Discover Sustainability

Case Study

Wood you believe it? Electric vehicles and engineered wood from an environmental perspective

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Abstract
In the transition to a circular bioeconomy, engineered wood products can help achieve environmental policy targets. Wood has been used as a raw material for various industries for centuries and the automotive industry could utilize wood as a structural component in vehicles. This study investigates the environmental performance of a battery compartment for electric vehicles that relies on engineered wood as a structural component. In a life cycle assessment, the wood hybrid battery compartment was compared to an industry standard over its whole life cycle with two differing end-of-life scenarios. The results indicate that the wood hybrid battery compartment creates substantially less impact over its whole life cycle. The biggest potential for impact savings is identified in the resource extraction- and production phase. In the use phase, the lightweight battery compartment also generates less environmental impact since the use of engineered wood leads to a more lightweight vehicle overall. A material reutilization of engineered wood components in the end-of-life phase further reduces the environmental impact of the wood hybrid battery compartment. The results of this study indicate that the manufacturing of wood engineered structural components for electric vehicles is beneficial from an environmental perspective.

Keywords Life cycle assessment · Circularity · Engineered wood · End-of-life · Electric vehicle · Battery compartment · Automotive

Abbreviations

CFF	Circular Footprint Formula
EoL	End of Life
ISBC	Industry Standard Battery Compartment
WHBC	Wood-Steel Hybrid Battery Compartment
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MCI	Material Circularity Indicator
MDF	Medium-Density Fiberboard
MRS	Material Reutilization Score

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MEM Material Efficiency Metric
SE Energy Utilization Scenario
SM Material Utilization Scenario

1 Introduction

The automotive industry is facing societal and political pressure to increase the sustainability performance of its business practices. For instance, the automotive industry must reduce the greenhouse gas emissions of their fleet [1] and since October 2022 the European Commission reached an agreement that all new cars and vans registered in Europe will need to be zero-emission by 2035 [2]. Furthermore, the reusability and recyclability of components and materials used in vehicles should be increased to 85% of the average weight of a vehicle [3]. In this context, lightweight design has emerged as a strategic solution to reduce vehicle weight by substituting conventionally used materials like cast iron and steels with lighter materials [4].

Wood was used extensively as a lightweight material in the first half of the twentieth century, whether for the skeletons of the first airships [5, 6] or for airplane-fuselages in monocoque design [7]. After the Second World War, wood was used due to the low up-front investment in machinery required, which still makes it attractive to the "makers" of today. In the last decade, wood as a material in mechanical engineering has gained attention again as a renewable material that can potentially reduce the environmental impact of products [8, 9]. However, to find its way into modern vehicle development, it must be assessable by means of computer-aided methods [10], e.g. for crash-safety [11], topology or noise-vibration-harshness analyses [12]. This also requires adequate material models in simulation and characterization methods [13], be it quasi-statically [14] or dynamically [15]. Process control and digital twinning are key to control the degree of variation of this naturally grown material, reducing high safety factors and unleashing its lightweight potential [16].

Especially in civil engineering, thanks to advances in material sorting and the development of wood products such as cross-laminated timber, wood has gained broad interest [17]. A further boost has come from wood modification, which is the collective term for methods that improve the performance of wood in terms of durability, mechanical performance or functionality. Although wood modification has been studied since the early 1900s [18], it has boomed in the last two decades. By modifying wood, e.g. by partial delignification and densification, the tensile strength of the material can be increased by more than 250% with the density only increasing by 100% while at the same time improving dimensional stability [19]. Wood is a naturally grown material with a high degree of variation, but it also features a high specific strength along its fibers, even exceeding that of ultra-high strength steel. It has about 1/10th of its density, which means that components have a higher package volume. As a result, new design principles and approaches are needed with functional integration being a key element [20].

In the automotive sector, wood is currently used in the form of wood-plastic composites for car interiors and mostly as a substitute for plastics [21, 22]. In recent years, several studies have investigated the technical feasibility of using wood to build structural components in vehicles [10, 12, 23, 24]. It was shown that wood can be advantageous compared to conventional materials like steel from a sustainability (i.e., environmental, social and socio-economic) perspective [8, 9, 25]. However, it was also shown that the environmental benefits are mainly due to weight reduction in the use phase and not necessarily due to the substitution of steel with wood [9].

Besides structural, economic and functional demands, there are also requirements in terms of safety and sustainability when applying wood as a structural component in automotive vehicles. In electric vehicles, the battery compartment plays a vital role as a structural component, protecting the cells and modules from abusive, damaging external loads and environmental influences. When using wood in the manufacturing of battery compartments, safety requirements such as mechanical, thermal, electrical and functional safety need to be considered. The occupants must be protected from the chemical, electrical and mechanical dangers of a cell [26, 27].

With the new battery directive [28], which was issued as a part of the European Green Deal in 2020, there are also legislative requirements in place when it comes to sustainability: The regulation requires the eco-design and recyclability by design [29]. This includes the life cycle analysis of batteries, the introduction of a carbon footprint label declaring the environmental impact of all battery value chains placed on the EU market as well as guidelines and standards for repurposing batteries from electric vehicles covering testing, grading and safety guidelines [30, 31]. For battery compartments, this implies the provision of means for reusing, remanufacturing and recycling: This can be achieved by using recyclable materials, reducing the quantities of used materials, enhancing the identifiability of materials and maximizing the reparability [32]. To achieve these goals attention needs to be focused on the applied materials and their possible reutilization in the end-of-life (EoL).

