



Comparative sustainability assessment of lithium-ion, lithium-sulfur, and all-solid-state traction batteries

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Abstract

Purpose Traction batteries are a key component for the performance and cost of electric vehicles. While they enable emission-free driving, their supply chains are associated with environmental and socio-economic impacts. Hence, the advancement of batteries increasingly focuses on sustainability next to technical performance. However, due to different system definitions, comparing the results of sustainability assessments is difficult. Therefore, a sustainability assessment of different batteries on a common basis considering the three sustainability dimensions is needed.

Methods This paper investigates the sustainability of current and prospective traction battery technologies for electric vehicles. It provides a common base for the comparison of the predominant lithium-ion batteries with new technologies such as lithium-sulfur and all-solid-state batteries regarding the environmental and socio-economic impacts in their supply chain. A life cycle sustainability assessment of ten battery types is carried out using a cradle-to-gate perspective and consistent system boundaries. Four environmental impact categories (climate change, human toxicity, mineral resource depletion, photochemical oxidant formation), one economic performance indicator (total battery cost), and three social risk categories (child labor, corruption, forced labor) are analyzed.

Results The assessment results indicate that the new battery technologies are not only favorable in terms of technical performance but also have the potential to reduce environmental impacts, costs, and social risks. This holds particularly for the lithium-sulfur battery with solid electrolyte. The environmental benefits are even amplified with a higher share of renewable energy for component and battery production. Nevertheless, hotspots related to the high energy demand of production and the supply chain of the active materials remain.

Conclusions This article emphasizes the need to evaluate different battery technologies on a common basis to ensure comparability of the results and to derive reliable recommendations. The results indicate that the lithium-sulfur battery with solid electrolyte is preferable since this battery has the best indicator scores for all impact categories investigated. However, all-solid-state batteries are still under development so that no conclusive recommendation can be made, but further development of these battery technologies appears promising.

Keywords Comparative sustainability assessment · Lithium-ion battery · Lithium-sulfur battery · All-solid-state battery · Cradle-to-gate · Life cycle assessment · Life cycle costing · Social life cycle assessment

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1 Introduction

The emission of greenhouse gases (GHG) from the combustion of fossil fuels is an important driver of global warming. Especially in the transportation sector, which contributed with 23% to global GHG emissions in 2018 (IEA 2020), considerable reductions of GHG emissions need to be achieved to curb the global temperature rise. In this context, vehicle electrification is a promising strategy. Traction batteries in battery electric vehicles (BEVs) can store and release energy without direct GHG emissions. However, battery production,

including the extraction and processing of raw materials, is associated with large amounts of GHG emissions (Chordia et al. 2021; Emilsson and Dahllöf 2019). This could lead to burden-shifting to upstream life cycle phases and consequently counteract the potential advantages of BEVs.

Besides GHG emissions, several other harmful emissions need to be considered to avoid burden-shifting across environmental impact categories. For example, the emission of nitrogen oxides is responsible for the formation of photochemical oxidants that cause damage to human and animal respiratory organs and plants (Goedkoop et al. 2013). Moreover, it is important to consider the socio-economic aspects of batteries. For instance, the competitiveness of BEVs over conventional vehicles with internal combustion engines is influenced considerably by the cost of the batteries. In addition to that, politicians and consumers demand socially responsible and transparent battery supply chains to prevent child labor and forced labor as well as to preserve further human rights.

Next to the sustainability aspects, the technological properties of batteries can have a major impact on the design of supply chains. As currently used lithium-ion batteries (LIBs) have reached a mature stage of development, prospective battery technologies such as lithium-sulfur batteries (LSBs) and all-solid-state batteries (ASSBs) are being intensively researched because it is predicted that these battery technologies can provide higher specific energies, higher safety, and lower cost (Duffner et al. 2021b).

Consequently, the sustainability and technological aspects must be considered when designing sustainable battery supply chains. However, current research usually focuses on one sustainability dimension only (see Sect. 2.2). Hence, possible trade-offs between the three sustainability dimensions are not identified, and recommendations might be derived that benefit one dimension but strain other dimensions. Furthermore, comparing scientific articles is difficult because the studies differ in assumptions (e.g., regarding the applications or system boundaries), underlying databases, and impact assessment methods, resulting in a lack of transparency. Thus, a common and transparent basis is required to assess batteries regarding all three sustainability dimensions to guarantee a holistic comparison of different battery technologies and to derive recommendations for battery development.

This study seeks to carry out a comparative sustainability assessment of current and prospective battery technologies in the context of electromobility based on consistent and comparable system boundaries, assumptions, and impact assessment methods. To this end, life cycle inventories (LCIs) for the production of ten batteries are created, considering the three dimensions in a life cycle sustainability assessment (LCSA)-oriented approach to identify hotspots and improvement potentials.

The remainder of this article is structured as follows: Sect. 2 describes the state of research on current and prospective batteries and provides a literature review on sustainability assessment studies of batteries. The assessment method and the study's setup are described in Sect. 3. Sec. 4 presents the assessment results, and Sect. 5 discusses them. Conclusions are provided in Sect. 6.

2 State of research

2.1 Characterization of current and prospective battery technologies

The most commonly used battery technologies for BEVs are LIBs (Dunn et al. 2021; Melin 2020). Over the past decade, various types of LIBs with different active materials have been deployed in BEVs. The prevalent positive active materials were lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA), whereas the formerly widespread lithium iron phosphate (LFP), lithium manganese oxide (LMO), and lithium cobalt oxide (LCO) only played a minor role (Dunn et al. 2021). This relies on the advantageous properties (e.g., specific energy, energy density, safety, lifetime, power, and costs) of NMC and NCA (Andre et al. 2015). Nevertheless, it is predicted that the market share of LFP will increase due to technological improvements (Dunn et al. 2021).

Since the aforementioned LIB types have already reached a high level of maturity, substantial further improvements regarding specific energy or energy density are not expected (Duffner et al. 2021b; Placke et al. 2017). This is contrary to the ambition of using lightweight and small traction batteries that enable long ranges over a long lifetime at moderate costs. Additionally, LIBs are associated with safety issues due to the limited operating temperature range and materials used. For example, a typical liquid electrolyte consists of flammable and volatile materials that react with water and oxygen (Zubi et al. 2018). Therefore, new battery technologies that enable a higher specific energy and energy density, as well as cause fewer safety issues, are required. Two promising technologies are LSBs and ASSBs (Duffner et al. 2021b; Placke et al. 2017).

