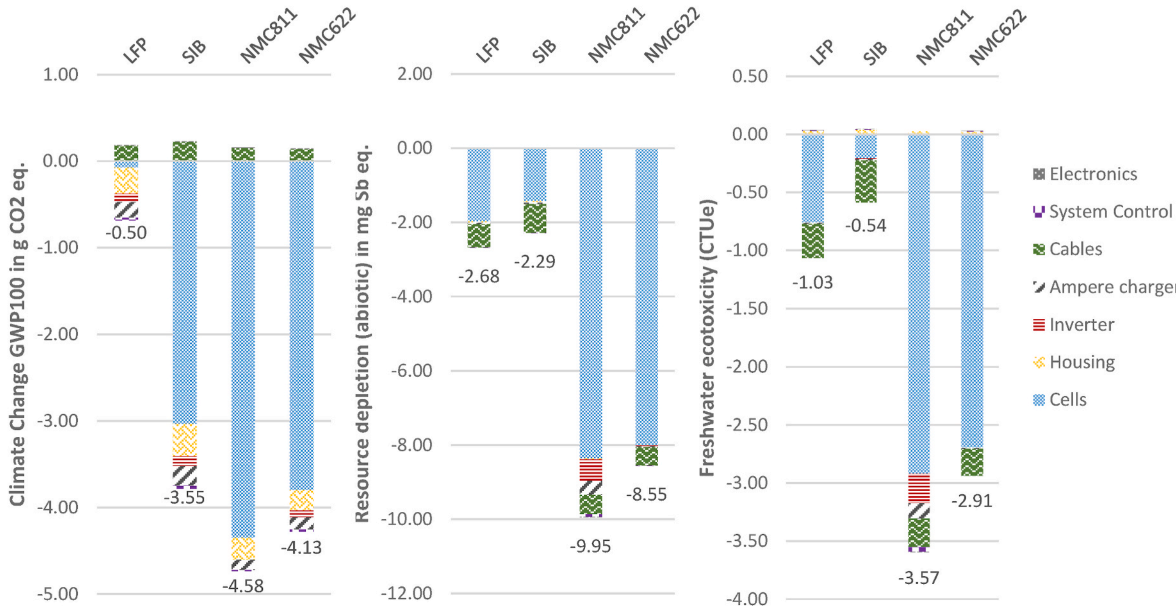

Fig. 6. Impact of the EOL phase on climate change (GWP), mineral, fossil & renewable resource depletion (ResD) and Freshwater ecotoxicity (ETox). Values given per kWh of energy delivered over lifetime of the HSS (FU).

