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LCI METHODOLOGY AND DATABASES

Climate impact and energy use of structural battery composites in electrical vehicles—a comparative prospective life cycle assessment

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Abstract

Purpose Structural battery composites (SBCs) are multifunctional carbon fibre composites that can be used as structural elements in battery electric vehicles to store energy. By decreasing the weight of the vehicle, energy consumption in the use phase can be reduced, something that could be counteracted by the energy-intensive carbon fibre production. The purpose of this study is to shed light on such life-cycle considerations.

Method Prospective life cycle assessment is used to compare the future cradle-to-grave climate impact and energy use of SBCs in battery electric vehicles to conventional metals and lithium-ion batteries. Additionally, the influences from different technology development routes, primarily related to the carbon fibre production, are assessed. The functional unit is the roof, hood, and doors of a battery electric vehicle with maintained flexural stiffness used for 200,000 km. To capture the multifunctionality of the material, the lithium-ion battery is also included in the functional unit.

Results and discussion Results show that SBCs have a large potential to decrease the life cycle climate impact and energy use of battery electric vehicles, especially following routes focusing on decreasing the use of fossil resources, both for raw materials and as energy sources. The comparative assessment of multifunctional or recycled materials to conventional materials introduces several methodological challenges, such as defining the functional unit and choice of allocation approach for distributing burdens and benefits between life cycles in recycling. This study illustrates the importance of using both the cut-off and end-of-life recycling allocation approaches to capture extremes and to not provide biased results. This study also highlights the importance of considering the ease of repairability in comparative studies, as damages to car parts made from SBCs are likely more difficult to repair than those made from conventional materials.

Conclusions SBCs have the potential to reduce the life cycle climate impact and energy use for most scenarios compared to conventional materials. Three main methodological challenges were found: the comparison to a material with a well-established recycling system throughout its life cycle, the need for expanding the system boundaries to include the lithium-ion battery, and the difference in repairability of SBCs compared to the conventional material.

Keywords Life cycle assessment · Prospective · Carbon fibre composites · Multifunctional materials · Climate impact · Energy use

1 Introduction

Structural battery composites (SBCs) are multifunctional carbon fibre composites that can be used as structural elements in battery electric vehicles (BEVs) to store energy. The multifunctionality is achieved by the fibres providing mechanical integrity as in conventional composites, as well as lithium (Li)-ion insertion and conduction of electrons. The polymer matrix not only distributes load but also provide ionic conductivity (Asp et al. 2021). The use of SBCs may not only lead to a decrease in the weight of the vehicle's structural parts, in the same way as a conventional carbon fibre composite would, but also to a decrease in the size of

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the Li-ion battery because energy can be stored in the structural parts of the vehicle (Carlstedt and Asp 2020). Consequently, the use of SBCs has the possibility to, for example, extend the range of BEVs, decrease the energy consumption during the use phase, and/or avoid parts of the production of the Li-ion battery, and consequently to reduce the life cycle environmental impact of BEVs.

It is known that the production of carbon fibre composites in general is energy intensive compared to the production of conventional materials. Consequently, using these materials in BEVs does not automatically lead to a lower environmental impact compared to the use of other materials, even if energy consumption is reduced during use due to a lower weight (Das 2011; Witik et al. 2011). While SBCs are likely to have the same problem regarding an energy intensive manufacturing phase, they could, however, as mentioned above, also further decrease the weight of the vehicle by reducing the size of the Li-ion battery. Little research has been conducted on the environmental impact of SBCs in BEVs. However, there is agreement that further assessments of the environmental impact of SBCs are needed (Hermansson et al. 2021; Zackrisson et al. 2019).

This study assesses the environmental impacts of SBCs in battery electric passenger cars compared to conventional materials and batteries, as well as the influence of different technology development routes, using life cycle assessment (LCA). The passenger car was selected for this first case study due to data availability. Other possible applications of SBCs in vehicles include electric buses, ferries, trucks, and aircrafts; however, more research is needed on the implementation of SBCs in these vehicles. The aim of the study is to determine (1) the life cycle environmental impact of shifting to SBCs in BEVs and (2) the most promising technology development routes for decreasing the life cycle environmental impact of SBCs in BEVs. The study also identifies and evaluates the main challenges in the assessment of SBCs using LCA, and offers possible solutions to overcome these. As there is no full-scale production of SBCs today, a future-oriented approach is needed.

Future-oriented LCAs are sometimes referred to as ex-ante LCAs. In ex-ante LCAs, the future impacts of a technology are evaluated by scaling up and assessing a range of different scenarios in which the technology could operate and are compared to an evolved version of the incumbent technology (Cucurachi et al. 2018). One type of ex-ante LCAs is prospective LCAs. Arvidsson et al. (p. 1287, 2018) define prospective LCA as "studies of emerging technologies in early development stages, where there are still opportunities to use environmental guidance for major alterations". Prospective LCA can help identify windows of opportunity for material developers to decrease the environmental impacts (Arvidsson et al. 2018). Note that the outcomes of a future-oriented LCA should not be seen as a definite result but as a contribution to technology development (Villares et al. 2017). The evaluated technology development routes include foreground system changes (i.e., in parts of the system that material developers can influence): using bio-based raw materials for fibre precursor production, using microwave technology in carbon fibre production, and the recycling of composites and recovery of fibres. Furthermore, the background system (i.e., parts of the system that cannot be directly influenced by material developers) changes to a carbon lean energy system and to an increased use of recycled metal input for the conventional vehicle were also considered. As some technology routes are likely to be implemented simultaneously, we also assess the possible impacts of SBCs in different futures, developed by combining policy and legislation directions in a coherent way. By doing so, we can provide guidance to material and vehicle developers, policy developers, as well as LCA practitioners.

2 Background

2.1 Structural battery composites

SBCs are multifunctional composites with the ability to simultaneously store and deliver electrical energy while carrying mechanical loads. They consist of carbon fibres, traditionally produced from a polyacrylonitrile (PAN) precursor, embedded in a polymer matrix just like conventional high-performance carbon fibre composites. The main difference is that in SBCs, the carbon fibres act as a host for Li-ions and conduct electrons while also reinforcing the material. The matrix material in the SBC is a two-phase structural electrolyte containing conventional liquid electrolyte with a bisphenol A-based methacrylate polymer that, upon solidification, transforms to a heterogeneous material with two percolating phases; the solid polymer phase provides mechanical load transfer, while the liquid electrolyte mixture containing lithium salts provides ion conductivity. The positive and negative electrodes of the SBC are insulated from each other by a separator whose thickness and pore structure influences both the mechanical and electrochemical performance of the cell. A thin separator with sufficient pore properties increases the elastic modulus and the energy density of the SBCs as it enables an overall higher fibre volume fraction and reduces the resistance. A thicker separator decreases the elastic modulus and the energy density (Asp et al. 2021; Xu et al. 2022). Current SBCs use a commercial lithium iron phosphate (LFP) coated aluminium foil as positive electrode. Work is ongoing to replace this with an LFP-coated carbon fibre-based positive electrode (Carlstedt et al. 2022; Sanchez et al. 2021). Figure 1 shows a schematic image of such an SBC battery cell.