Figure 1 depicts the main differences between LIBs, LSBs, and ASSBs. LSBs use sulfur instead of metal oxides as positive active material and lithium metal instead of graphite as negative active material. The properties of lithium and sulfur enable a higher theoretical specific energy. Furthermore, safety issues are improved due to a higher operating temperature range (Fotouhi et al. 2017; Manthiram et al. 2017; Zhang et al. 2018). However, the practical energy density is restricted due to the composition of the cathode and the lower nominal voltage of LSB

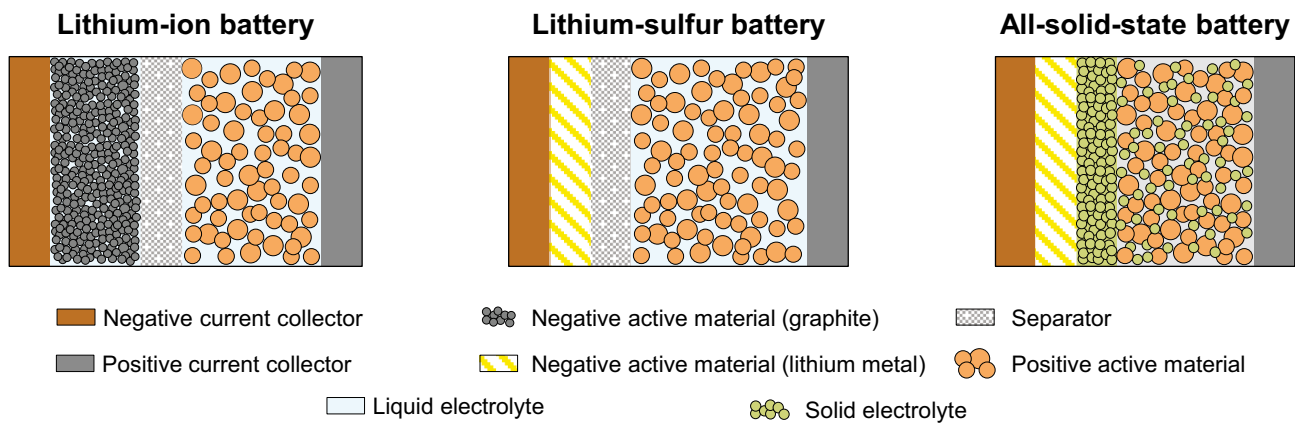


Fig. 1 Schematic structure of LIBs, LSBs, and ASSBs (adapted from Duffner et al. 2021a, b; Janek and Zeier 2016)

cells compared to LIB cells (Cleaver et al. 2018; Fotouhi et al. 2017; Liu et al. 2020; Zhang 2013). Furthermore, the so-called shuttle effect limits the lifetime of LSBs (Cleaver et al. 2018; Fotouhi et al. 2017; Zhang 2013). Both aspects are in conflict with the goal of using small batteries in BEVs over a long lifetime.

The distinctive feature of ASSBs is the solid electrolyte, which also acts as separator. This enables the use of lithium metal as negative active material while using the same positive active materials as in LIBs and LSBs. Furthermore, the solid electrolyte is added to the positive active material to increase conductivity (Duffner et al. 2021b; Randau et al. 2020). Using solid electrolytes can increase the specific energy and energy density and prevent the shuttle effect of LSBs. ASSBs require fewer components and materials to manufacture the battery pack since no additional separator and cooling system are needed. In addition, the solid electrolyte can enhance the safety of the batteries (Gao et al. 2018; Janek and Zeier 2016; Manthiram et al. 2017; Randau et al. 2020).

However, ASSBs are also associated with challenges that must be resolved before commercialization. New production processes and a dry room environment are required because the materials used are susceptible to moisture, making up scaling challenging (Schnell et al. 2018, 2019).

2.2 Sustainability assessment of batteries

The different characteristics and compositions of the battery technologies influence the environmental, economic, and social impacts (Aichberger and Jungmeier 2020; Barke et al. 2021; Duffner et al. 2020). A common approach to quantify these impacts is LCSA, which comprises individual assessment methods for each sustainability dimension, namely life cycle assessment, environmental life cycle costing, and social life cycle assessment (Finkbeiner et al. 2010;

Kloepffer 2008; UNEP/SETAC 2011). Since the LCSA approach is used in this study to assess the three dimensions of traction batteries, the following literature review examines studies that use LCSA methods. Table 1 provides an overview of selected peer-reviewed studies dealing with the environmental and socio-economic impacts of traction batteries. Their contribution to the scientific literature is classified according to three criteria: sustainability dimension, life cycle scope, and investigated battery technology.

Most of the analyzed studies focus on one of the three sustainability dimensions, primarily environmental or economic. Only one study focuses exclusively on the social dimension, and seven studies consider two or more sustainability dimensions simultaneously.

The life cycle phases found within the scope of the analyzed studies comprise raw material extraction, battery production, use phase, and end-of-life. All investigated studies consider the first two phases. However, most studies focus on battery production while the raw material extraction is modeled with background data (e.g., from the ecoinvent database). The remaining phases are assessed only by few authors, and generic data is often used instead of a detailed assessment.

Finally, the right-hand part of Table 1 shows which battery technologies were assessed. Note that LIB-NMC includes all possible compositions of NMC, such as NMC111, NMC622, or NMC811, where the numbers describe the proportion of the active material components. The column *other* includes batteries usually not used in BEVs, such as nickel–cadmium batteries. LIB-NMC is the most often analyzed technology, often accompanied by another battery technology for comparison. For example, Deng et al. (2017) focus on the environmental assessment of LSBs, but they compare their results to a LIB-NMC111.

Only a few studies assess a wide range of battery technologies on a common basis. For instance, Peters and Weil

Table 1 Overview and classification of selected sustainability assessment studies for traction batteries

Study	Dimensions			Scope				Technology						
	Environmental	Economic	Social	Materials	Production	Use	End-of-life	LIB-LMO	LIB-NCA	LIB-LFP	LIB-NMC	LSB	ASSB	Other
Notter et al. (2010)	●	○	○	●	●	●	●	●	○	○	○	○	○	○
Zackrisson et al. (2010)	●	○	○	●	●	●	○	○	○	●	○	○	○	○
Majeau-Bettez et al. (2011)	●	○	○	●	●	●	○	○	○	●	●	○	○	●
Dunn et al. (2012)	●	○	○	●	●	○	●	●	○	○	○	○	○	○
Ellingsen et al. (2014)	●	○	○	●	●	○	○	○	○	○	●	○	○	○
Faria et al. (2014)	●	○	○	●	●	●	●	●	○	○	○	○	○	○
Li et al. (2014)	●	○	○	●	●	●	●	○	○	○	●	○	○	○
Patry et al. (2015)	○	●	○	●	●	○	○	●	●	●	●	○	○	○
Sakti et al. (2015)	○	●	○	●	●	○	○	○	○	○	●	○	○	○
Berg et al. (2015)	○	●	○	●	●	○	○	●	●	●	●	●	○	●
Dunn et al. (2015)	●	○	○	●	●	●	●	●	○	●	●	○	○	●
Hendrickson et al. (2015)	●	●	○	●	●	○	●	●	○	●	●	○	○	○
Lastoskie and Dai (2015)	●	○	○	●	●	●	○	●	○	○	●	○	●	●
Nelson et al. (2015)	○	●	○	●	●	○	○	●	○	○	●	○	○	○
Wood et al. (2015)	○	●	○	●	●	○	○	○	○	○	●	○	○	○
Ambrose and Kendall (2016)	●	○	○	●	●	●	○	●	●	●	●	○	○	●
Kim et al. (2016)	●	○	○	●	●	○	○	○	○	○	○	○	○	●
Reuter (2016)	●	●	●	●	●	●	●	○	○	●	●	○	○	○
Troy et al. (2016)	●	○	○	●	●	○	○	○	○	○	○	○	●	○
Berckmans et al. (2017)	○	●	○	●	●	○	○	○	○	○	●	○	○	○
Deng et al. (2017)	●	○	○	●	●	●	●	○	○	○	●	●	○	○
Hao et al. (2017)	●	○	○	●	●	○	○	●	○	●	●	○	○	○
Arvidsson et al. (2018)	●	○	○	●	●	○	○	○	○	○	○	●	○	○
Cerdas et al. (2018)	●	○	○	●	●	●	●	○	○	○	●	●	○	○
Keshavarzmohammadian et al. (2018)	●	○	○	●	●	○	○	○	○	○	○	○	●	○
Peters and Weil (2018)	●	○	○	●	●	○	○	●	●	●	●	○	○	●
Schmuck et al. (2018)	○	●	○	●	●	○	○	○	●	○	●	○	●	●
Berg and Zackrisson (2019)	●	●	○	●	●	●	●	○	○	●	●	○	○	○
Dai et al. (2019)	●	○	○	●	●	○	○	○	○	○	●	○	○	○
Philippot et al. (2019)	●	●	○	●	●	○	○	○	●	○	○	○	○	○
Thies et al. (2019)	○	○	●	●	●	○	○	○	○	○	●	○	○	○
Wentker et al. (2019)	○	●	○	●	●	○	○	●	●	●	●	○	○	●
Zhao and You (2019)	●	○	○	●	●	●	●	●	○	○	●	○	○	○
Kallitsis et al. (2020)	●	○	○	●	●	○	○	○	○	○	●	○	○	○
Schnell et al. (2020)	○	●	○	●	●	○	○	○	○	○	●	○	●	○
Smith et al. (2020)	●	○	○	●	●	○	○	○	○	●	○	○	●	○
Sun et al. (2020)	●	○	○	●	●	○	●	○	○	○	●	○	○	○
Barke et al. (2021)	●	●	●	●	●	○	○	○	●	●	●	●	○	○
Chordia et al. (2021)	●	○	○	●	●	○	○	○	○	○	●	○	○	○
Duffner et al. (2021a)	○	●	○	●	●	○	○	○	○	○	●	○	○	○
Lopez et al. (2021)	●	○	○	●	●	○	○	●	○	○	○	●	○	●
Thies et al. (2021)	●	●	●	●	●	○	○	○	○	○	●	○	○	○
Wang and Yu (2021)	●	●	○	●	●	○	●	○	○	○	●	○	○	○
This study	●	●	●	●	●	○	○	○	●	●	●	●	●	○