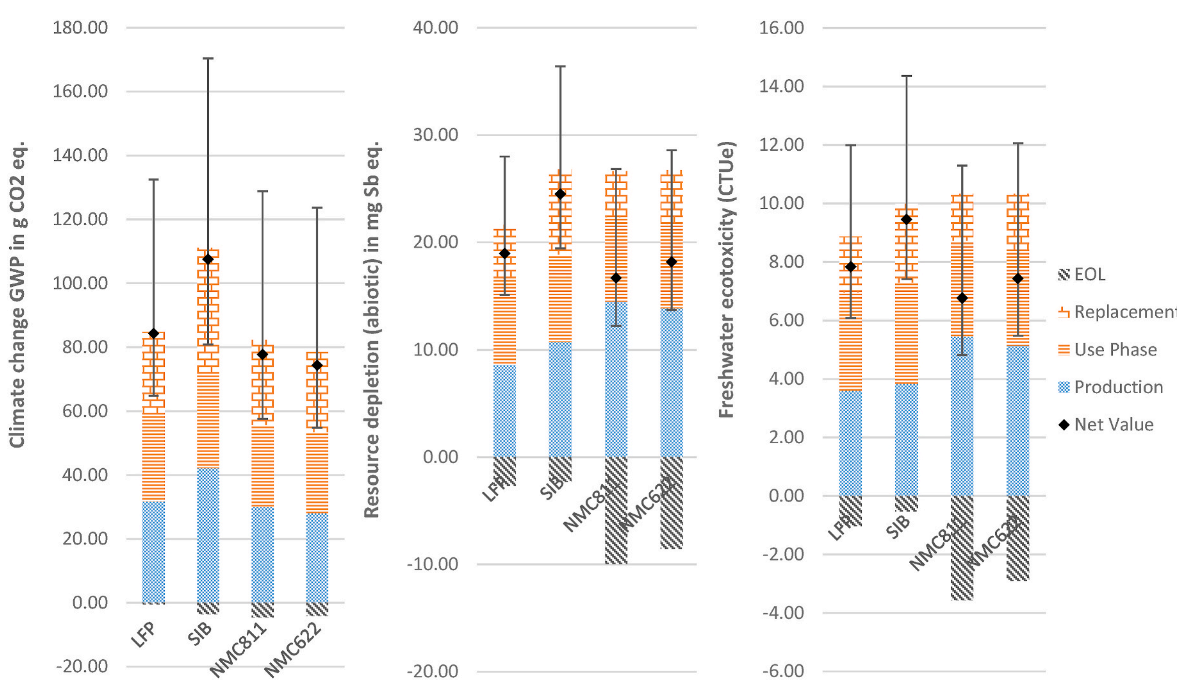

Fig. 7. Impacts of the full life cycle of an HSS on climate change (GWP), mineral, fossil & renewable resource depletion (ResD) and Freshwater ecotoxicity (ETox). Values given per kWh of energy delivered over lifetime of the HSS (FU). The dot marks the net result corresponding to the numeric value provided above each column, and the error bars indicate the range of possible results when varying the number of cycles per day (2 cycles for lower bound and 0.5 cycles for upper bound).

the outcomes on the variation of the following parameters is assessed: [A] Number of cycles per day (0.5 and 2 full cycle equivalents instead of 1 per day), [B] energy density (varied by ± 10 percent), [C] standby electricity consumption (5 W and 40 W instead of 22.5 W), [D] charge-discharge round-trip efficiency of the system (varied by 78.5% (Munzke et al., 2017) and 97.5% (manufacturer data)), [E] lifetime in years and cycles of all components (varied by ± 10%), [F] recycling rates best and worst case scenario, (see SI). For the sake of compactness, only the results for GWP are presented (Fig. 8). The results for the other two impact categories (freshwater ecotoxicity and resource depletion) are provided in the SI.

While the number of daily cycles has a high impact on the overall results, the impact of varying energy density is marginal and has only an impact in the magnitude of around 8% on final GWP results. This comes also true for the other considered impact categories.

4. Discussion

4.1. Comparison with other studies

The comparison of the obtained results with those from previous studies is challenging due to the differences in scope, system boundaries,