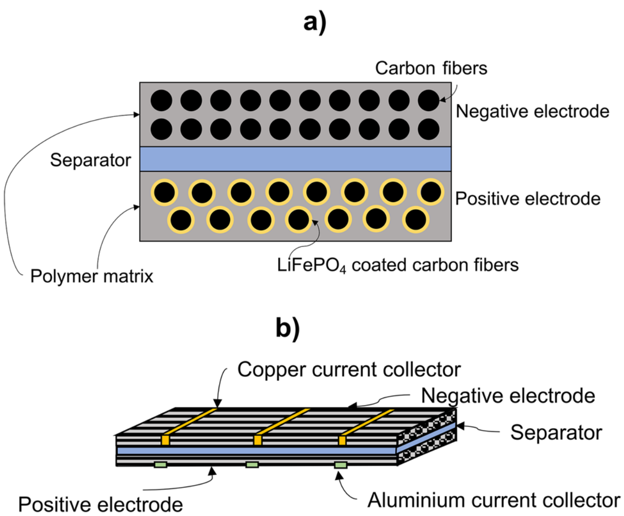

Fig. 1 A schematic image of a structural battery composite cell cross section (**a**) and in overview (**b**)

There are two main challenges to SBCs compared to conventional carbon fibre composites. First, the fibres need to have the capability for lithiation and delithiation. Early studies (Fredi et al. 2018; Hagberg et al. 2016; Kjell et al. 2011; Snyder et al. 2009) show that carbon fibres can perform on par with ordinary graphite-based commercial electrode materials. The ability for commercially available PAN-based carbon fibres to host lithium is close to that of the theoretical maximum for pure graphite. This comes at the cost of a loss of ultimate tensile strength as a consequence of some lithium being permanently trapped resulting in strain development, although reversible, in the fibres (Jacques et al. 2014). Second, the polymer matrix of the SBC must be able to provide structural integrity and Li-ion conduction at the same time, two properties that often counteract each other, i.e., it is possible to achieve high ionic conductivity but then without mechanical rigidity, and vice versa (Asp et al. 2019).

2.2 Future technology development

In addition to prospective large-scale production of SBC, we also consider the following possible future technology development options: (1) using bio-based raw materials for carbon fibre production, (2) using microwave heating in carbon fibre production, and (3) recycling of the SBCs and recovery of fibres. These routes have earlier been identified as interesting routes and defined for carbon fibre composites (Hermansson et al. 2022b) and are thus also applicable to SBCs, as the SBC in essence is a carbon fibre composite with added functionality. Note that there are also potential future developments of the Li-ion battery, but this is outside the scope of this paper.

A possible bio-based raw material for carbon fibre production is lignin (LIBRE 2016). Lignin is an aromatic molecule found in wood and can be recovered from pulp mills and bio-refineries to be used in different products (Ragauskas et al. 2014). Previous research has shown that using lignin as a raw material for carbon fibre production has great potential to decrease their environmental impact, but that this depends on how the allocation of environmental impacts between the multiple outputs of a biorefinery or a pulp mill is done (Hermansson et al. 2019). It should be noted that the feasibility of using lignin-based carbon fibres in SBCs would ultimately depend on the properties of the resulting carbon fibres. Research has, however, shown that carbon fibres based on a cellulose-lignin precursor material can have properties that make them potentially useable as active electrode material in batteries and structural batteries (Le et al. 2020; Peuvot et al. 2019).

Microwave technology has been suggested as a means to decrease energy consumption in carbon fibre production with as much as 90% compared to using a conventional pyrolysis process in furnaces (Lam et al. 2019). Implementing this route in SBC manufacturing also requires that the quality of the resulting carbon fibres is high enough and that they have the right properties, which is something that is yet to be evaluated.

Recycling of SBCs is currently not done, but it has been shown that the recycling and recovery of the carbon fibres is a promising route for decreasing the environmental impact of carbon fibre composites, see for example the work by La Rosa et al. (2016) and Meng et al. (2017). There are several methods to reclaim carbon fibres from composites, such as mechanical recycling, thermal techniques, and chemical techniques such as solvolysis (Dong et al. 2018). A suitable route for reclamation of the carbon fibre electrodes in SBCs could be by chemical methods (Asp and Greenhalgh 2015). Chemical fibre reclamation processes have been reported to have very high retention of mechanical properties and fibre length (Jiang et al. 2009). Another approach, commercially available for conventional carbon fibre composites, is the recovery of fibres through pyrolysis processes (Witik et al. 2013), a method with a relatively high technology readiness level (TRL) compared to the other recycling approaches. However, to what extent the electrolyte and the lithiation of the carbon fibres influence the recycling process and the quality of recovered materials remains to be researched.

3 Method

3.1 Structural battery composite production

There is no large-scale production of SBCs today. Therefore, the inventory for the SBC manufacturing was compiled based on lab data, estimates by experts, and data found in

Table 1 The inventory for producing the structural battery composite, not considering potential losses in parts manufacturing

Structural battery composite part	Material	Mass %	Vol%	Source
Positive electrode	Carbon fibre	13	12	Primary data
	$LiFePO_4$	20	9.5	
	Polyvinylidene fluoride	1.1	1.0	
	Carbon black	1.3	1.1	
	Electricity (kJ)	n/a	n/a	Zackrisson et al. (2019)
Negative electrode	Carbon fibre	17	16	Harnden et al. (2022)
Electrolyte	Polymer matrix	15	22	Primary data and Tasneem and Siam Siraj (2022)
	Liquid electrolyte	15	19	
Separator	Cellulose fabric	8.6	9.7	Primary data
Current collectors	Aluminium	n/a	n/a	Johannisson et al. (2021) and Tasneem and Siam Siraj (2022)
	Copper	n/a	n/a	
Casing	Epoxy	2.2	3.2	Primary data
	Carbon fibre	6.3	5.9	
Manufacturing	Electricity (kWh)	n/a	n/a	Zackrisson et al. (2019)
	Gas (kWh)	n/a	n/a	
Total		100	100	

Primary data refers to any data based on expert estimations and collected in the laboratory within the scope of this study. For details about calculations and assumptions, see the Supplementary Information

the literature. The specific case we investigate is a carbon fibre (−), carbon fibre/$LiFePO_4$ (+) structural battery with a cellulose separator.

The starting point for the SBC inventory is an energy-harvesting composite similar to SBC (Harnden et al. 2022). We assume the same thickness and volume fractions as for the energy harvesting composite for the negative electrode layer: 49 vol% carbon fibres and 51 vol% electrolyte. The electrolyte in the SBC is primarily based on bisphenol A dimethacrylate lithium triflate and lithium bis(oxalato) borate dissolved in ethylene carbonate, and propylene carbonate. The same carbon fibres in the negative electrode cannot function as positive electrode without functionalization. Here, this means that they are coated with a layer of primarily $LiFePO_4$, which is assumed to be done by means of electrophoretic deposition (Zackrisson et al. 2019). We assume that the solvents used in the electrophoretic deposition in large-scale operations can be reused and that the losses are minor (less than 0.5% (Zackrisson et al. 2019)), and are thus excluded from the life cycle inventory. After coating, the carbon fibres become thicker and consequently take up more volume in the positive electrode layer, thus reducing the relative amount of carbon fibres and electrolytes compared to the negative electrode layer. We assume that the positive electrode layer consists of 37 vol% carbon fibres, 29 vol% $LiFePO_4$, 27 vol% electrolyte, and a total of 7 vol% carbon black and polyvinylidene fluoride. The electrode layers are separated by an electrically insulating separator, in our specific SBC, a cellulose fabric, and the electrical current is collected by means of aluminium and copper current collectors. After production, it is assumed that the battery cells are laminated into a casing made from 65 vol% carbon fibres and 35 vol% epoxy for protection. The volume of material needed for the case is assumed to be 10 vol% of the battery cell. As there is no large-scale production of SBCs today, the energy use in the manufacturing process was assumed to be equivalent to that of the production of Li-ion battery manufacturing, as the methods used are similar (Zackrisson et al. 2019). We assume the manufacturing of the parts is to be done using automated manufacturing methods with 10% losses and that the waste generated in manufacturing goes to landfills. The final SBC is assumed to have an effective modulus of 70 GPa and an energy density of 70 Wh/kg, and we assume that the power density is the same as for Li-ion batteries, even though the power of the SBCs produced today is something that needs further improvement. The inventory for the SBC is presented in Table 1, and the details are found in the Supplementary Information. On battery pack level, i.e., for the group of battery cells connected in series or in parallel, designed to provide the desired voltage and capacity for a specific application (including casing), the fibres constitute 34 vol%, the electrolyte/polymers 44 vol%, and the rest is other parts, such as separator and $LiFePO_4$.