● Included ○ Not included

(2018) use seven studies to create common LCIs and to ensure comparability. Nevertheless, they focus on the environmental dimension and LIBs, while LSBs and ASSBs are not considered. A wide range of battery technologies is also considered by Berg et al. (2015), Schmuck et al. (2018), and Wentker et al. (2019). However, these studies focus on the economic dimension. Furthermore, they do not calculate the cost at pack level so that costly materials and components (e.g., battery management system (BMS)) are not included. Barke et al. (2021) assess a wide range of battery technologies and consider all three sustainability dimensions. However, they omit ASSBs in their assessment, and there is a lack of data transparency, making it difficult to use this study for comparison.

Even if the data are presented transparently, it is challenging to compare battery technologies between different studies for several reasons. One reason is the different goals and scopes of the studies. For example, the definition of the functional unit has a decisive influence on the comparability of results due to incompatibility between functional units. Further influential parameters can be the definition of the scale and location of the production facilities due to the energy demand, country-specific electricity mix, or socio-economic conditions (Chordia et al. 2021; Thies et al. 2021; Wentker et al. 2019). Besides, the publication date influences the comparability. For example, the databases (such as the ecoinvent database or the Argonne National Laboratory's GREET® model) or the various impact assessment methods (such as ReCiPe, ILCD, and CML) evolve over time, leading to differences in the results and thus to significant differences in indicator scores (Chordia et al. 2021). Lastly, different impact indicators are reported due to varying classification and characterization approaches across the impact assessment methods, making it challenging to compare the results.

These aspects highlight the need for a transparent, consistent, and holistic sustainability assessment of current and prospective battery technologies, which will be carried out next.

3 System definition

This LCSA study aims to analyze and compare the environmental, economic, and social impacts of ten different batteries for BEVs on a common basis. The investigated batteries differ in their cell chemistries (see Table 2). Four LIBs, one LSB, and five ASSBs are considered. The batteries were selected to represent both the current state-of-the-art and two promising battery technologies that can achieve higher specific energy in the future. NMC622, NMC811, NCA, and LFP are selected as the positive active materials for the LIBs based on their current market share (Dunn et al. 2021). The sulfide-based lithium phosphorus sulfide (LPS) is selected as the solid electrolyte due to its predicted high ionic conductivity (Mauger et al. 2019). In the case of the LSB, it is assumed to use lithium bis(trifluoromethylsulfonyl)amid (LiFTSi) instead of lithium hexafluorophosphate (LiPF6) as lithium salt for the liquid electrolyte due to better compatibility with lithium metal, which is used as negative active material for the LSB (Lopez et al. 2021). Lithium metal is also used in the ASSBs. The remaining batteries use graphite as negative active material.

The functional unit of this study is the production of one battery pack with a capacity of 80 kWh, which is equivalent to the capacity of a large SUV such as the Jaguar i-Pace. The battery pack is used in a BEV, and it is assumed that it lasts the lifetime of the BEV, so only one battery pack is needed in all ten cases (Sacchi et al. 2022).

To ensure the common basis, the ten batteries are evaluated within the same system boundaries (see Fig. 2). The foreground system is divided into component production and battery production. It is assumed that the production steps of the latter are located in one facility in Germany. For the component production, it is assumed that the production takes place in China, except for the positive active material and the solid electrolyte, which are produced in Germany. The production steps of the foreground system are connected

Table 2 Investigated batteries in the LCSA study

Name	Positive active material	Negative active material	Electrolyte	Nominal Voltage [V]
LIB-NCA	NCA	Graphite	Liquid (LiPF6)	3.68
LIB-LFP	LFP	Graphite	Liquid (LiPF6)	3.28
LIB-NMC622	NMC622	Graphite	Liquid (LiPF6)	3.75
LIB-NMC811	NMC811	Graphite	Liquid (LiPF6)	3.75
LSB	Sulfur	Lithium metal	Liquid (LiFTSi)	2.20
ASSB-NCA	NCA	Lithium metal	Solid (LPS)	3.68
ASSB-LFP	LFP	Lithium metal	Solid (LPS)	3.28
ASSB-NMC622	NMC622	Lithium metal	Solid (LPS)	3.75
ASSB-NMC811	NMC811	Lithium metal	Solid (LPS)	3.75
ASSB-LSB	Sulfur	Lithium metal	Solid (LPS)	2.20