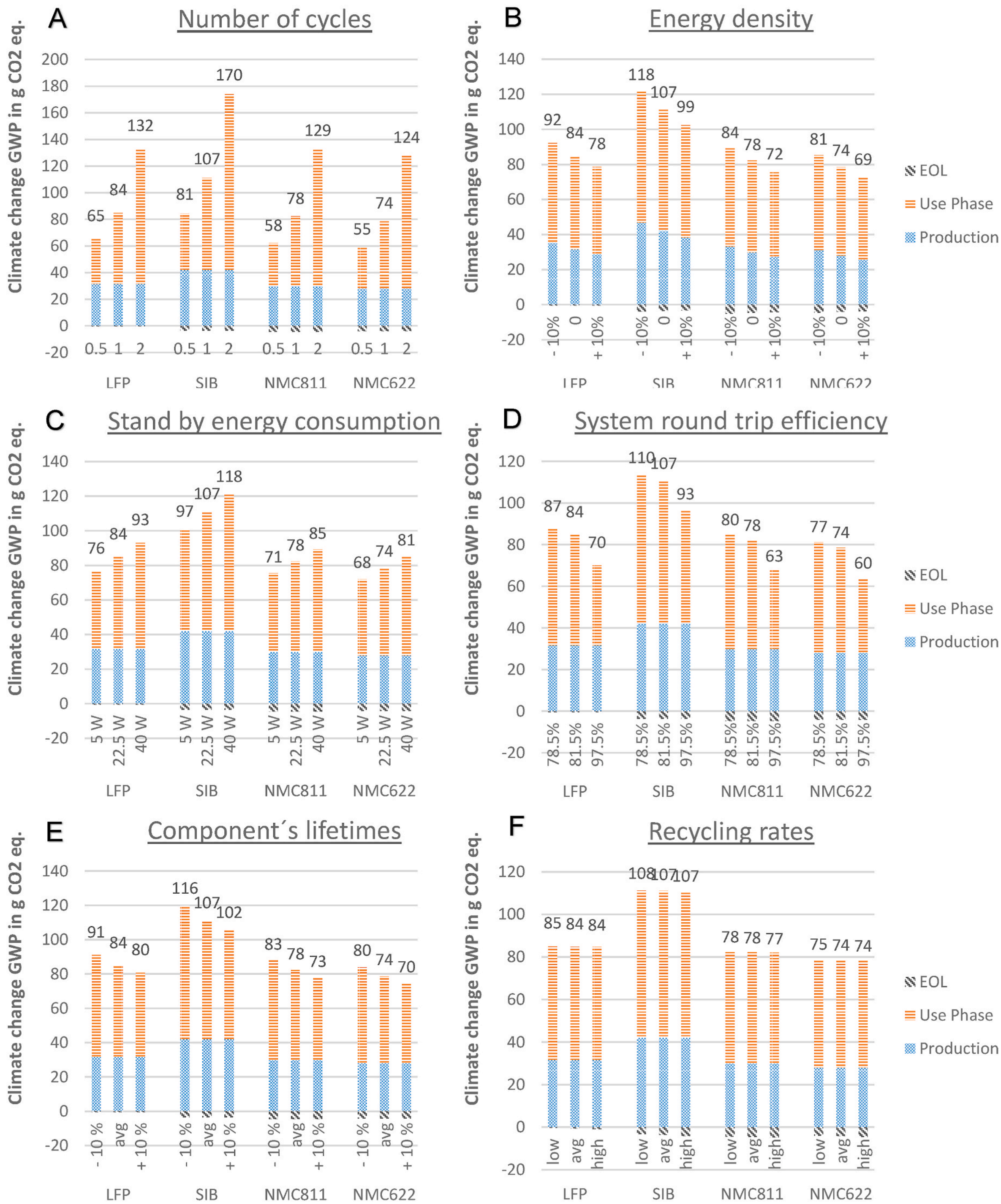

Fig. 8. Sensitivity Analysis: Impacts of the full life cycle of an HSS on climate change (GWP), with varying key parameters: [A] Number of cycles per day, [B] energy density, [C] standby electricity consumption, [D] charge-discharge round-trip efficiency of the system, [E] lifetime in years and cycles of all components, [F] recycling rates best and worst case scenario. Values given per kWh of energy delivered over lifetime of the HSS (FU).

system sizes and applications (Temporelli et al., 2020). Therefore, only the GWP results per kWh of electricity delivered by the HSS are presented in Fig. 9, limited to those works that have comparable scope i.e., for increase of PV self-consumption using a cradle-to-gate approach (considering only production and use phase). The results of all studies are of a similar magnitude, with a decreasing trend over time. Similar can be observed for studies on vehicle batteries, where improvements in modelling, data quality but also progress in manufacturing and economy of scale effects cause a trend towards decreasing GWP (Emilsson and Dahllöf, 2019; Porzio and Scown, 2021) For the study by Carvalho et al. (2021) it has to be noted that the charging electricity is not only PV, but a mix of wind and PV electricity, resulting in a slightly lower impact from the use-phase compared to the other works that assume exclusively PV electricity. It was included nevertheless, being the impact on the total results comparably small.