The EoL (and use-) stage are connected with the most uncertainties [33] as these occur only in the future and depend on factors like the user behavior or regulatory constraints with regards to EoL pathways in different countries of the world. To assess the use stage of vehicles in life cycle assessments (LCA), models like the New European Driving Cycle or the Worldwide Harmonized Light Duty Test Procedure provide emission factors for average driving cycles [34]. The EoL is strongly influenced by the geographical context in which the vehicle is disposed of. Different countries have different regulations and practices in place on how to handle products and materials at the EoL. This also requires ease of disassembly through detachable joints, but also the standardization of design and architecture [35]. In the EoL of a vehicle, the reusable parts are dismantled, and the remainder is shredded and sorted [36, 37]. Compared to metals, which are separated from the shredded parts, all other materials (e.g., plastics rubber, wood or textiles) are currently either incinerated or landfilled [38–40]. Increasing resource efficiency as promoted by the circular economy or bioeconomy strategy means to use materials and products multiple times to increase the utilization time [41]. Therefore, it is necessary to investigate the potential impacts of future scenarios in which wood is used in automotive applications.

Cossu and Lai (2015) have investigated different management options for vehicles at the EoL and concluded that a combination of recycling and energy recovery is necessary to achieve the targets set by the EU directive 2000/53/EC [3]. The targets set in this directive are a material recovery rate of at least 95% by vehicle weight, with no more than 10% of this mass permitted to be recovered as energy and less than 5% to be deposited in landfills. This directive has been used in determining target material recovery rates in some LCAs on vehicles EoL in the European context [42, 43].

Modelling the EoL of vehicles is currently not always covered in LCAs. Studies which do consider the EoL focus on assessing the global warming potential but less on other impact categories [44]. Additionally, impact categories addressing resource use like the resource depletion potential are frequently overlooked in the analyses. Yet, it should be prioritized when assessing the impacts of the EoL, as it considers the rate at which resources are consumed [42]. Adding to the complexity, methodologically there are many ways to model the system boundaries for the EoL of a vehicle with no consensus on the single best approach. The most implemented approaches are the cutoff and the avoided burden approach [44]. To account for different recycling contents and rates, the European Union introduced the circular footprint formula (CFF), which was developed within the product environmental footprint method. In their study, Accardo et al. (2023) implemented and compared the traditional avoided burden method and the CFF. Their results showed a higher global warming potential with the CFF compared to the avoided burden method.

To gain a more comprehensive understanding of the EoL stage, it is beneficial to incorporate further circularity indicators alongside LCAs to monitor circularity variables throughout the supply chain [45]. Circularity indicators can enhance decision-making by integrating technical quality specifications, such as recyclability or reusability [46]. In the context of the automotive industry, Matos et al. (2023) have implemented five circularity indicators: the Recycling Desirability Index, the Material Reutilization Score, the Value-Based Resource Efficiency Indicator, the Material Circularity Indicator and the Circularity Indicator for automotive plastic parts [47]. Mansuino et al. (2024) focused on Swedish automotive products and emphasize the improvement and evaluation of the methodological framework by collecting qualitative and quantitative data to calculate scores for individual aspects of the indicators [48]. However, only one of those studies incorporated LCA into their analyses in which the circularity and environmental performance through LCA of two different battery cells was assessed [49]. In general, there has been limited research examining the implementation of both LCA and circularity indicators within the automotive context.

In this study we present a LCA in which the environmental impact of a novel wood-steel hybrid battery compartment (WHBC) manufactured from laminated wood and steel is being compared to an industry standard battery compartment (ISBC). This study contributes to the field of LCA research by exploring the sustainability potential of renewable materials in electric vehicle design. The results from the assessment of this key component may have implications on the manufacturing of other components of electric vehicles. If structurally important components in electric vehicles, such as battery compartments, can be manufactured with this novel approach and are environmentally less impactful, then many other components of electric vehicles may also be manufactured in a similar manner.

This paper aims to explore the following research objectives with the region of Austria and Europe as focus:

- Depict the future EoL pathways and circularity based on circularity indicators for the wood-hybrid battery compartment

- Assess the potential environmental impacts incl. hotspots of the ISBC and WHBC for electric vehicles
- Compare the circularity of the ISBC and WHBC

2 Method, materials and data

2.1 Case study description

In this paper, a lightweight battery compartment for electric vehicles will be investigated and compared to an industrial standard used in fully electric vehicles. The battery compartment was chosen as the object of the case study for two reasons: It is a voluminous and structurally important component in electric vehicles which offers a large potential for substituting materials. Furthermore, there has not yet been a consolidation from a design perspective. Thus, it represents an ideal vehicle for implementing sustainable structural construction due to the potential for innovation, dynamics and change in this area. Both compartments investigated are illustrated in Fig. 1.

The ISBC is based on a standard battery compartment used in a well-known electric vehicle series. A more detailed description of properties of the ISBC can be found in a related work [12]. The WHBC consists of the following main components: underfloor, frame, cell holders, center web and lid. The underfloor is a laminate with a 15 mm thick poplar laminate core and an inner and outer layer of 0.8 mm thick high-strength steel. A special adhesive is used to bond the steel layers to the laminate core. This layup aims to provide a strong and rigid structure to protect the batteries against intrusions from below. To protect the surrounding edge of the underfloor from environmental and chemical exposure, it is covered with modified veneer layers. Studies on the chemical resistance of modified veneers like radiata pine [50] and birch [51] were conducted. The frame is composed of an internal poplar glulam core and a surrounding steel shell. The cross-section of the frame is 30 × 90 mm and the surrounding high-strength steel shell has a thickness of 0.8 mm. One major function of the frame is to protect the batteries from side intrusions, such as a pole impact. The mechanical performance of the frame has been evaluated using three-point bending tests on different wood cores such as birch, poplar and paulownia. The cell holders that surround the batteries are made from a cork composite consisting of cork granules, natural fibers and a binder. In total 18 cell holders are integrated into the battery compartment, with the cooling system being part of the cell holders. The center web, which is constructed of glued laminated timber, houses the central strands of the cooling- and power system. The top side of the battery compartment is covered with a lid made of a laminar structure, including cork composite, a thin steel layer and a