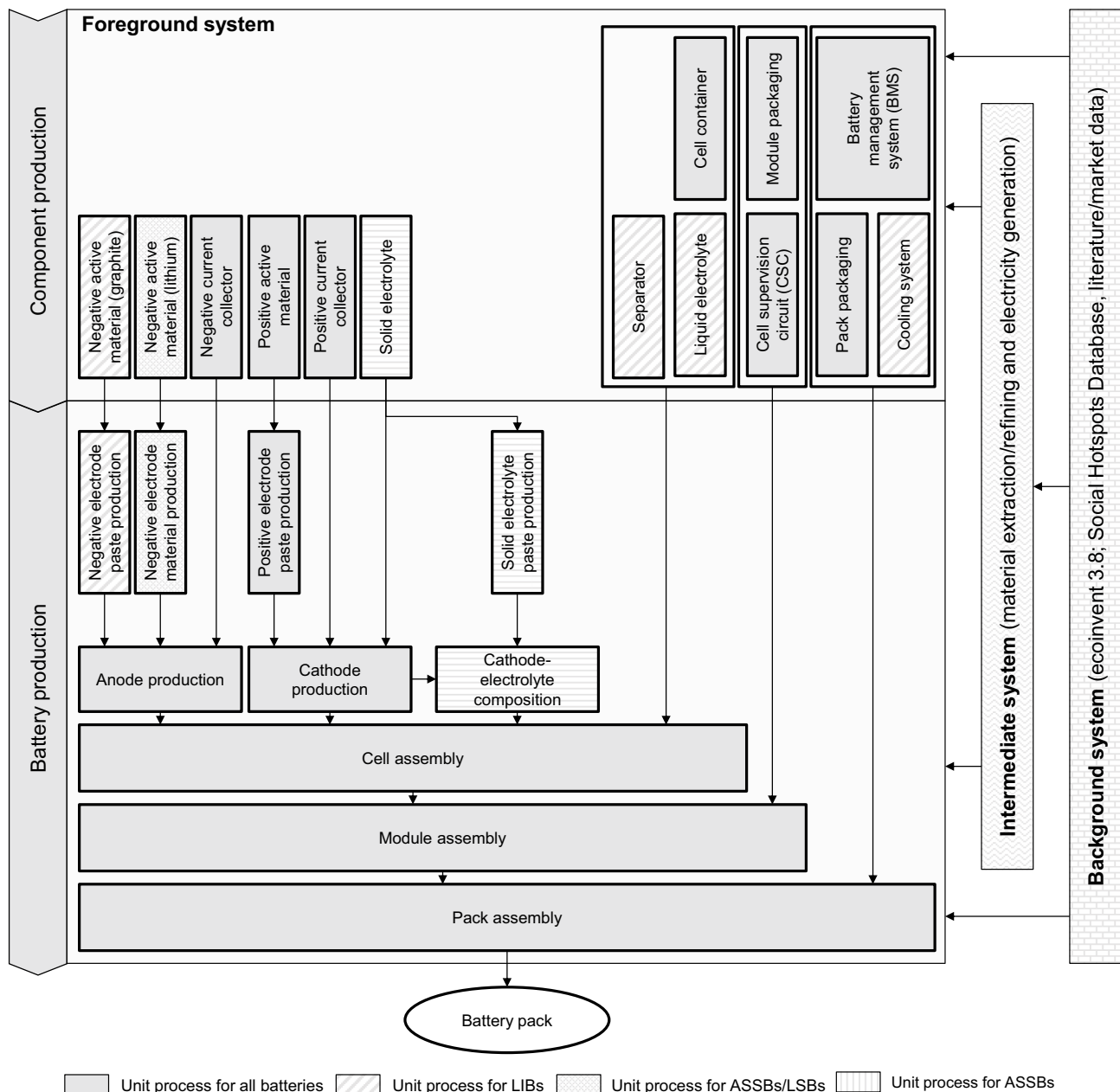


Fig. 2 System boundary of the investigated batteries

to an intermediate and a background system. The intermediate system includes unit processes that reflect the extraction and refining of raw materials and electricity generation based on data from the background system, which comprises the ecoinvent 3.8. cutoff database, the Social Hotspots Database (SHDB), and further literature data (Norris and Norris 2015; Wernet et al. 2016). The SHDB provides country-specific data for different sectors to calculate the medium risk hours of 24 social impact categories, such as risk of child labor. More details on the SHDB can be found in supporting information 1.

Furthermore, the background system has a direct connection to the foreground system, for example, to include exchanges of the SHDB in the respective unit processes to allow the calculation of the social indicator scores. In total, the system boundaries reflect a cradle-to-gate approach. The EoL phase is not considered, even though recycling of LIBs is already being carried out and large-scale plants have been announced for the next few years (Heimes 2022). An overview of recycling routes currently in use can be found in Blömeke et al. (2022), Harper et al. (2019), and Sommerville et al.

(2021). However, recycling of ASSBs is not yet established and is in the early stages of research, leading to the limitation of the system boundaries (Doose et al. 2021).

Furthermore, the use phase is excluded since this study aims to compare the impacts of the battery production of various battery types. The supporting information S1-1 provides detailed information on the system boundaries and the production steps considered.

The ReCiPe Midpoint (H) V1.13 method and the impact assessment method of the SHDB are used to assess the environmental impacts and social risks, respectively (Goedkoop et al. 2013; Norris and Norris 2015). For the economic assessment, the environmental life cycle costing method from the perspective of the battery producer is applied to estimate the total battery cost to an original equipment manufacturer.

Several tools and data sources are used to set up the LCIs of the ten batteries. The Battery Performance and Cost model 4.0 (BatPaC) is used to determine the composition of the batteries and essential parameters of the battery factory (Nelson et al. 2019). Since the BatPaC model is an Excel tool for calculating battery design and cost for currently available battery technologies, it is extended to also calculate the battery design of LSBs and ASSBs. Therefore, for example, the components not needed for these battery technologies are deleted from the Excel spreadsheets, and the remaining data are adjusted to represent the characteristics of LSBs and ASSBs. Figure 3 shows the key parameters of the batteries as well as the mass distribution of their components. The ASSB-LSB is the lightest battery and the LIB-LFP the heaviest. Further information on the calculation of the battery design and their mass fractions can be found in the supporting information S1-1.1.1.

The material flows and economic key parameters for the battery factory are derived from the BatPaC and assigned to

the respective unit processes. The BatPaC results for the production of 100,000 battery packs per year are further combined with data from the scientific literature to estimate the electricity demand of the battery factory (Degen and Schütte 2022; Deng et al. 2017; Keshavarzmohammadian et al. 2018; Nelson et al. 2015; Nelson et al. 2019; Sun et al. 2020; Wang et al. 2020; Yuan et al. 2017). A detailed overview of the electricity demand can be found in supporting information S1-1.1.4.

Scientific literature is also used to generate the LCIs for the unit processes of component production (Deng et al. 2017; Ellingsen et al. 2014; Keshavarzmohammadian et al. 2018; Wang et al. 2020; Wernet et al. 2016). Additionally, the LCIs of the positive active materials NCA, LFP, NMC622, and NMC811 are based on the GREET® model (Wang et al. 2020).

The system analysis and impact assessment are conducted using the Python-based “Brightway2” framework (Mutel 2017). Supporting information S1 and S2 provide a detailed overview of the intermediate and foreground system’s unit processes.

4 Results

4.1 Environmental impact assessment results

The presentation of the environmental impact assessment results focuses on four impact categories, namely climate change (CC), human toxicity (HT), mineral resource depletion (MRD), and photochemical oxidant formation (POF). These impact categories were selected due to their high relevance in the context of batteries. The indicator scores per kWh battery pack capacity are depicted in Table 3. The results of the remaining impact categories are depicted in supporting information S3.