Regarding the peripheral components, especially within the focus of this work, the literature review in Section 1.2 showed that the majority of BESS assessments do include the peripheral components, though majorly based on data for automotive applications. In the following, the findings from this work using 'real' inventory data from the disassembly

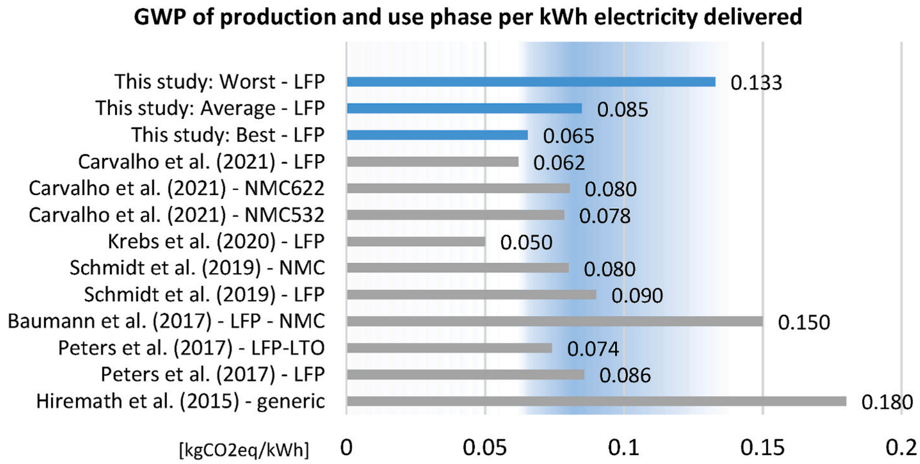

Fig. 9. Comparison of GWP of production and use phase per one kWh electricity delivered for Li-Ion HSS (*Averaged over both assessed NMC-HSS). *excluding the impacts for PV-Panel production.

of an existing HSS are compared with the findings of previous studies.

In terms of mass balance, the BMS constitutes 2.5% of a single battery module, or 1.4% of the whole system, equivalent to 0.2867 kg/kWh. This is a value in between those found in the reviewed publications, where values of 3.7%/0.352 kg/kWh (Ellingsen et al., 2014), 2% (Hiremath et al., 2015) and 1.1% (Ryan et al., 2018) can be found, or 0.3805 kg BMS/kWh (Schmidt et al., 2019). The corresponding environmental impacts make up around 34% of the total for GWP (manufacturing impacts only i.e., cradle-to-gate), significantly lower than the 11–13% found by Hiremath et al. (2015), but comparable to the ~4% indicated by Ellingsen et al. (2014). Other works do not explicitly provide impacts for individual peripheral components. Vandepaer et al. (2018) state that the BMS is an important driver of resource depletion impacts, with the contribution of the BMS being particularly high in the ADP category, and Ellingsen et al. (2014) find a contribution of the BMS of ~10% to the total ADP, though with another impact assessment methodology (what might have a significant impact on the results (Peters and Weil, 2016). However, the comparability between studies is limited since the definition of the BMS also varies i.e., using BMS as aggregate for all control logic and electronic components (Ellingsen et al., 2014).

The power electronics (electronics, inverter and ampere charger), making up 11% of the total mass of the HSS, contribute 30% to the total GWP impacts obtained for the assessed HSS (in the reference LFP configuration). This is in line with the 25–46% obtained by Le Varlet et al. (2020), the only available study on HSS where values specific for the power electronics are provided. However, Stenzel et al. (2016) state that apart from the cells, the inverter and electronics affect the impacts in the ResD category due to their content of specific metals, but do not provide values. Similar is found in this study, where the power electronics have a share of 41% in the ResD category for the production of the LFP-HSS. Regarding the modelling approach for the power electronics, many existing studies use the ecoinvent 500 kW inverter (Baumann et al., 2017; Peters and Weil, 2017; Schmidt et al., 2019) (see also Table 1). A comparison of this unit with the disassembled inverter of the HSS showed that the impacts of the ecoinvent inverter are 57% lower for GWP and 51% lower for ResD than those of the measured inverter (not considering the EOL). Therefore, the impacts of the power electronics might be underestimated in the studies, that considered this ecoinvent inverter.

Without distinguishing the different peripheral components, Schmidt et al. (2019) find the contribution of all peripheral components including all hardware, software and services to the total GWP of the HSS to be around 20%. This is comparable to the results obtained in this work, although not exactly the same components were included in the calculation.