It is important to remember that the inventory does not necessarily reflect the actual future industrial manufacturing of SBCs as we compiled the data set using a mix of data gathered from the lab (electrolyte production) and from discussions with experts (volume fraction of carbon fibres in the positive electrode layer, amount of $LiFePO_4$ for coating, the casing composition) and literature (volume fraction of carbon fibres in the negative electrode layer, current collectors, and the energy use in manufacturing), which implies that there may be some inconsistencies.

3.2 Life cycle assessment—methodology

In this study, we use an attributional prospective approach. The goal is to compare the life cycle environmental impact of using SBCs in BEVs instead of the conventional materials, metals, and Li-ion batteries, as well as to assess what technology development routes that could aid in a reduction of environmental impacts of SBCs.

Assessing emerging materials using LCA is challenging, and in this case, the multifunctionality of the SBC adds an extra dimension. The new materials produced are not necessarily direct replacements to the conventional material because the functions of the new material are not equivalent. An option to mitigate this is by expanding the system boundaries to achieve functional equivalence between compared systems (Hetherington et al. 2014). In accordance with this, the system boundaries of this study are expanded to also include the Li-ion battery of the BEV, along with the structural parts, in the functional unit, to cover the lightweighting as well as the energy storage in the same structural components. This expansion is in line with the original system expansion approaches in the LCA standard ISO 14044, or the idea of a "basket function" (Heimersson et al. 2019). The resulting functional unit for the study is therefore the roof, hood, and doors of a BEV with maintained flexural stiffness used for 200,000 km, as well as the Li-ion battery.

The vehicle with the parts being considered in this study is shown in Fig. 2.

In this study, we assess climate impact using the IPCC 2013 method and the energy use using cumulative energy demand (CED), both provided by Ecoinvent 3.8. The CED method includes both renewable and non-renewable energy sources (aggregated to one single value in this study). Climate impact is chosen as this is linked to legislation and policies such as the Paris Agreement (UN Climate Change 2023), and energy use is chosen as this is an important aspect for the manufacturing and vehicle industry. In addition to this, climate impact often correlates well with many other impact assessment categories (Janssen et al. 2016). We also assess the ozone depletion, water use, natural land transformation, and terrestrial acidification, all using the ReCiPe midpoint (H) method. However, as we lack direct emissions data for production/manufacturing processes, these results are more uncertain and are therefore placed in the Supplementary Information.

All materials' production, car part manufacturing use, and end-of-life processes are assumed to take place in Europe, using Europe specific data as much as possible. The reason for this choice is that the energy systems in Europe are connected (see e.g. Ekvall et al. (2023) for more information). Transportation of materials and waste are excluded if not already included in the market datasets used.

The basic outline of a SBC's life cycle can be found in Fig. 3. All modelling was done using OpenLCA v. 1.11 and Ecoinvent 3.8 Cut-off (Wernet et al. 2016) if not stated otherwise. Details about the modelling can be found in the Supplementary Information.

The roof and doors of the conventional BEV are produced from steel (primary low alloy steel and sheet rolling followed by deep drawing is assumed), whereas the hood is produced from aluminium (primary aluminium ingot and sheet rolling followed by deep drawing is assumed). The resulting parts in the conventional vehicle consist of 36 kg of steel and 5 kg of aluminium. We handle the scrap from the deep drawing in two ways in separate case studies: (1) the scrap leaves the system in an open loop, and (2) the scrap returns to the car part manufacturing system again in a closed loop.

To maintain the same flexural stiffness as the metal car part, the SBC vehicle parts would need a resulting mass of 14 kg. Any mounting of the vehicle parts and painting are excluded as the impacts related to these activities are assumed to be approximately the same for both types of vehicles.

The substitution of steel and aluminium with SBCs leads to a reduction in vehicle weight through material replacement as well as a decrease in battery size. This results in a decrease in energy consumption during the use phase, which is here credited to the SBC system as avoided electricity production. The avoided energy use in the use phase (called the energy reduction value (ERV)) is assumed to be 0.069 Wh/kg*km (Johannisson et al. 2019). In addition to this, the decreased battery size leads to an avoided production of NMC111 battery with an assumed energy density of 143 Wh/kg at pack level (Dai et al. 2019). An avoided production of 7 kg NMC battery is thus also credited to the SBC system. Note that, as this study is attributional, we do not consider any potential rebound effects such as increased driving due to lower cost for the consumer.

In this study, we assume that the SBC car parts are discarded at the end of the vehicle life cycle and incinerated. The metal car parts are assumed to be recovered with 5% being sent to disposal (in line with the European Union's Directive 2000/53/EC), and it is assumed that there is no considerable quality degradation of the metals (in line with what is suggested for the Circular Footprint Formula for steel and aluminium sheets (Bollen et al. 2019)). It is assumed that 50% of the Li-ion battery is recovered (in line with the European Union's Directive 2006/66/EC). We model the

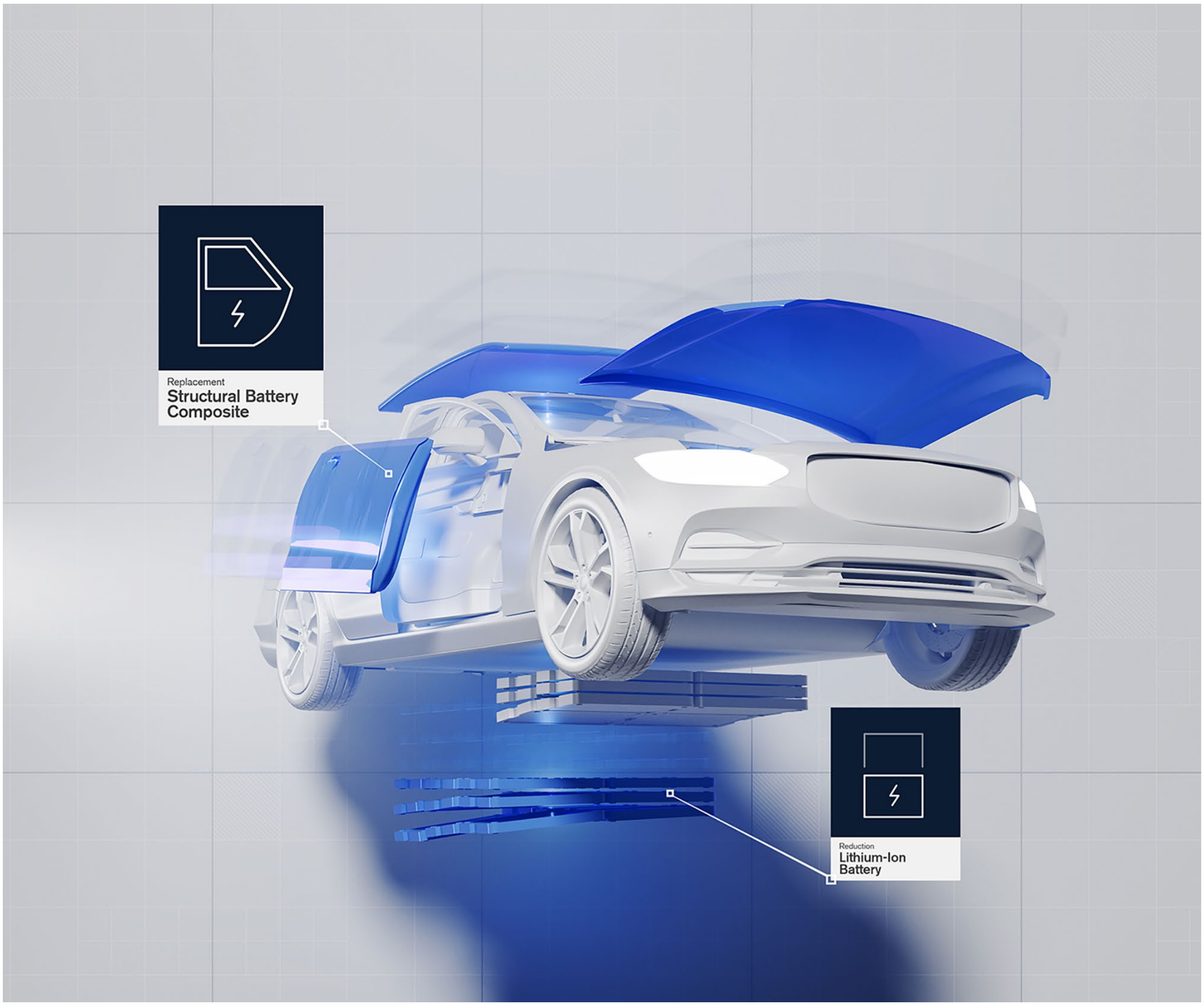

Fig. 2 The battery electric vehicle with the parts being considered in the life cycle assessment in blue colour. Picture made by Boid