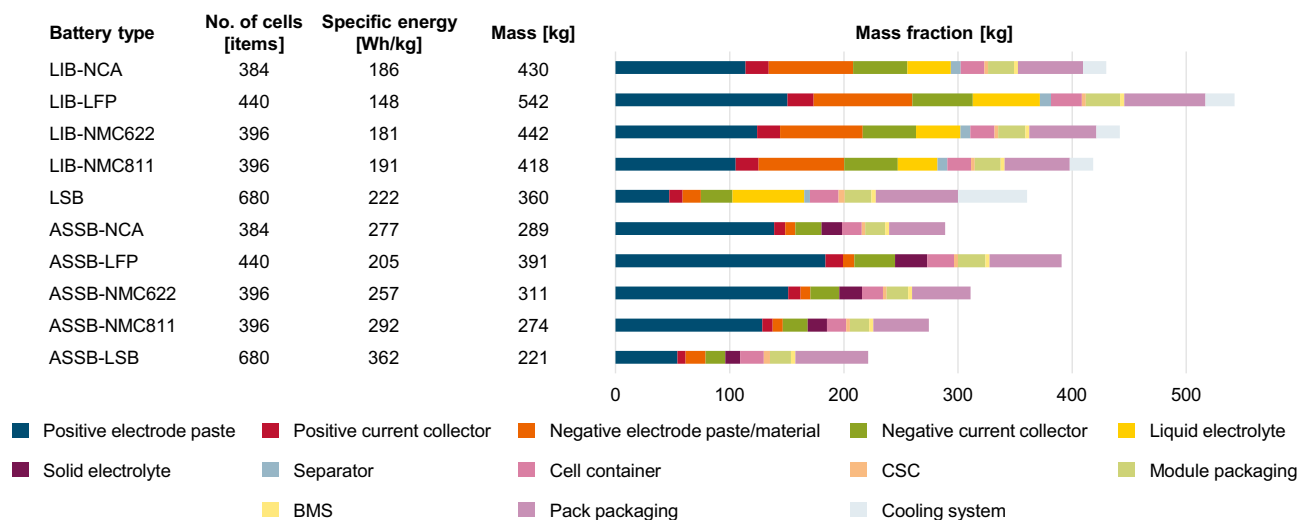


Fig. 3 Mass fractions, number of cells, and specific energy of the battery packs

Table 3 Assessment results of the environmental impact categories per kWh battery pack

Impact category	Unit	LIB-NCA	LIB-LFP	LIB-NMC622	LIB-NMC811	LSB	ASSB-NCA	ASSB-LFP	ASSB-NMC622	ASSB-NMC811	ASSB-LSB
Climate change	kg CO ₂ -eq.	110.54	91.25	110.76	102.34	90.34	120.97	111.43	123.08	111.84	79.63
Human toxicity	kg 1,4-DCB-eq.	254.46	240.16	254.13	243.81	163.84	193.63	205.98	203.71	181.51	132.03
Metal resource depletion	kg Fe-eq.	125.51	56.21	154.55	116.76	36.30	107.59	43.04	139.09	102.01	27.37
Photochemical oxidant formation	kg NMVOC-eq.	0.59	0.41	0.57	0.55	0.34	0.53	0.37	0.51	0.49	0.26

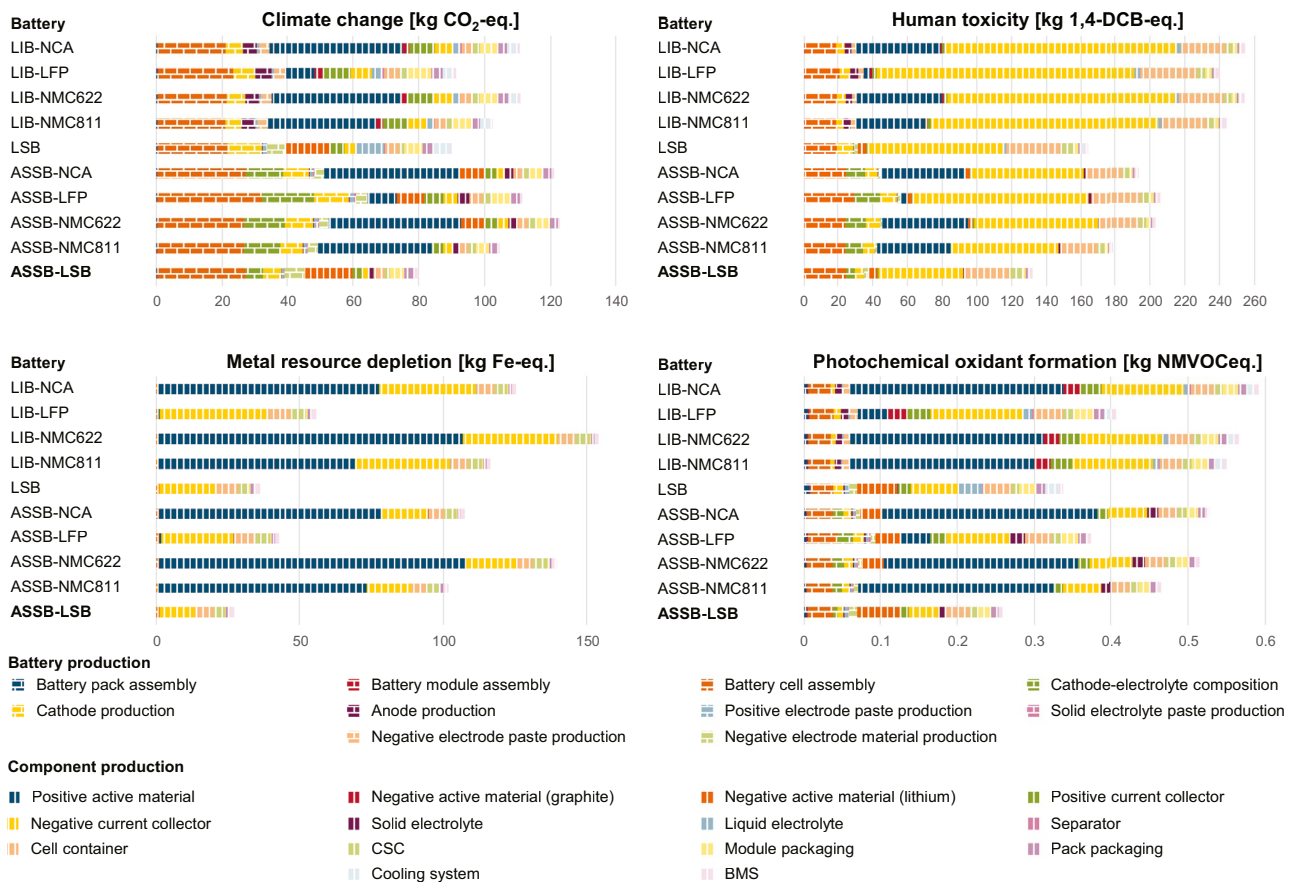
Worst indicator score of impact category ■ ■ ■ ■ Best indicator score of impact category

In terms of HT, MRD, and POF, the impact scores of all ASSBs are lower than those of LIBs and LSB. Only for CC, the ASSBs using NCA, LFP, NMC622, and NMC811 emit more GHG per kWh battery pack than the corresponding LIBs (e.g., the ASSB-NMC811 has a higher indicator score than the LIB-NMC811). This can be explained by the higher electricity consumption for producing these batteries. For the other impact categories, the electricity demand for battery production has a minor impact so that the higher specific energy and the resulting lower mass of the ASSBs show their advantageousness.

The battery with the lowest indicator scores in all four impact categories is the ASSB-LSB for mainly two reasons. First, the ASSB-LSB has the highest specific energy since

this battery requires fewer and lighter materials. Consequently, the corresponding emissions related to the production of these materials are lower. Secondly, the materials used in the ASSB-LSB and LSB are associated with lower impacts. This is especially reflected by the bar for the positive active material in Fig. 4, which shows that the environmental impacts seem negligible in the case of sulfur. In contrast, NCA, LFP, NMC622, and NMC811 have a much stronger influence on the indicator scores.