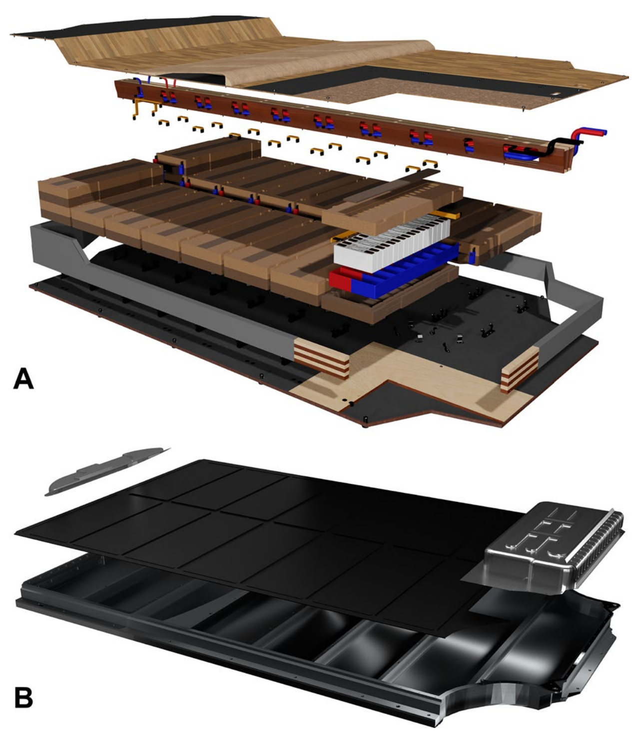

Fig. 1 Illustration of the assessed battery compartments, **A** Depiction of the WHBC, **B** Illustration of the ISBC

special parquet flooring system. The idea behind this layup is to integrate several functions, such as fire protection and passenger compartment flooring, into a single structure. The overall battery compartment dimensions are 2680 mm × 1540 mm × 215 mm.

2.2 Goal and scope definition

The aim of this paper is to assess and compare the potential environmental impacts of the WHBC and ISBC in several impact categories. As functional unit a battery compartment for an electric vehicle with a potential capacity of 77 kWh is defined since the battery compartment is designed for a specific car model. The battery compartment is furthermore a structural component capable of safely storing and thermally managing battery cells. The lifetime of the battery compartment is assumed to be the travelling distance of 200 000 km in Austria which reflects the predicted service life of vehicles [52, 53]. It is assumed that the battery compartments are manufactured and disposed of in Austria. The total weight of the ISBC and WHBC are 200,28 kg and 144,5 kg, respectively.

The system boundaries applied in this assessment are depicted in Figs. 2, 3. The resource extraction- and production-, the use- and the EoL phase are included in this study. In Fig. 3 two alternative EoL scenarios are depicted. The respective process steps for each scenario are differentiated by color, both scenarios are described in detail below.

The life cycle inventories (LCI) for the ISBC and the WHBC were developed within a research project, detailed information can be found in a related publication [12]. Assumptions on the use phase are based on the literature [54, 55]. The EoL steps (i.e., disassembly, shredding, separation and treatment) are based on literature as well and the energy demand is calculated with reference to existing studies.

Foreground data include the material and energy demand in the production of the battery compartments as well as the energy demands in the sorting and shredding process in the EoL phase. All other (background-) data was obtained from Ecoinvent 3.10.

The impact from the production of both battery compartments is fully attributed to the battery compartments. Recycled materials and recovered energy in the EoL are subtracted from the respective impact of the battery compartment since it is assumed that they can substitute primary materials and energy. A detailed list of the used processes can be found in the supplementary material. The LCA was conducted with the software SimaPro.