end-of-life of the Li-ion battery by assuming it to be reused in another application, such as stationary energy storage (Zhu et al. 2021), and that the quality of the Li-ion batteries then only is 80% of a primary Li-ion battery (Börner et al. 2022). We assume that the 50% of the Li-ion battery that is not reused is sent to an underground deposit for hazardous waste. The impacts related to recycling of metal and reuse of Li-ion battery are allocated using either the cut-off approach (impacts of the recycling process are allocated to the product in which the recycled material is used, and a credit is given for using recycled materials) or the end-of-life recycling approach (impacts of the recycling process are allocated to the product generating the recyclable material, and a credit is given for providing recycled materials), in two different scenarios for assessing recycling in prospective LCAs (Hermansson et al. 2022a). Note that the dataset for Li-ion battery by default includes recycled content (for example a small share of high-density polyethylene), meaning that there is a risk of some credits being double-counted when using the end-of-life recycling approach. The influence of this possible double-counting on end results and conclusions is, however, assumed to be minor.

The robustness of the results is tested in a sensitivity analysis where we varied the energy density and the effective modulus of the structural batteries, the energy consumption in the battery manufacturing process, as well as the mileage and ERV.

A challenge for industrial adoption of SBCs is maintenance (Ishfaq et al. 2023). This is a consequence of SBCs not having the same ease of replacement as conventional materials, and that a damaged SBC may need replacement rather than being repaired. Impacts related to damages from

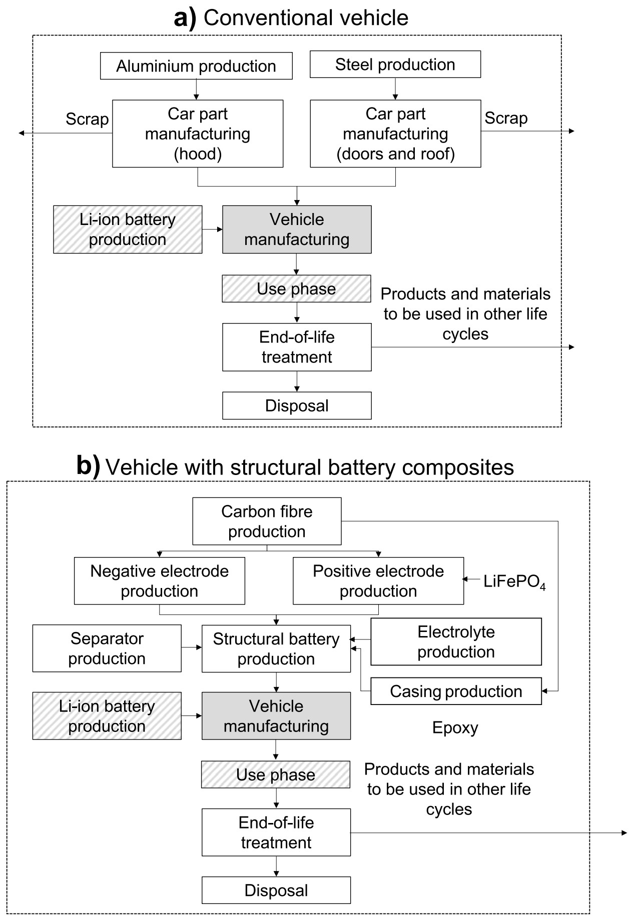

Fig. 3 The basic outline for the cradle-to-grave life cycle of the vehicle. The figure shows the main processes for the considered vehicle parts for a conventional battery electric vehicle (**a**) and a battery electric vehicle with structural battery composites (**b**). The lithium-ion battery production and the use phase (striped boxes) are only partly included as this is a comparative assessment. The vehicle manufacturing (grey box) is not included in the assessment (assumed to be similar for both vehicles)

accidents are generally not considered in LCAs but are nonetheless important, and excluding the risks of accidents could cause biased results (Fries and Hellweg 2014). In this study, the potential influence of accidents is assessed by assuming that conventional monofunctional materials can be easily repaired or are not affected at all by an accident, while the SBC would need replacement. As the functional unit relates to 200,000 km driven, the possible difference of ease of repair cannot be included in the average lifetime as this would change the function of the products assessed. We therefore use an 'irreparability factor' of 1.3 based on 1.4 million damages reported to insurance companies in Sweden in 2020 (Insurance Sweden 2022) distributed over the 5 million passenger cars in Sweden in 2021 (Transport Analysis 2022), meaning that there is a 30% risk of damages, resulting in an addition of 30% of the initial mass flow of SBC.

3.3 Technology development routes

In this study, we explore three different technology development routes influencing the foreground system for the SBC: (1) using lignin as a raw material for carbon fibre production, (2) carbonisation and stabilisation of the carbon fibres by means of microwave heating and, (3) recycling of the SBC car parts and recovery of fibres and polymer. In addition to this, we also assess the influence of changes to the energy system as well as the use of recycled metals in the conventional car part manufacturing. These background changes are applied both to the SBC vehicle and the conventional BEV, but no other further developments of the BEV are considered. In this part of the assessment, we only assess the influence from these routes separately; The influence from, e.g., using microwave technology or pyrolysis when using decarbonised energy, is explored in the scenarios described in Sect. 3.4.

The lignin used in the production of lignin-based carbon fibres is assumed to be produced in an Organosolv pulping process (using data from Moncada et al. (2018)). We use mass allocation to partition the impacts between the products of the mill as this can be argued to be more suitable for explorative studies where prices of side streams can be influenced by the market situation or changes in demand which are hard to predict (Coelho et al. 2022). The production of lignin-based carbon fibres is based on the same dataset as the production of PAN-based carbon fibres, but adapted to fit the inherent properties of lignin (Das 2011). Note that lignin must sometimes be mixed with a polymer to reduce brittleness of the carbon fibres (Collins et al. 2019). This is, however, something that is not considered in this assessment. We also assume that the rest of the battery chemistry is the same as for SBCs based on PAN-based carbon fibres. For carbon fibre production using microwave heating, we assume that microwave technology reduces the energy consumption by 93.5% in the carbon fibre production phase (Lam et al. 2019). We assume that the material yield and nitrogen gas consumption for the inert environment is the same as when using furnaces and that the resulting fibres from these routes (both PAN-based and lignin based) have the same properties when used in the SBCs as the PAN-based fibres produced using conventional methods.