However, the ASSB-LSB shows different hotspots that vary by impact category. For CC, battery production is responsible for 57% of the impact. This depends mainly on the electricity generation in Germany, which has a high share of fossil sources. The electricity generation also has

**Fig. 4** Allocation of the environmental assessment results to unit processes per kWh battery pack

the strongest influence in terms of the unit process *negative active material (lithium)*, which has a share of 18% of the emissions. Considering HT, battery production and the unit process *negative active material (lithium)* have smaller shares of 28% and 4%, respectively. Instead, the unit processes *negative current collector* and *cell container* have a high influence with shares of 37% and 20%, respectively. These high shares are related to the copper production chain. Similar causes are also found for MRD. However, battery production is responsible for only 2% of the emissions in this impact category, while the *negative current collector* and the *cell container* account for 45% and 24%, respectively. In addition, the CSC is responsible for 14% of the indicator scores. For this impact category, this is also mainly due to the copper production chain, with additional impacts related to mining other metals for the production of the sensors. Compared with HT and MRD, the *negative active material (lithium)* has a more decisive role for POF, with a share of 22%. This is related to electricity generation in China. Since electricity generation plays a role regarding the emission of NMVOC and equivalent substances, battery production is responsible for 27% of the emissions. However, since electricity generation in Germany emits fewer NMVOC equivalents per kWh, the effect is smaller compared to CC. The *negative current collector* and *cell container* have a share of 15% or 12%, which shows that the copper production chain has a more minor influence.

4.2 Socio-economic impact assessment results

For the socio-economic assessment, four impact categories are investigated in detail: total battery cost for the economic dimensions, risk of child labor (RoCL), risk of corruption (RoC), and risk of forced labor (RoFL) for the social dimension. These impact categories were selected due to the strong influence of batteries on the cost of a BEV and social concerns associated with the battery supply chain. The calculated indicator scores per kWh battery pack capacity are depicted in Table 4.

The socio-economic assessment results show similarities to the environmental assessment results. Most notable, the indicator scores decrease when a solid electrolyte substitutes the liquid electrolyte. Furthermore, Fig. 5 shows that battery production has a strong influence with shares from 28 to 45% for the total battery cost. In contrast, the shares for the social

impact categories related to battery production are neglectable, as the risk of a socially disadvantageous situation concerning the impact categories investigated in Germany is low.

The battery with the lowest indicator values is the ASSB-LSB, with the exception of RoCL, where the ASSB-LFP has a slightly lower indicator score. In general, the difference between the ASSB-LFP and the ASSB-LSB is small in terms of the social impact categories. The relatively low indicator scores of the ASSB-LSB is a consequence of the much lower influence of the positive active material, which is, e.g., responsible for 48% of the medium risk hours of RoC in the case of the ASSB-NMC622. At the same time, there is virtually no risk associated with the production of the positive active material of the ASSB-LSB.

However, there are some hotspots related to the ASSB-LSB. Battery production accounts for 43% of the total battery cost, which is affected particularly by personnel and energy costs as well as the depreciation of machinery and buildings. The remaining costs depend on the material costs. In the case of the ASSB-LSB, especially two components have a strong influence: CSC and the *negative active material (lithium)*. These two components are responsible for 21% and 10% of the total battery cost, respectively. Furthermore, the costs associated with these two components are much higher than the other ASSBs, resulting from the number of battery cells required for the battery pack.

In comparison, the CSC and the *negative active material (lithium)* are also the two components responsible for the most medium risk hour equivalents regarding the social impact categories. However, the indicator scores of RoCL, RoC, and RoFL are much higher for the CSC, which is reflected by the respective shares. For example, CSC has a share of 36% of the medium risk hour equivalents of RoCL, while the *negative active material (lithium)* has a share of 15%. This is largely due to the higher risk of child labor in China's electronic sector compared to Chile's mining sector.

4.3 Scenario analysis

Sections 4.1 and 4.2 show that the electricity mix and the used materials are important drivers of the LCSA results. Therefore, this section examines two different scenarios. The first scenario investigates how an electricity mix of 100% renewables for battery production affects the indicator

Table 4 Assessment results of the socio-economic impact categories per kWh battery pack

Impact category	Unit	LIB-NCA	LIB-LFP	LIB-NMC622	LIB-NMC811	LSB	ASSB-NCA	ASSB-LFP	ASSB-NMC622	ASSB-NMC811	ASSB-LSB
Total battery cost	US-Dollar	158.95	154.00	161.96	155.74	140.60	148.68	146.08	154.79	144.30	123.48
Risk of child labor	Eq. medium risk hours	259.33	233.84	261.36	242.91	205.20	175.13	135.16	179.62	162.29	135.33
Risk of corruption	Eq. medium risk hours	352.00	280.94	347.97	329.32	250.51	261.35	176.39	260.42	244.22	170.73
Risk of forced labor	Eq. medium risk hours	335.32	326.05	350.23	311.97	286.43	219.40	191.12	237.89	199.30	189.85

Worst indicator score of impact category  Best indicator score of impact category

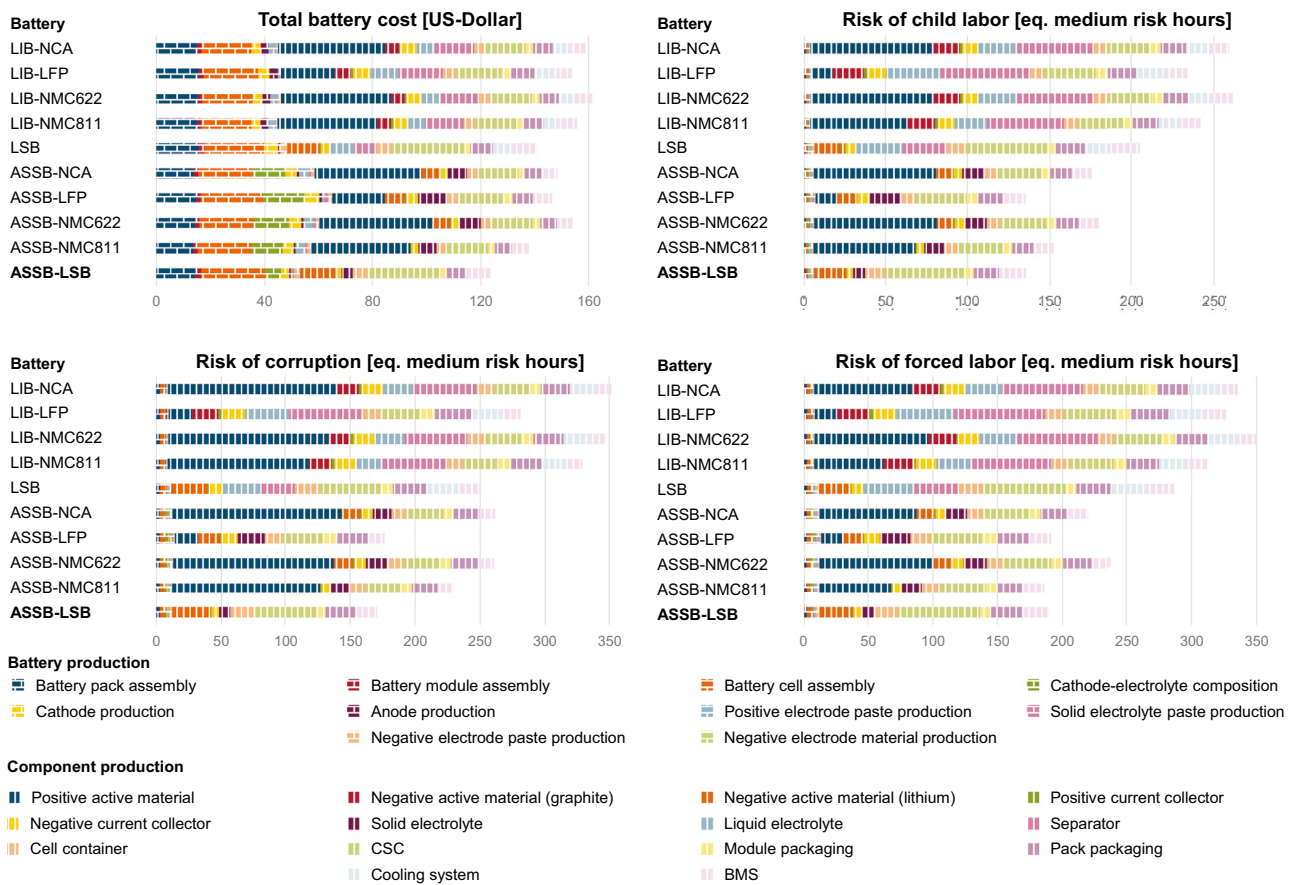


Fig. 5 Allocation of the socio-economic assessment results to unit processes per kWh battery pack

scores. The second scenario analyzes the consequences of changing the value added of battery materials.