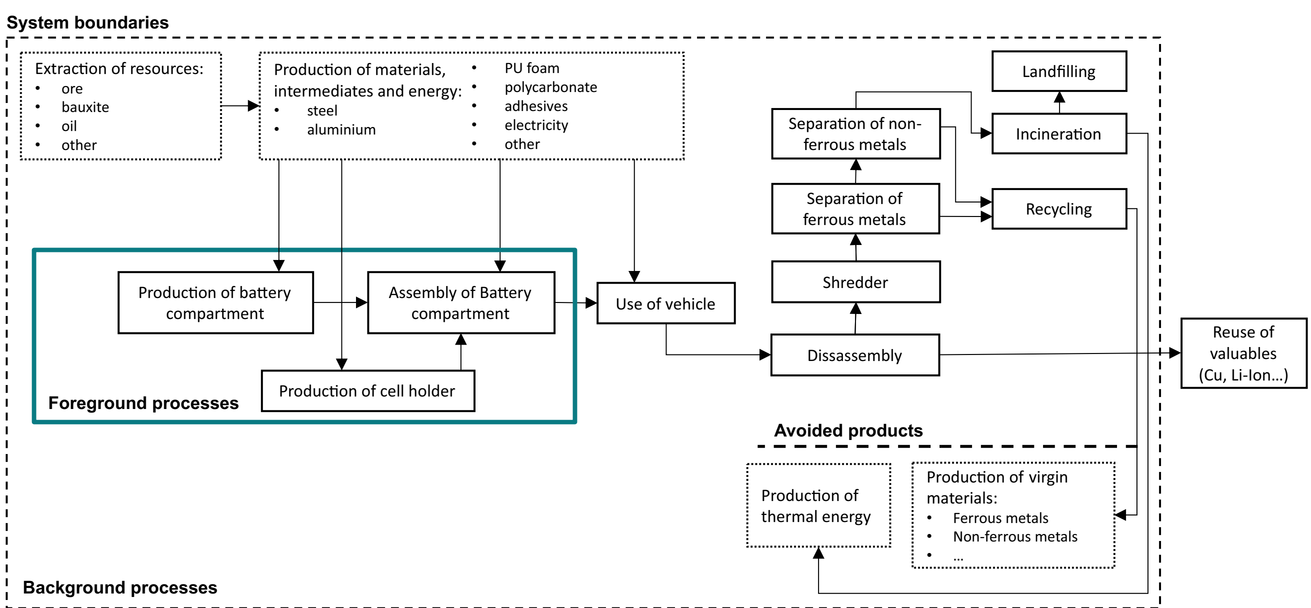

Fig. 2 Product system including system boundaries of the ISBC

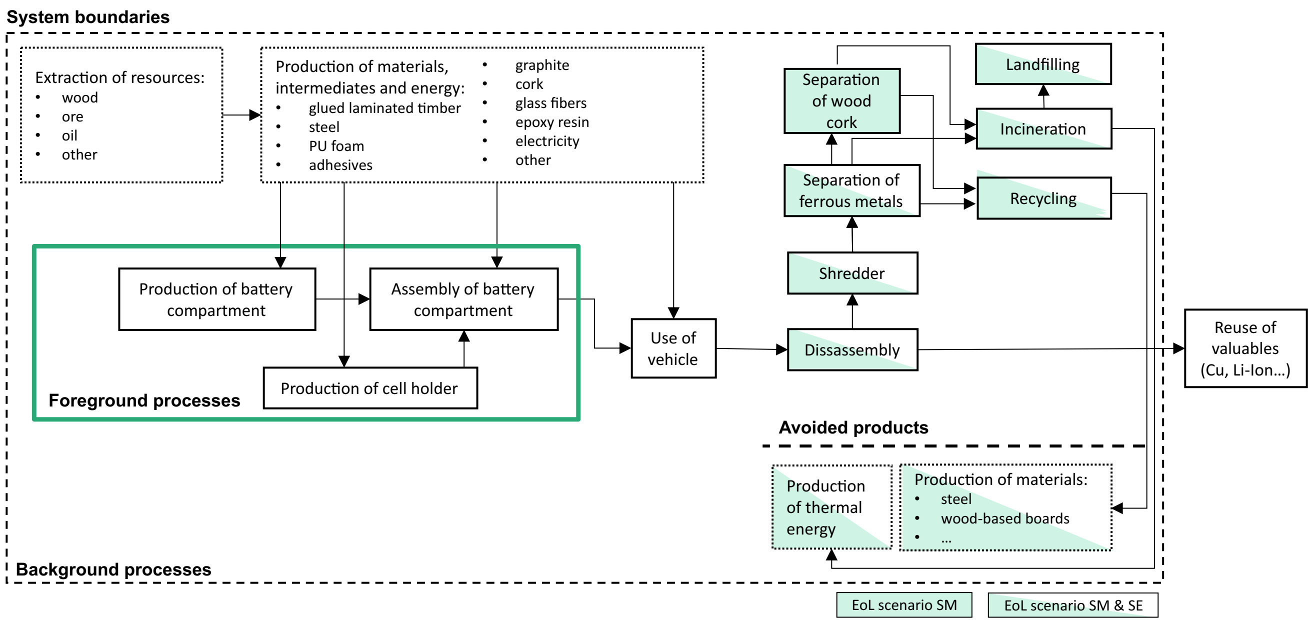

Fig. 3 Product system including system boundaries of the WHBC for the two EoL scenarios SM und SE. Process steps which are highlighted in green are only considered in the scenario SM. Process steps which are colored green and white are considered in both EoL scenarios

2.3 Life cycle phases

2.3.1 Resource extraction—and production phase

The WHBC investigated is mainly made of steel, glued laminated timber and cork composite, in contrast to the ISBC, which is mainly manufactured from aluminium alloys and steel. A detailed overview of the used materials for both battery compartments is given in Table 1. The glued laminated timber is sourced from poplar which is assumed to have a density of 450 kg/m^3 [56].

2.4 Use phase

In the use phase only the electricity demand to power the vehicle is considered. To calculate the influence on electricity demand of differing weights during the use phase, a linear correlation between electricity demand and weight is assumed [54, 55] and no maintenance or replacement of parts is considered. An energy demand of 8.43E-05 kWh/

Table 1 Materials used for the production of the two battery compartments

	ISBC		WHBC	
Battery compartment	Aluminium alloy	93.50 kg	Steel, low-alloyed	79.48 kg
	Aluminium cast	4.69 kg	Glued laminated timber	33.75 kg
	Steel, low-alloyed	26.09 kg	Cork composite	1.24 kg
	Bonded Mica	7.92 kg	EPI glue	1.64 kg
	PU foam, flexible	0.85 kg	1kPUR glue	0.18 kg
	glue	0.03 kg		
Cell holders	Aluminium complex alloy	43.2 kg	Graphite	4.2 kg
	Polycarbonate	9.6 kg	Cork composite	16.8 kg
	PU foam, rigid	14.4 kg	Glass fibers	1.4 kg
			Epoxy resin	5.6 kg
	Total weight	200.28 kg	Total weight	144.5 kg

kg*km is assumed [57]. Since the vehicles with the respective battery compartment will travel mainly in Austria, the Austrian average energy mix is considered in the use phase.