For the recycling of the SBC car parts, it is assumed that 95% of the car parts are recovered and recycled. The recycling of SBC is assumed to be done by means of pyrolysis requiring 30 MJ/kg (as was reported for the pyrolysis of carbon fibre composites (Witik et al. 2013)). The recycled fibres from the pyrolysis process are assumed to have a tensile strength reduction of 18% compared to primary fibres (which is reported for carbon fibres recovered using fluidised bed technology (Pickering et al. 2015), and we assume that it also applies to our case), and the recovered fibres are

Table 2 The three constructed futures for the life cycle assessment. Adapted from Hermansson et al. (2022b)

	Settings in foreground system	Settings in background system
Scenario 1: Bioeconomy	- Fibres are produced from bio-based raw materials* - Fibres are produced using microwave heating* - Car parts are incinerated*	- Energy mix transitions towards being fossil-carbon lean - Metal car parts are made using primary metals - There is legislation to reduce extraction of fossils from the ecosphere; cut-off allocation approach
Scenario 2: Circular economy	- Fibres are produced using fossil-based raw materials* - Fibres are produced using conventional technologies* - Car parts are recycled, and materials recovered used in other products	- Energy mix remains the same - Metal car parts are made using a share of recycled metals - There is legislation to promote recycling and recovery of materials; end-of-life recycling approach
Scenario 3: Circular bioeconomy	- Fibres are produced using bio-based raw materials* - Fibres are produced using microwave heating* - Car parts are recycled, and materials recovered used in other products	- Energy mix transitions towards being fossil-carbon lean - Metal car parts are made using a share of recycled metals - There is legislation to reduce extraction of fossils from the ecosphere; cut-off allocation approach

*Only SBCs

assumed to be used in another composite product with less demand on tensile strength than SBCs. The electrolyte in the battery cell together with the epoxy in the casing are assumed to be recovered as an oil-like substance (Cunliffe et al. 2003), equivalent to petroleum, with a conversion rate of 100%, even though it is likely to be lower in reality. Due to lack of knowledge regarding emissions from the fibre reclamation plant when the polymers are being recovered, we do not consider any emissions other than those related to the energy needed. Any processes related to dismantling and collection of discarded parts and waste have been excluded. Just as for the modelling of the conventional materials recycling, we apply both the cut-off approach and the end-of-life recycling approach, as is recommended by Hermansson et al. (2022a) for prospective LCAs, to allocate the burdens and benefits from recycling of SBC.

3.4 Generating future scenarios

The different development routes described in Sect. 2.2 can be combined into different plausible futures based on how strong the connections between them are in terms of which underlying trends in society that are drivers for them (Langkau and Erdmann 2021). The scenarios were constructed using the method developed by Langkau et al. (2023). Initially, the scenarios used in this study were constructed for a case study comparing car mirror brackets made from carbon fibre composites and fibreglass by Hermansson et al. (2022b). They constructed three different plausible futures: 1) bioeconomy future, 2) circular economy future, and 3) circular bioeconomy future (Hermansson et al. 2022b). The bioeconomy future has policies and legislation focusing on decreasing the use of fossils and instead using bio-based materials, the circular economy has a focus on recycling and waste reduction, and the circular bioeconomy is a combination of the two, focusing on reducing the use of fossils and waste generation as well as on using recycled and bio-based materials. The future scenarios in this paper are based on the same future scenarios as those constructed by Hermansson et al. (2022b), but are adapted to fit the specific case of SBCs. The settings for the scenarios are found in Table 2.

4 Results and discussion

4.1 The influence of different technology development routes

Figures 4 and 5 show the resulting life cycle climate impact and energy use for the BEV transitioning to SBC for the selected components for the two different allocation approaches applied. Net total values for other impact categories are found in the Supplementary Information; they do, however, to a large extent match the results for climate impact and energy use.

The results show that the SBC has a great potential to decrease the climate impact and energy use of BEVs compared to using the conventional materials steel and aluminium as metal structural parts. The reduction depends primarily on the avoided production of Li-ion battery and on reduction of energy consumption in the use-phase, but the impacts from manufacturing of the SBC are significantly higher than those of the metal car parts. As the results are heavily influenced by the avoided impacts related to Li-ion battery production, it is important to consider that assuming another type of battery in the vehicle will influence the results. For example, using

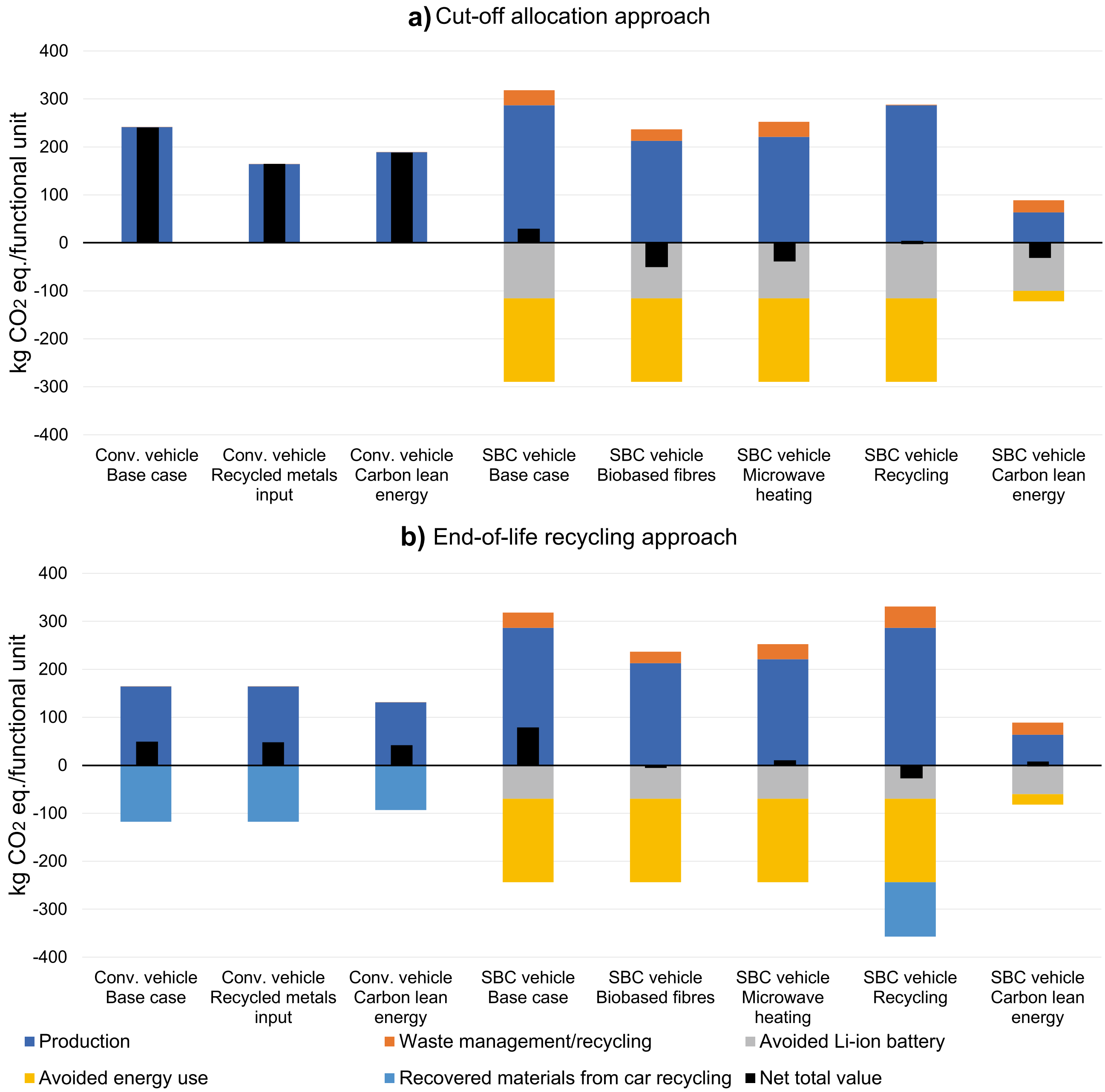

Fig. 4 The life cycle climate impact of using the selected elements in a conventional battery electric vehicle and of one with the elements replaced by structural battery composites (SBCs); present scenario base case and for different technology development routes using the cut-off allocation approach (**a**) and the end-of-life recycling allocation approach (**b**). The black bar indicates the net total value

another dataset for a battery with a $LiMn_2O_4$[1] cathode could decrease the credit for avoided battery production with at least 35%. On the other hand, the lower energy density of the $LiMn_2O_4$-battery leads to a larger credit from avoided energy use in the use-phase due to a reduced mass of the vehicle, which compensates for this to some extent.