To modify the electricity mix of the production facility in Germany, a new unit process for the electricity mix is modeled based on a prediction by Jacobson et al. (2017). The exchanges related to the economic and social dimensions remain the same, i.e., there are no changes in the socio-economic indicator scores. Consequently, Fig. 6 illustrates the results of the four environmental impact categories. The figure shows the indicator scores assigned to component and battery production for the base case and the case with an electricity mix of 100% renewables. Overall, the impacts of CC, HT, and POF decrease, while the impacts of MRD increase slightly. The increase for the latter depends on the impacts of building renewable energy plants. However, the increase is smaller than 3%. The observed effect is larger for the former three impact categories. Particularly for CC, the impact decreases between 26 and 48%. Especially the GHG emissions related to ASSBs can be reduced by using electricity from 100% renewables due to the high electricity demand for battery production. Consequently, almost all ASSBs have

a lower indicator score than the respective LIBs with a liquid electrolyte, contrary to the base case.

The second scenario analysis is intended to provide insight into how sensitive the total battery cost is if the value added of the key cathode and anode materials changes, which could be the case if, for example, the price of electricity or wages in a particular country increase. For this purpose, the value added of eleven unit processes of the main anode and cathode materials is doubled each. The results and the change compared to the base case are shown in Table 5. For the negative active materials, it can be observed that the change of the value added of lithium metal has a higher influence on the total battery cost than graphite. In particular, in the case of ASSB-LSB and LSB, there could be a significant change, depending on the high percentage of lithium metal in these batteries. In the case of positive active materials, the largest changes are associated with cobalt sulfate and nickel sulfate, affecting the total battery cost with NCA and NMC. Doubling the value added of sulfur, manganese sulfate, or iron sulfate has a negligible effect on the total battery cost, showing a possible advantage of using these materials. In addition, it can be inferred that ASSBs are less sensitive

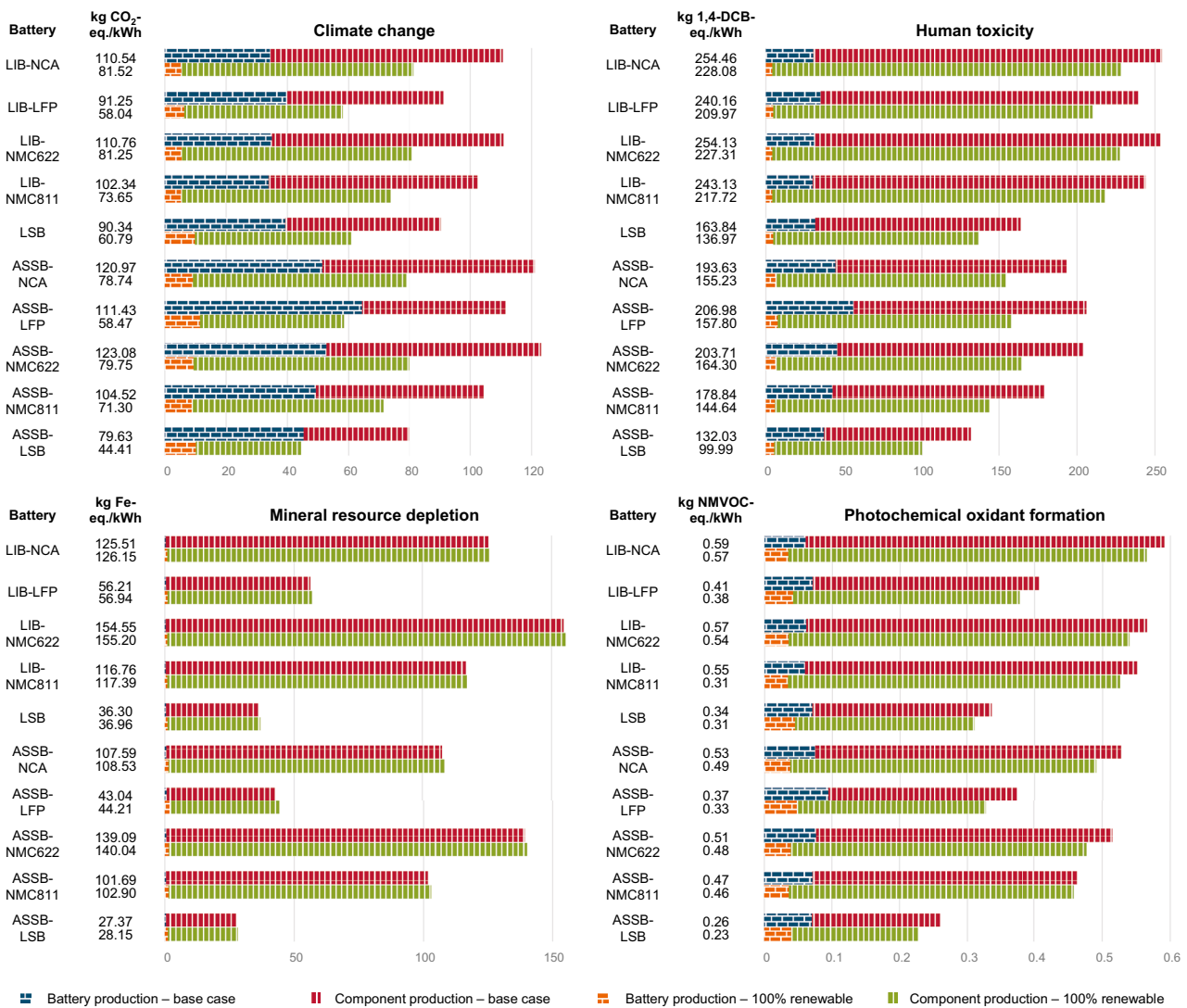


Fig. 6 Results of the first scenario analysis — changes in environmental indicator scores due to the use of 100% renewable energy in battery production

to changes in the value added of aluminum and copper since fewer of these materials are needed in the cases studied.

5 Discussion

Section 4 indicates that ASSB-LSBs have the lowest indicator scores for all impact categories and thus have a high potential to reduce environmental and socio-economic impacts compared to currently used batteries. This depends mainly on the materials used in ASSB-LSB, as they are associated with lower environmental and socio-economic impacts. Especially for sulfur-based active material, the indicator scores are much lower compared to those of other positive active materials. Additionally, fewer materials are required for ASSB-LSBs due to their high specific energy.

Therefore, further development of these batteries seems to be promising for carmakers since the cost of the batteries is lower, and they are associated with lower environmental impacts and social risks. However, the development of the ASSBs may take some time so that it is crucial to improve the currently used battery technologies in the coming years as well.