2.5 End-of-life phase

In the EoL phase of electric vehicles, reusable components such as batteries are stripped from the car and may be used in a second life cycle [36, 37]. The remainder of the car is then shredded and separated into a magnetic-metal fraction, a heavy-material fraction and other residues such as textiles, rubbers and plastics [38, 39]. This paper exclusively assesses the environmental performance of battery compartments, the EoL phase only investigates the shredding of the battery compartments and the consequent sorting of the used materials. The reuse of valuable parts in the battery is not included, the focus here is on the battery compartment and therefore the recycling of electronic components and Li-Ion battery cells is not considered.

Depending on the respective material, certain recycling processes can be assumed. For example, metal recycling is a well-established technology and recycling rates for steel and aluminium are usually well above 50% [58]. In the EoL-phase of the ISBC, it is assumed that after shredding 74% of the aluminium alloy and aluminium cast [59], 20% of the aluminium complex alloy [60] and 90% of steel are separated, remelted and reused [61]. The remainder of the materials is incinerated to obtain heat except for the bonded mica which is assumed to be disposed of in a landfill (no data could be found on EoL practices for bonded mica; since it is manufactured from silicon, which is the second most abundant material in earth's crust [62], no special treatment at the EoL was considered). In the WHBC, steel is the most abundant component of the battery compartment. As with the ISBC, a recycling quote of 90% is assumed.

Glued laminated timber and cork composite are other important components to be accounted for in the WHBC. The main obstacles of reutilizing waste wood are impurities and chemicals, which are mainly present in low-quality waste wood [63]. Due to the state of current regulations in Austria, it is uncertain if glued laminated timber can be utilized other than by incineration to obtain heat. Since the utilized wood in the WHBC is exclusively glued laminated timber, it can be assumed that it can be downcycled and thus reused in other low-grade wood-based products after its initial use [64]. The cork composite may also be reused by simply remolding it after its first life cycle [65]. Current regulations in Austria do not allow for recycling or reuse of wood engineered products [66] but with more elaborated process technologies for separation, legislation may change in the future.

To account for this, two EoL scenarios have been defined for the WHBC: In the scenario material utilization (SM), it is assumed that 75% of the used laminated timber is reused for manufacturing medium-density fiberboards (MDF) and 75% of the cork composite is reused as cork composite, with the remainder being incinerated. In the alternative scenario energy utilization (SE), it is assumed that all of the laminated timber and cork composite are incinerated to obtain heat. The other materials used in the WHBC such as glues, graphite and epoxy resin are assumed to be incinerated in both scenarios. The following heating values have been assumed for the respective material: 20 MJ/kg for glued laminated timber [67], 19 MJ/kg for the cork composite [68], 32.8 MJ/kg for graphite [69], 30 MJ/kg for epoxy resin [70] and 7.7 MJ/kg for all polymer-based glues and thermoplastics [71].

A study reports that glass fibers may be recycled with novel processing technologies, but also state that they cannot replace newly manufactured glass fibers in terms of mechanical properties [72]. Since the glass fibers are used as isolation material, it is assumed that there are high quality requirements which only virgin glass fibers can satisfy and thus it is assumed that these are deposited in a landfill.

The recycling of traction batteries generally begins with the collection of the battery systems and dismantling, e.g. the removal of the battery cells or battery modules from the battery compartment to subsequently recycle both the batteries and the compartment [73]. For an equivalent analysis, it is assumed that the battery compartments are first shredded and then fractionated into different materials. The aim in this process step is to separate steel, aluminium and wood as well as the cork composite as extensively as possible. Depending on the material composition and approach, different sorting methods are used until the remainder of the materials, which are not recyclable, are thermally utilized (Fig. 3).

To quantify the energy needed, the respective energy demand of a process is compared with the necessary output. For each step, the demand is calculated with the estimated performance of the processing unit, the achievable throughput and the mass to be treated is described by (Eq. 1). The system specifications are taken from specifications of process machineries based on literature. The energy output is defined as the recycling quote of the product and the heating value for incineration as shown by (Eq. 2).

$$Energy\ Input = Power * \frac{Recycled\ Mass}{Throughput} \tag{1}$$

$$Energy\ Output = Heating\ Value * Recycled\ Mass \tag{2}$$

Table 2 shows the processes of the various scenarios and their specific energy demand for the process applications as well as the achievable outputs. For the shredding process, a nominal power of 250 kW is assumed for all scenarios [74]; the throughput for all shredding- and sorting processes is 5000 kg/h [74–78]. The separation of ferrous metals such as steel is usually based on magnetism [76, 79], while non-ferrous metals such as aluminium are separated using eddy currents [78, 79]. In the case of wood and cork separation, it is assumed that all sorting systems consume about the same amount of energy, since in addition to the available sensors, conveying- and manipulation energy is primarily required. Industrial applications to separate wood and cork include sorting based on density, e.g. using sediment separators [39], optically assisted sorting systems [80] as well as X-ray [81] and infrared technology [82].

As depicted in Table 2, the shredding process has the largest relative energy consumption. Sorting processes require approximately 10% of the shredding process per separation step, depending on the design. In addition, depending on the materials involved, material recovery for reintegration into the life cycle is of crucial importance.