4.2. Relevance of use and EOL phase

The results show that there is a considerable impact stemming from the standby and use-phase, often disregarded or insufficiently modelled (Baumann et al., 2017). Often, only the efficiencies of inverter and battery cells are considered, disregarding other aspects like consumption of electronics and standby demand. Similar, datasheet values about efficiencies of HSS are often very optimistic, providing values of far over 90%. This might be true for specific cases (like low power drain, no standby) but not necessarily represents reality, where very different values can be found depending on the analysed system, but also the application (Weniger et al., 2019). The efficiency of ~82% used in this work is based on measurements of existing HSS (though not of the specific model assessed) is considered to be a more realistic value (Munzke et al., 2021; Weniger et al., 2019). However, the impact of this parameter on the results is high and more and better data will be needed for reducing the corresponding uncertainty. A good formalisation of a suitable approach can be the use of a system performance index as presented in Weniger et al. (2019). This is relevant for HSS, but might be even more for larger ESS, where additional refrigeration is required, control rooms and other periphery that need to be included in the balance. Also, the assumed number of standby hours (6000) depends on the actual use profile of the specific application and can vary significantly. Here, the definition of representative standard use cases or -applications could help to increase the comparability of future studies, including also use real life data for use phase (Le Varlet et al., 2020).

Second, also the cycle life of the HSS plays an important role for its total environmental performance. The SIB system has a low technological maturity. Here, new developments in cycle life time, efficiency as well as energy density can lead to a higher competitiveness.

Regarding the EOL phase, a reduction of the total GWP impacts from recycling of between 2% and 15% is obtained, with the lowest benefits for LFP. This is due to the low recycling potentials of LFP batteries compared to the other cell chemistries as well as the high energy demand of the recycling processes (c.f. 2.5 Recycling). Under ResD and ETox aspects the results depend strongly on the cell chemistry, with reductions of 69% (ResD) and 65% (ETox) for the NMC^{811} and NMC^{622} batteries, but a very limited benefit for the LFP and SIB. Also, the peripheral components obtain, despite their comparably high contribution to manufacturing impacts, low benefits from recycling. Their shorter lifetime adds impacts from replacement, making these components one of the keys for further improving the total environmental performance of HSS.

4.3. Limitations and future work

The comparison with previous works has shown that the results can vary within a very high magnitude. This work advances the quality of HSS assessments by contributing detailed original inventory data from an existing HSS. Still, there are some limitations that need to be taken into account when interpreting the results and comparing these with other studies.

While the composition and mass balances of the assessed HSS is provided with a high level of detail, this is not the case for other important parameters. Cycle life, efficiency and standby consumption, responsible for a major share of environmental impacts, are taken from other studies and do not necessarily correspond to the assessed system. Although efficiency values are given by the manufacturer, these seem to be very high and probably represent rather an ideal case of optimal operation conditions (e.g., very low power drain) than the values achieved in real life. Here, defining some standard applications with a representative (battery) load profile would allow to obtain realistic values for efficiency and standby consumption that are readily comparable between systems. More data on daily load and generation profiles for HSS would contribute to generating such standard cases. Also, other HSS might have completely different layouts and material demands (BYD Europe. 2019, Tesla, 2018), and the results of this work are not necessarily representative for these systems. Depending on the system designs (e.g., AC or DC coupled, integrated or external inverter, etc.) the environmental impacts, but also their key drivers might vary significantly.

Also, while the results for the LFP cells do correspond to an existing system, this is not the case for the remaining cell chemistries. Here, the battery cells are simply assumed to be replaced by similar cells with another chemistry, assuming that the number of battery modules might increase due to lower energy density, but that all remaining components of the HSS remain the same. This might not reflect reality, with other cell chemistries possibly requiring other layouts or different control and management components. Although probably not decisive, these additional uncertainties need to be taken into account when comparing results between the different systems. Also, it has to be highlighted, that SiBs can have very different electrode chemistries which might results in different impacts (Peters et al., 2021). The results indicated here are therefore representative only for the assessed NMMT-type cell chemistry of this type of emerging battery.