[1] Using the Ecoinvent dataset "battery production, Li-ion, rechargeable, prismatic| battery, Li-ion, rechargeable, prismatic| Cutoff, U–GLO" and assuming that 8.6-kg battery could be replaced.

The impacts related to manufacturing of the SBC are mainly connected to the carbon fibre production and the energy use in the battery manufacturing process. In fact, these two parts of the life cycle account for almost 90% of the SBC's cradle-to-gate climate impact and energy use. The production of the PAN-based carbon fibres is, as earlier described, based on data found in literature and databases and may not truly reflect the production process of carbon fibres produced for SBCs. In the future, it would be valuable to collect primary data for carbon

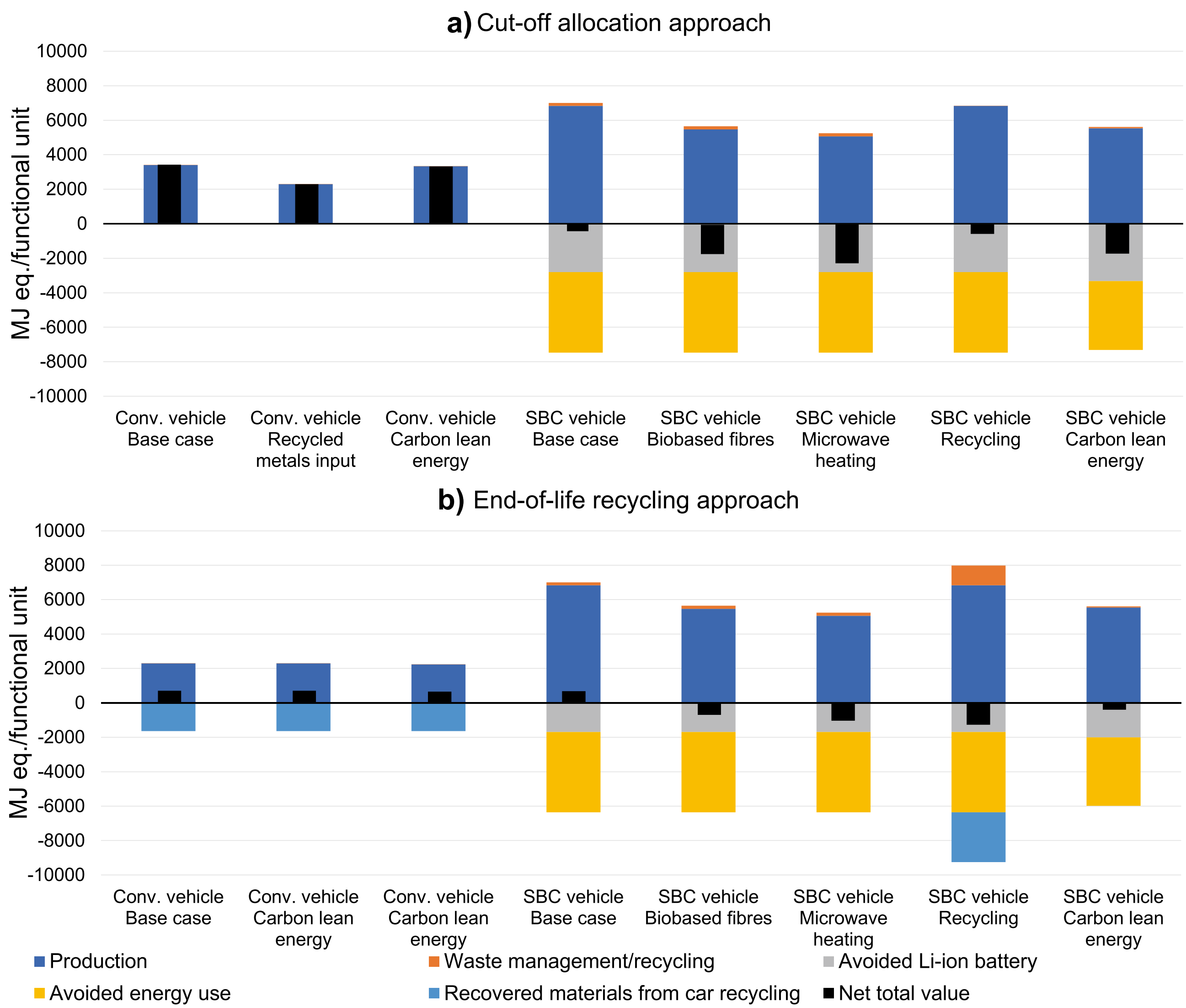

Fig. 5 Life cycle energy use of using the selected elements in a conventional battery electric vehicle and of one with the elements replaced by structural battery composites (SBCs); present scenario base case and for different technology development routes using the cut-off allocation approach (**a**) and the end-of-life recycling allocation approach (**b**). The black bar indicates the net total value

fibres produced specifically for SBCs. The results show that using lignin as a raw material and microwave heating for carbon fibre production are beneficial for decreasing the environmental impact of the SBC vehicle. This is partly due to the raw material being bio-based instead of fossil-based, which means that there are no emissions of fossil carbon from the material during carbonisation and partly due to the assumption that lignin requires less energy for carbonisation than PAN does due to its inherent properties, as reported by Das (2011). We allocate the impacts from the Organosolv process (production of lignin) on a mass basis, resulting in an allocation factor for lignin of 0.34. Using another allocation approach, such as an economic one, which would depend on the future supply and demand of lignin, could give a very different allocation factor (see for example Hermansson et al. (2022b) where the allocation factor ranges from 0.3 to 1 depending on future lignin demand). A higher allocation factor would result in a higher impact per kg of lignin (Hermansson et al. 2020), and thus per kg of SBC. Using microwave heating decreases the impacts due to a significantly lower energy use in the carbon fibre production phase. Results also show that by recycling the SBC, the environmental impacts can be decreased, but to what extent depends on the allocation approach used to distribute impacts between life cycles in the modelling.

The use of SBCs also introduces the possibility of distributing the energy storage throughout the vehicle, thus reducing the need for cables. This could have a large influence on the results, both from avoided cable production and vehicle mass (see the Supplementary Information for calculations and details). More research should be put into assessing how much the cumulated electric wire length of the vehicle could be reduced by using SBCs and how this would influence the environmental impacts.

Results in Figs. 4 and 5 also show that in a carbon lean energy system, the SBC vehicle is likely to perform well compared to the conventional vehicle. However, the modelling is not entirely consistent, as this change could not be applied in all the background systems due to how the database and its datasets are constructed, i.e., the energy supply would have to be manually changed throughout the system. This means, for example, that the impact related to the avoided battery production is likely to be smaller if all energy flows could be updated in a consistent manner.

Assessing the prospective environmental impact of SBCs in comparison to conventional materials in vehicles poses a challenge in different ways. One is that vehicles today have a well-established recycling system to handle waste metals throughout manufacturing and in their end-of-life. This is not the case for the SBC vehicle (however, this was assumed as a possible technology development route). The recycled metals also introduce a cascade of allocation issues throughout the system for all considered cases. Another thing that also results in cascading allocation issues is the introduction of the Li-ion battery in the functional unit, which due to legislation needs to be recycled. The different results provided by the two different allocation approaches in Figs. 4 and 5 illustrate the importance of carefully selecting the allocation approach, and of being transparent with this choice to avoid any bias. Another challenge is related to the possible future development of Li-ion batteries, although they are potentially at a fairly mature and optimised state. As technology matures for SBC, it is likely that the technology for Li-ion batteries also improve to some extent, something that is not considered in this study. As the credit for avoided Li-ion battery production is important for the end-results, any further developments of the battery production that leads to a lower environmental impact will likely have an important influence.