2.6 Impact assessment

The impact assessment considers all previously mentioned life cycle phases, as an impact assessment method ReCiPe 2016 (H, long-term emissions included) was chosen. This method was selected for its integration of midpoint and endpoint categories which provides a comprehensive assessment of the environmental impacts of the novel wooden steel hybrid battery compartment across many different aspects. The avoided burden of materials in the EoL is considered as credit for the production of the initial respective battery compartment and is therefore deducted from the impact [84].

Furthermore, three indicators, which aim to measure resource efficiency and circularity are assessed: the Material Reutilization Score (MRS), the Material Circularity Index (MCI) and the Material Efficiency Metric (MEM). The MRS, MCI and MEM quantify the circularity of a product in between a range of 0 and 1, with higher scoring products being more circular and sustainable. The MRS includes the recyclability as well as the recycled content to formulate a score [85], the MCI additionally considers whether a material is reused or just recycled and the recycling efficiency [86]. The MEM formulates a ratio dependent on the amount of virgin- and recycled material used in the manufacturing of a product [87]. All of the mentioned indicators directly consider the share of recycled material whereas only the MCI additionally rewards the utilization of reused material.

3 Results

3.1 Comparative results

Figure 4 indicates the environmental impact of the battery compartments at the endpoint level. The biggest potential reduction of environmental impacts is achieved in the resource extraction- and production phase in all three endpoint categories as indicated in Fig. 4. The WHBC demonstrates the greatest potential improvement relative to the ISBC in the endpoint category human health. In the use phase, the WHBC exhibits superior performance due to potential energy savings resulting from its reduced weight. As mentioned above, no repairs nor replacement of any parts have been considered in the use phase, only the consumption of electricity for the electric drive train. Regarding the EoL phase, the ISBC shows greater potential for avoided burdens through material reutilization. However, this is primarily attributable to the high-impact materials used in its initial production phase. Overall, it is apparent that the WHBC is the preferable alternative from an environmental perspective.

Figure 5 shows the performance of the ISBC and WHBC in each individual category on a midpoint level. The performance in both EoL scenarios was normalized, where 0 represents the best performance (minimal environmental impact) and 1 the highest relative impact. The WHBC demonstrates better environmental performance across all categories except land use for the scenario SE. Notably, the WHBC exhibits substantial impact reduction potential in fine particulate matter formation, ozone formation, terrestrial acidification, terrestrial ecotoxicity and human carcinogenic toxicity. In the SM

Table 2 Specifications for the EoL for both battery trays

Process		ISBC		WHBC			Sources
		Input	Output	Input	Output (SM)	Output (SE)	
Shredding		36.05 MJ		26.01 MJ	–	–	[74, 75]
Sorting	Separation of steel	2.88 MJ	23.48 kg steel (90% RR)	2.08 MJ	71.53 kg steel (90% RR)		[61, 74, 79]
	Separation of aluminium	1.88 MJ	104.63 kg aluminium (74% RR)	–	–	–	[77, 78]
	Separation of wood / cork composite	–	–	0.94 MJ	25.31 kg wood (75% RR) 13.53 kg cork composite (75% RR)	–	[83]
Energy- and material recovery		Various polymers (7.7 MJ/kg)	191.58 MJ	Wood (20 MJ/kg)	168.8 MJ 25.31 kg	675 MJ	[67]
				Cork composite (19 MJ/kg)	85.69 MJ 13.53 kg	342.76 MJ	[68]
				Graphite (32.8 MJ/kg)	137.76 MJ		[69]
				Epoxy resin (30 MJ/kg)	168 MJ		[70]
				Various polymers (7.7 MJ/kg)	14.01 MJ		[71]