The EOL modelling further adds uncertainty, the recycling process assumed for this work a generic process designed for NMC battery cells. The inputs when processing other cell types might vary significantly, and thus the impacts associated with the process. These aspects are not covered by the recycling process model; more detailed, cell-specific data would be required for reducing uncertainty. Also, the present assessment assumes closed-loop recycling. While it does account for the need for re-processing recovered secondary material and the corresponding process inputs, it does not consider quality aspects such as purity, which might be decisive for a re-use of secondary materials in a circular way.

From a methodological perspective, future works should also consider as cut-off or consequential LCA system models beside APOS, which has been selected here. Beside that other LCIA methods as e.g. Environmental footprint methods should be considered to provide a broader perspective on potential impacts (European Commission, 2021).

5. Conclusion

This work provides in-depth assessment of a battery home storage system (HSS) following a full life-cycle approach. Mass balances and the corresponding inventory data for all components are obtained from the complete disassembly of a commercial HSS, thus providing new insights into the actual drivers of environmental impacts of such HSS and contributing to improve the quality of existing inventory data.

The total GWP of the HSS is found to be 84 g CO_2eq/KWh of electricity delivered by the HSS over its lifetime in a residential PV application, or 31 g CO_2eq/KWh delivered over lifetime when excluding the use-phase impacts. Correspondingly, the use-phase is at least as important for the total environmental impacts of an HSS as the manufacturing, though often disregarded of insufficiently modelled. A high sensitivity on the actual efficiency of the HSS is given, in combination with a high discrepancy between the values provided by the HSS manufacturer in the datasheet (97%) and real-life field measurements that obtained average values of 82%, though not for the same system. This is one of the principal sources of uncertainty, and standardised load profiles for determining typical efficiencies for HSS in representative standard applications could help to reduce uncertainties significantly and to increase comparability of systems. The proposal for an update of the European Battery Regulation (European Commission, 2020) might be a good opportunity to include such a standard profile and the requirement to disclose the corresponding performance parameters, enabling better comparability also for end-users.

Similarly, the cycle lifetime of the HSS (or its components, respectively) is a major determinant for their net impacts. Short lifetimes lead to more frequent replacements of components and correspondingly increased impacts. While commercial HSS usually provide information about cycle lives, efficiency and energy density in the manufacturer datasheet, this information is not available for emerging cell chemistries like the sodium-ion batteries (SIB) considered in this work. Here, the assumption of a cycle life of 2000 cycles in combination with a rather low energy density (due to the still lower technological maturity) drives up total impacts. Reaching competitive cycle stability, efficiency and energy density is therefore one of the keys for emerging cell chemistries for becoming competitive with existing LIB in terms of environmental impacts. It is worth mentioning that also the cycles strongly depend on the PV size, location and amount and type of daily load (e.g., family with kids, company etc.), but also the battery size in relation to the PV installation.

Third, the electronic components, especially inverter, ampere charger, control electronics and cables, contribute a major share to the total manufacturing impacts in all three assessed categories (global warming, resource depletion and ecotoxicity). In combination with their poor recyclability, they are responsible for 32 up to 50% of the net impacts (manufacturing impacts minus recycling benefits) of the HSS in all three categories, while at the same time usually modelled only in a very simplified way and based mainly on standard inventory data. In contrast, the results of this work are based on a piece-by-piece dismantling of an existing HSS and show a very high level of detail. Still, they represent one single system with a specific system design and are not necessarily representative for a generic HSS. Impacts from other e.g., DC-coupled systems do not require an own inverter on HSS side and might therefore show a better environmental performance than the AC coupled system assessed in frame of this research. Here, more first-hand data is clearly needed to reduce uncertainties further and to obtain a better picture of the variability between systems.

CRediT authorship contribution statement

Friedrich B. Jasper: Investigation, Formal analysis, Methodology, Conceptualization, Validation, Writing – original draft, Visualization. **Jana Späthe:** Methodology, Investigation, Formal analysis, Writing – original draft. **Manuel Baumann:** Conceptualization, Supervision, Writing – review & editing, Project administration. **Jens F. Peters:** Conceptualization, Supervision, Validation, Writing – review & editing. **Janna Ruhland:** Writing – review & editing, Resources. **Marcel Weil:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132899.

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