The analyses also highlight some hotspots related to the production of ASSB-LSBs. First, the energy demand is predicted to increase due to the requirement for a more sophisticated production environment. Thus, the electricity mix for battery production has a strong impact in the context of CC. To reduce these impacts, natural gas could be used instead of electricity in some of the cell manufacturing processes, as the use of natural gas, e.g., for the drying process, causes less CO₂ equivalent emissions compared to the

Table 5 Results of the second scenario analysis — total battery cost and changes to the base case if value added of respective battery materials doubled

Battery		Aluminum	Cobalt sulfate	Copper	Graphite	Iron sulfate	Lithium carbonate	Lithium hydroxide	Lithium metal	Manganese sulfate	Nickel sulfate	Sulfur
LIB-NCA	[\$/kWh]	159.53	165.19	163.03	164.01	158.95	161.66	160.60	158.95	158.95	160.84	158.95
	Change	0.36%	3.93%	2.57%	3.18%	0.00%	1.71%	1.04%	0.00%	0.00%	1.19%	0.00%
LIB-LFP	[\$/kWh]	154.68	154.00	158.66	159.93	154.06	157.86	156.35	154.00	154.00	154.00	154.00
	Change	0.44%	0.00%	3.03%	3.85%	0.04%	2.51%	1.53%	0.00%	0.00%	0.00%	0.00%
LIB-NMC622	[\$/kWh]	162.54	170.77	166.00	166.92	161.96	164.73	161.96	161.96	162.53	163.48	161.96
	Change	0.36%	5.44%	2.50%	3.07%	0.00%	1.71%	0.00%	0.00%	0.35%	0.94%	0.00%
LIB-NMC811	[\$/kWh]	156.31	159.47	159.77	160.88	155.74	158.21	157.24	155.74	155.98	157.46	155.74
	Change	0.37%	2.39%	2.59%	3.30%	0.00%	1.59%	0.97%	0.00%	0.16%	1.10%	0.00%
LSB	[\$/kWh]	141.08	140.60	143.41	140.60	140.60	146.75	140.60	144.69	140.60	140.60	140.64
	Change	0.34%	0.00%	2.00%	0.00%	0.00%	4.38%	0.00%	2.91%	0.00%	0.00%	0.03%
ASSB-NCA	[\$/kWh]	148.99	154.95	150.90	148.68	148.68	156.12	150.33	150.91	148.68	150.57	148.70
	Change	0.21%	4.22%	1.50%	0.00%	0.00%	5.00%	1.12%	1.50%	0.00%	1.28%	0.02%
ASSB-LFP	[\$/kWh]	146.54	146.08	149.41	146.08	146.14	155.68	148.44	148.59	146.08	146.08	146.12
	Change	0.31%	0.00%	2.28%	0.00%	0.04%	6.57%	1.62%	1.71%	0.00%	0.00%	0.02%
ASSB-NMC622	[\$/kWh]	155.13	163.64	157.22	154.79	154.79	162.37	154.79	156.98	155.37	156.32	154.82
	Change	0.22%	5.71%	1.57%	0.00%	0.00%	4.89%	0.00%	1.41%	0.37%	0.99%	0.02%
ASSB-NMC811	[\$/kWh]	144.60	148.25	146.43	144.30	144.30	151.35	145.82	146.50	144.56	146.12	144.33
	Change	0.22%	2.97%	1.61%	0.00%	0.00%	5.32%	1.14%	1.65%	0.19%	1.37%	0.02%
ASSB-LSB	[\$/kWh]	123.78	123.48	125.43	123.48	123.48	130.80	123.48	127.85	123.48	123.48	123.54
	Change	0.24%	0.00%	1.58%	0.00%	0.00%	5.93%	0.00%	3.53%	0.00%	0.00%	0.05%

German electricity mix (Degen and Schütte 2022). However, the aim is to reduce the use of natural gas in Germany in order to reduce dependencies on fossil fuels (Luderer et al. 2022). Beyond that, the first scenario analysis has shown that using an electricity mix with renewable energies offers great leverage for reducing the emissions allocated to battery production and would be advantageous over using natural gas in the long term.

Furthermore, the results show a strong influence of lithium metal on the environmental and economic impacts, which is also underlined by the second scenario analysis in the economic context. Components such as CSC or materials such as copper also negatively influence the socio-economic or environmental indicator scores. The amount of copper for the battery can be reduced by omitting the negative current collector (Schnell et al. 2018). Furthermore, ASSBs are still under development. Changes in production processes, composition, or structure could improve or deteriorate the respective indicator scores, so further assessments are needed to investigate these aspects in more detail and derive appropriate recommendations for action. These assessments can also include further battery technologies, which may be available for future BEVs.

The calculated indicator scores of the batteries are in a range of published studies (Aichberger and Jungmeier 2020; Barke et al. 2021; Mauler et al. 2021; Thies et al. 2019). However, this LCSA study provides a common basis that allows a fair comparison of different battery types. Nevertheless, in most cases, the data used in the background database are generic and global data sets. Therefore, collecting more specific and detailed data is necessary to ensure a higher data quality. This would further allow more detailed and spatially differentiated assessments and could provide better recommendations. A spatially differentiated approach is also important for economic and social assessments because the selection of countries can have a high influence on the economic and social indicator scores.

Furthermore, this study was limited to a cradle-to-gate approach. However, the characteristics (e.g., the battery mass) of the battery technologies could lead to differences regarding the indicator scores in the use phase. In addition, secondary materials are not considered in this study because the recycling processes of ASSBs are still at an early stage of research. However, using secondary materials could improve or worsen the indicator scores of the batteries studied (Popien et al. 2022). Thus, the scope should be extended in further studies.

Additionally, the SHDB only provides contextual information about the typical social situation in a country. The database does not provide information about differences in a country or a specific company. Therefore, the social assessment results can only sensitize companies to possible social

risks, which need to be investigated in more detail on a case-by-case basis to show whether the company needs to change something to avoid negative impacts.

6 Conclusion and outlook

This article emphasizes the need to evaluate different battery technologies on a common basis to ensure comparability of the results and to derive reliable recommendations. For this purpose, the production of ten different batteries representing current and prospective technologies was modeled, and LCIs on a common basis were created. The batteries are assessed regarding their environmental, economic, and social impacts using an LCSA-oriented approach leading to recommendations for various stakeholders.

The sustainability assessment results indicate that the ASSB-LSB is preferable since this battery has the best indicator scores for all impact categories investigated. Consequently, one could reduce the total battery cost as well as the environmental impacts and social risks. However, ASSBs are still under development, so there may be changes in composition or production steps that could influence these results and thus must be investigated further. This also leads to uncertainties, e.g., with regard to the energy demand of battery cell production, which will have to be evaluated more precisely in the future, also including the energy demand outside the production steps. Therefore, no conclusive recommendation can be made, but further development of these battery technologies appears promising. Furthermore, hotspots and potentials are identified that can be used to improve the impacts of ASSBs, such as changes in the composition of the battery packs or using 100% renewable energy for battery production. Additionally, the study's results can be used to develop the currently used battery technologies until ASSBs are commercially available.

In addition, the results highlight the high sensitivity to component and battery production assumptions. To analyze these sensitivities in more detail, this study can be a good starting point, as variations, e.g., for different locations, can be implemented straightforwardly. Due to the diversity of locations, a spatially differentiated assessment should be performed. These assessments can be used in a decision support model for battery and automotive manufacturers to plan their sourcing and location strategies. However, the data basis for materials supply chains needs to be improved to reflect spatially differentiated processes. Furthermore, the social situation of companies in respective countries must be evaluated in more detail for the social assessment. Moreover, secondary materials must be included as possible sources for battery production when more information regarding the recycling of ASSBs is available.

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Data availability All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declarations

Competing interests The authors declare no competing interests.

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