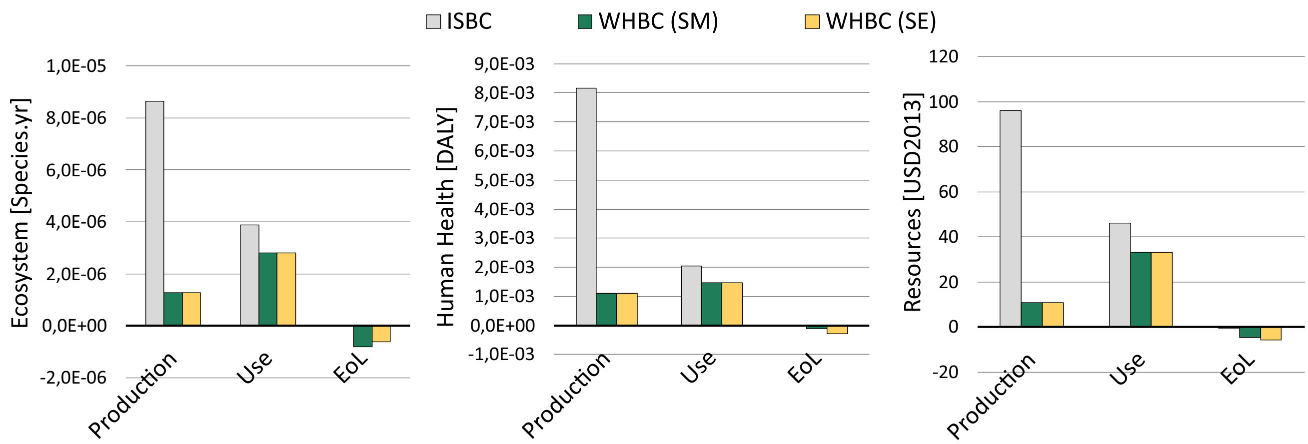

Fig. 4 Results of the LCA on an endpoint level

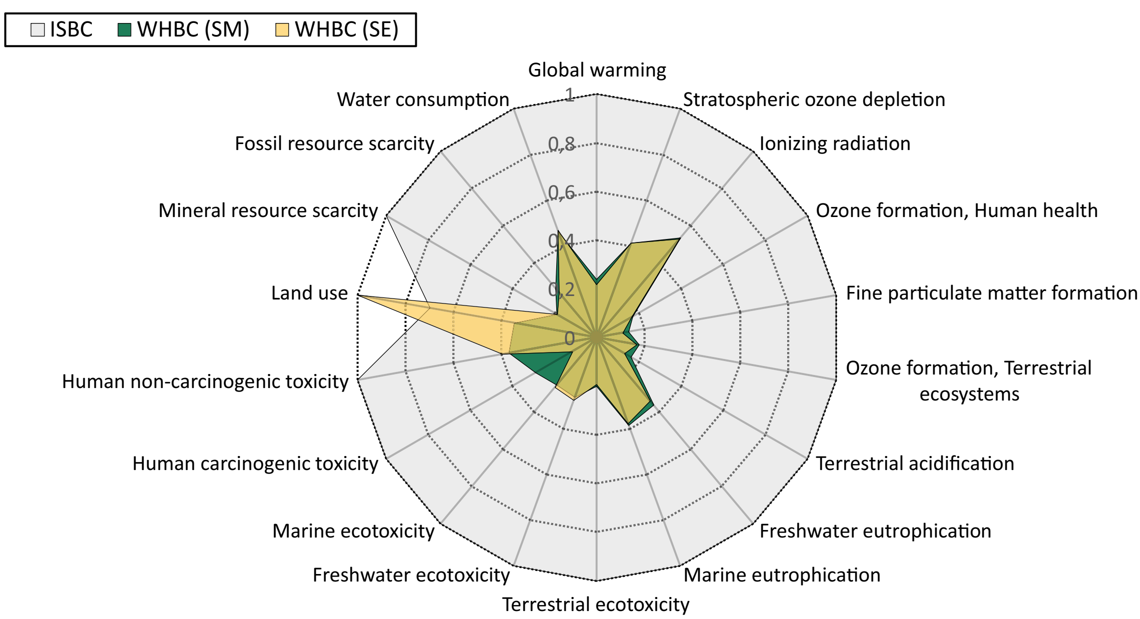

Fig. 5 Impacts on a midpoint level

scenario for WHBC, it is assumed that waste wood and cork composite can be reused to produce MDFs and additional cork composite. This approach yields a comparatively lower environmental impact than the SE scenario, where both waste wood and cork composite are incinerated for the recovery of heat. In the category land use the advantages of the material utilization in scenario SM, compared to a thermal utilization in the scenario SE, can be clearly observed. This suggests that thermal utilization of laminated timber and cork composite should be considered only when re- or downcycling options have been exhausted. Furthermore, the ISBC does not incorporate any engineered wood or cork composite and still has a relatively high impact in the category land use compared to the WHBC in the scenario SM.

3.2 Contribution analysis

A detailed analysis of the resource extraction- and production phase was conducted to identify hotspots, as this phase bears the highest environmental impact compared to the other lifecycle phases. Figures 6 and 7 show the environmental impact in the resource extraction—and production phase for the ISBC and the WHBC, respectively. As shown in Fig. 6, aluminium—and aluminium complex alloy have the biggest relative environmental impact in all categories due to the energy intensive production [88] and the quantity used in the ISBC. Another major contributor to the environmental impact is rigid PU foam which is mainly used in the cell holders of the ISBC. Besides that, steel, aluminium cast and