The influence of key parameters and assumptions (effective modulus, energy density, mileage, ERV, and energy use in manufacturing) on life cycle climate impact and energy use of SBCs used in a BEV was tested in a sensitivity analysis, and the results are shown in Fig. 6. The input data is found in the Supplementary Information. The results from the sensitivity analysis show that the climate impact and energy use are the most sensitive to changes in mileage, ERV, and energy density of the material. This highlights that the assumption of mileage and ERV of the vehicle should be done carefully, but also that using the vehicle for a longer time is beneficial as more energy can be saved throughout the life cycle. This could mean that using SBCs in vehicles such as taxis or buses, that are efficiently used, could be more environmentally beneficial than in a privately owned vehicle that is used only sparsely. Additionally, the sensitivity analysis shows that if there is a trade-off for material developers between increasing the effective modulus or the energy density of the SBC, increasing the energy density is more beneficial from an environmental point of view, given that this does not mean adding more carbon fibres and that the flexural stiffness of the car parts is maintained.

A challenge for SBC is that it is most likely not easily repaired and may need replacing if damaged (Ishfaq et al. 2023). The irreparability of the SBC car parts could be captured by an increase in the material used for the vehicle's life cycle with an irreparability factor to account for damages in those cases where a conventional vehicle's car parts could be easily repaired with little environmental impact (such as suction cups for dents) while the SBC car parts would instead need replacement. This is, however, something that would need proper and detailed statistics, but the principle and the possible resulting impact is nevertheless shown in Fig. 7. Figure 7 shows that including risks of damages could have a considerable influence on the end results. This highlights the importance of including risks of damages in the LCA to avoid bias, and, once again, the importance of being careful and transparent when choosing an allocation approach.

4.2 Possible future environmental impacts of structural battery composites

The technology routes in Figs. 4 and 5 were grouped into three different futures: a bioeconomy future, a circular economy future, and a circular bioeconomy future as described in Sect. 3.4. The results are shown in Figs. 8 and 9.

Results show that the lowest climate impact and energy use for the SBC are related to the two futures including a bioeconomy mindset, but these results should be carefully considered as the transitioning to a carbon lean energy system was not done in a fully consistent way, as earlier described. The results suggest that the most effective approach for policymakers to decrease the climate impact and energy use of SBCs in BEVs would be to promote a bioeconomy over promoting only a circular economy. Results show, however, that a combination is beneficial. For other environmental impact category results, see the Supplementary Information.

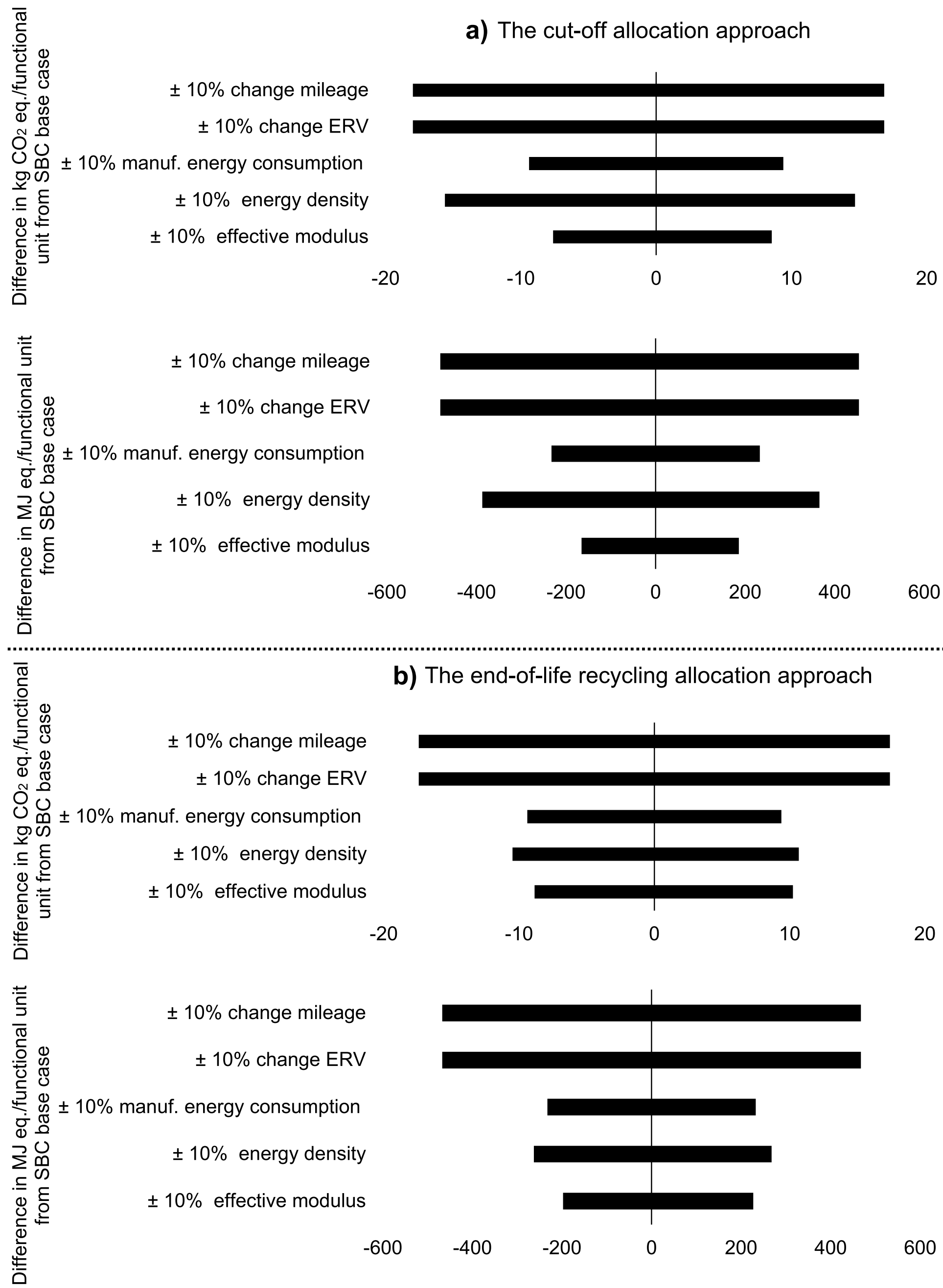

Fig. 6 Sensitivity analysis for changes in mileage, energy reduction value (ERV) energy consumption in the manufacturing, energy density of the structural battery composite (SBC), and effective modulus based on the SBC base case using the cut-off approach (**a**) and the end-of-life recycling allocation approach (**b**)

Note that the different technologies grouped in the scenarios have different TRLs, meaning that some are likely to happen sooner than others. For example, there is, as far as we know, no microwave heating used in carbon fibre production at a higher level than lab-scale, whereas recycling of carbon fibre composites by means of pyrolysis is already at a relatively high TRL (Rybicka et al. 2016). This means that the circular economy future is likely nearer in time than the bioeconomy future. This discrepancy between impact and likelihood to happen is a drawback using the applied method for generating scenarios.

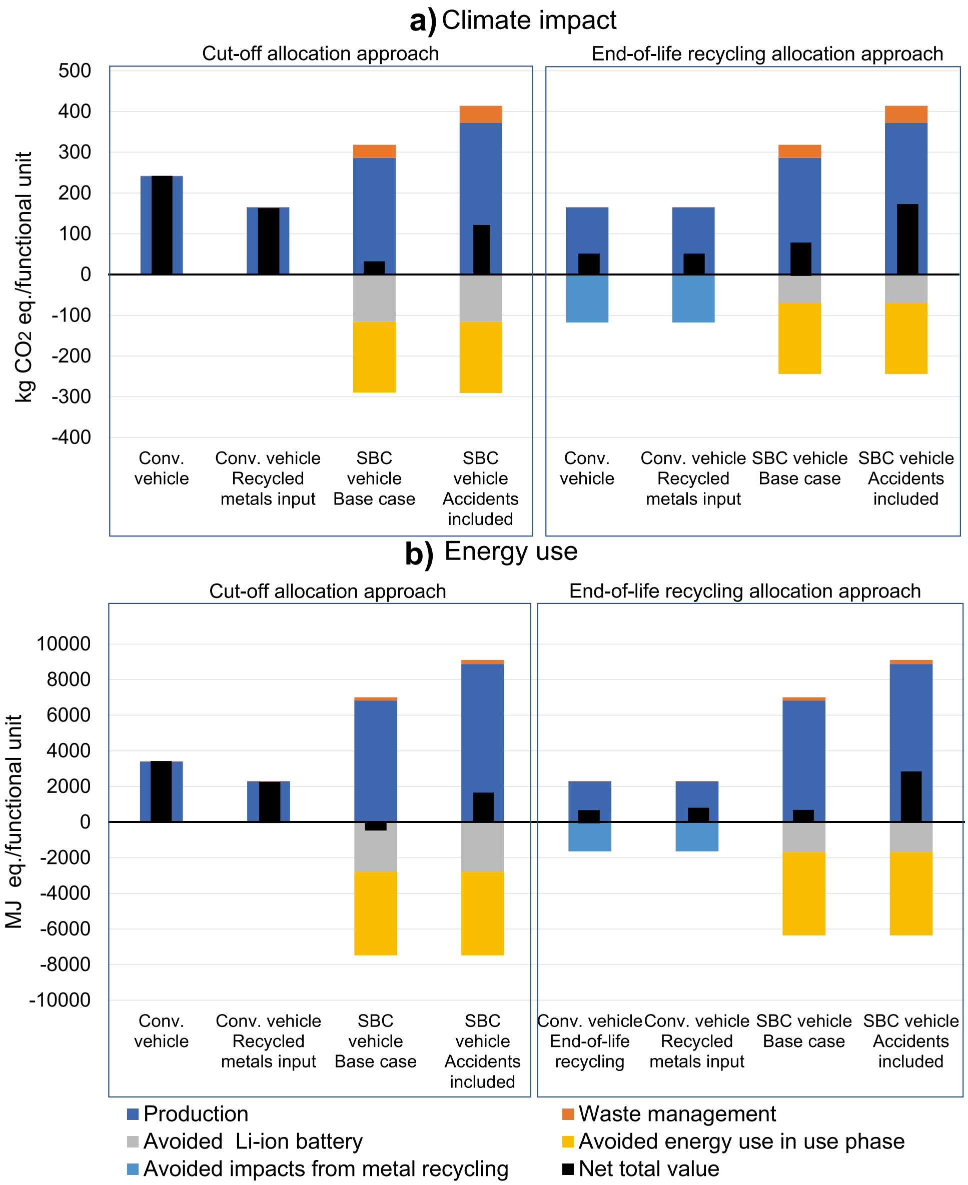

Fig. 7 The life cycle climate impact (**a**) and energy use (**b**) for the base cases for battery electric vehicles with conventional materials and structural battery composites (SBCs) not including accidents compared to when including accidents by incorporating an irreparability-factor of 1.3 applied to SBC materials used and sent to incineration and following different allocation approaches. The black bar indicates the net total value

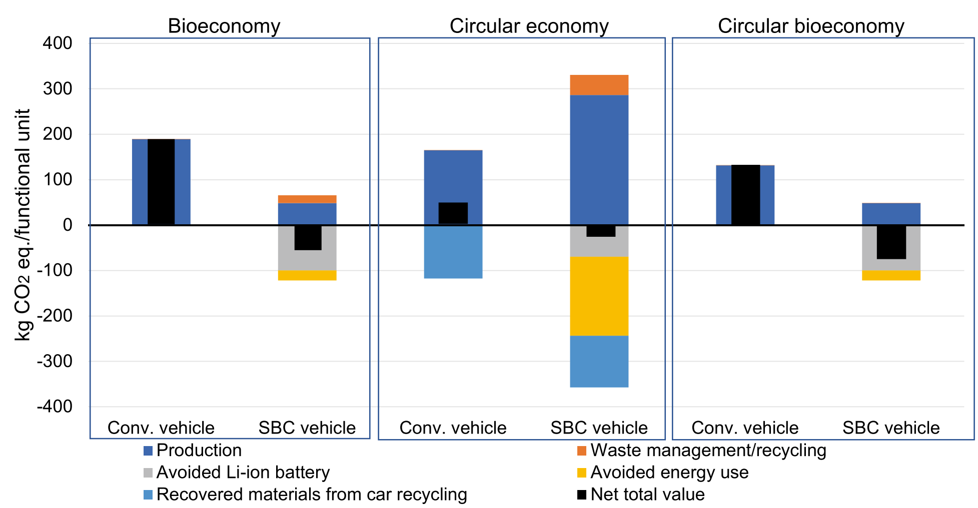

Fig. 8 The life cycle climate impact of using the selected elements in a conventional battery electric vehicle and for one with some details replaced by structural battery composites (SBCs); present scenario (today) and different futures. The black bar indicates the net total value

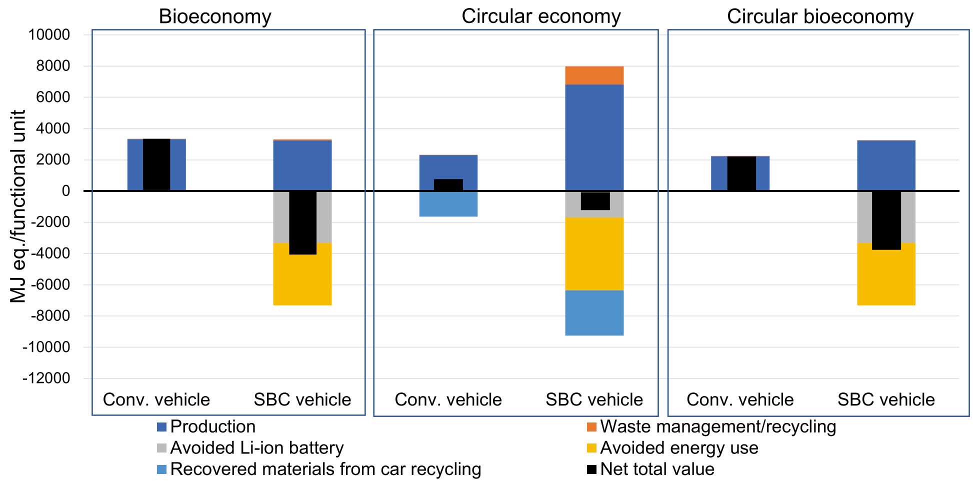

Fig. 9 The life cycle energy use of using the selected elements in a conventional battery electric vehicle and for one with some details replaced by structural battery composites (SBCs); present scenario (today) and different futures. The black bar indicates the net total value

5 Conclusions

This paper assesses the life cycle climate impact and energy use of BEVs when conventional metals and parts of the Li-ion battery are replaced with SBCs. Results show that the use of SBCs in BEVs will likely result in a lower environmental impact than conventional materials, and that using a bio-based precursor fibre, using microwave technology in carbon fibre production, and recycling of the SBC with recovery of fibres are all useful for decreasing the environmental impacts of SBCs further. When combining the technology development routes into different plausible futures, the most effective future for decreasing the environmental impact of SBCs is by focusing on reducing the use of fossils rather than a future with policies and legislation solely focusing on recycling; however, a combination would be most favourable.

This study identifies three main challenges when assessing SBCs using LCA: the comparison to a material with a well-established recycling system throughout its life cycle, the need for expanding the system boundaries to include the Li-ion battery which is being recycled or reused in another application, and the difference in repairability of the SBC compared to the conventional material. The two former challenges are both connected to the need for allocation between life cycles. The applied allocation approach has a strong influence on results, which stresses the importance of using both the cut-off and end-of-life recycling allocation approaches to capture extremes and to not provide biased results. To address the difference in repairability, we suggest using an irreparability factor, ideally based on detailed statistics.

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Data availability All data generated or analysed 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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