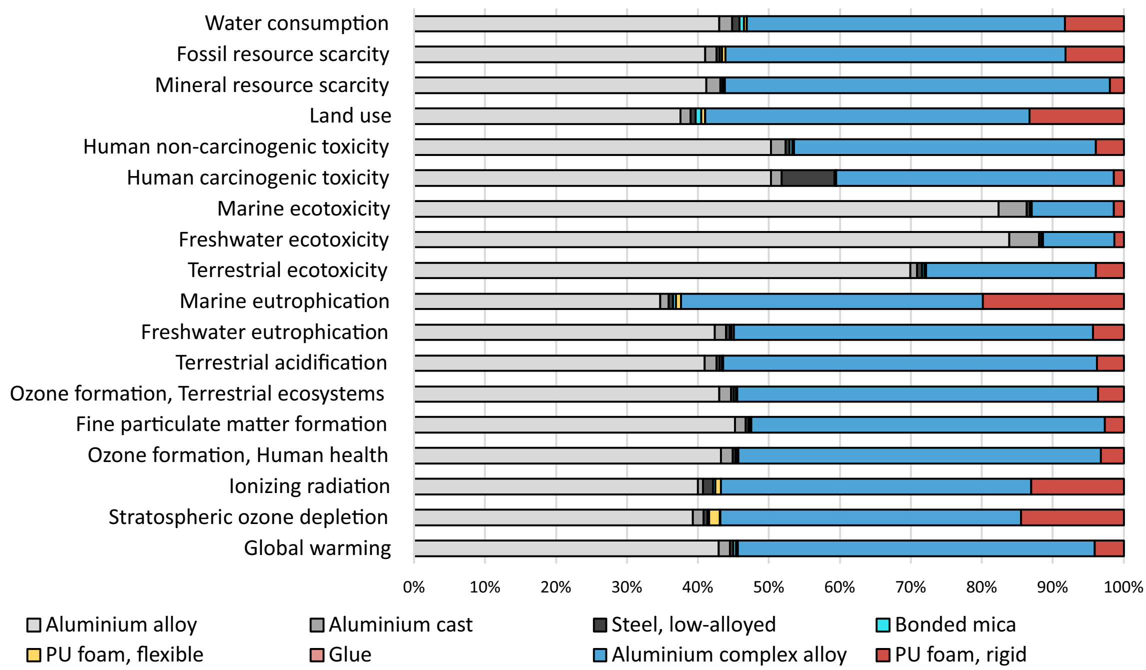

Fig. 6 Hotspots in the resource extraction—and production phase of the ISBC

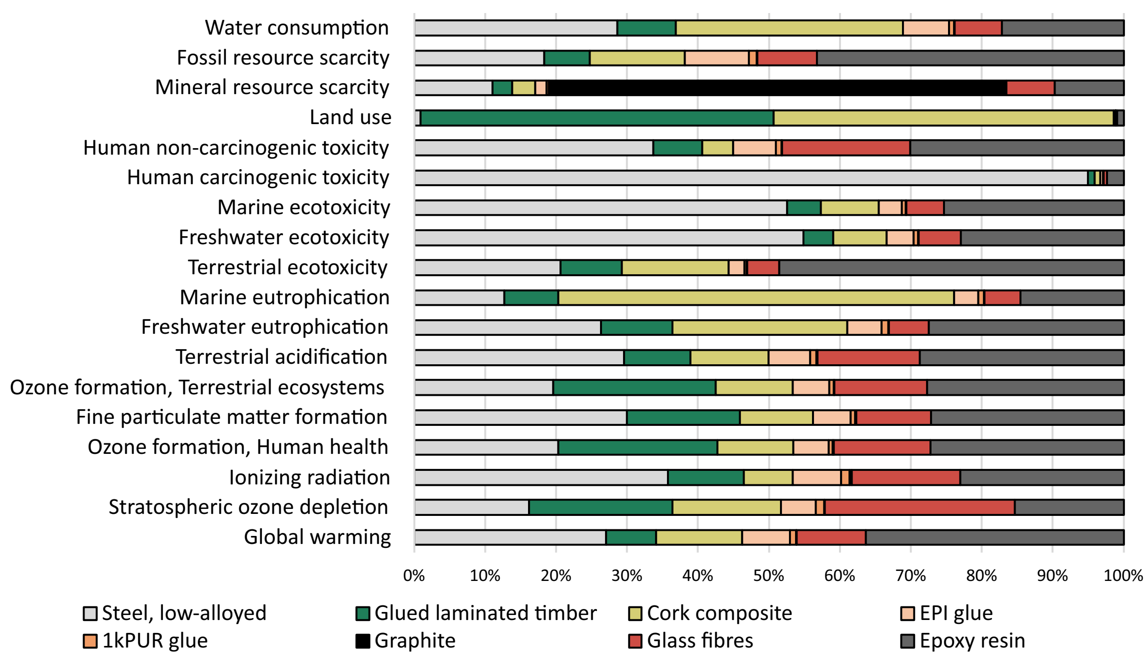

Fig. 7 Hotspots in the resource extraction—and production phase of the WHBC

polycarbonate, being materials, which are not used in extensive quantities, contribute to a lesser extent to the impact. To effectively reduce the impact of the ISBC, the development of innovative aluminum production methods are necessary which require less electric energy [88].

Figure 7 depicts the environmental impacts associated with the WHBC. In contrast to the ISBC, the WHBC exhibits more diversified relative impacts: No single material dominates the impacts in any category. Low-alloyed steel and epoxy resin emerge as large contributors to the environmental burden of the WHBC. Especially in the category human carcinogenic toxicity low-alloyed steel is responsible for over 90% of the impact. However, glued laminated timber and cork composite also contribute to the impact and they dominate the category land use. Glass fibers cause the relatively biggest impact in the category stratospheric ozone depletion. A further noteworthy result is the contribution of graphite to the impact in the category mineral resource scarcity. Graphite is currently not considered as a critical raw material, however recycling efforts in the production of lithium-ion batteries, where graphite is used as electrode material, have not yet been in focus [89].

3.3 Circularity performance

The circularity indicators were calculated for both battery compartments and the results are presented in Fig. 8. The WHBC in the (SM) scenario has the highest score for all three indicators. Since the WHBC produces less environmental impact than the ISBC it is not surprising that the indicators rank it as the less impactful alternative. The SM scenario demonstrates superior performance compared to the SE scenario, primarily due to its greater avoided burden. This advantage is attributed to the material utilization approach at the EoL stage. The disparity between the SE and SM scenarios for the WHBC is relatively minor when compared to the more substantial difference observed between the ISBC and the WHBC. Based on the results it can be argued that the WHBC in the scenario SM is the more circular alternative.

3.4 Uncertainty analysis

To account for the uncertainty inherent in the assumptions made and inventories used for the environmental impacts, a Monte Carlo analysis was conducted [84]. Since the resource extraction- and production phase is the life cycle phase with the highest impact, the uncertainty analysis focused exclusively on this phase. Uncertainties in the quantities of used materials have been simulated in 1000 iterations, the results are depicted in Fig. 9. The results have been normalized with 1 indicating a higher environmental impact in the respective category.

The Monte Carlo analysis demonstrates that changes in the material composition of the respective compartment do not influence the overall results. The WHBC consistently outperforms the ISCB by a substantial margin, with the exception of land use. In this category, even when considering extreme scenarios within the range of uncertainty, the WHBC will perform worse than the ISBC. This persistent trend in land use impact underscores the robustness of the initial findings and highlights a key trade-off in the environmental performance of the WHBC. The material reutilization of wood and cork composite at the EoL though can offset this relatively higher impact as depicted in Fig. 5.

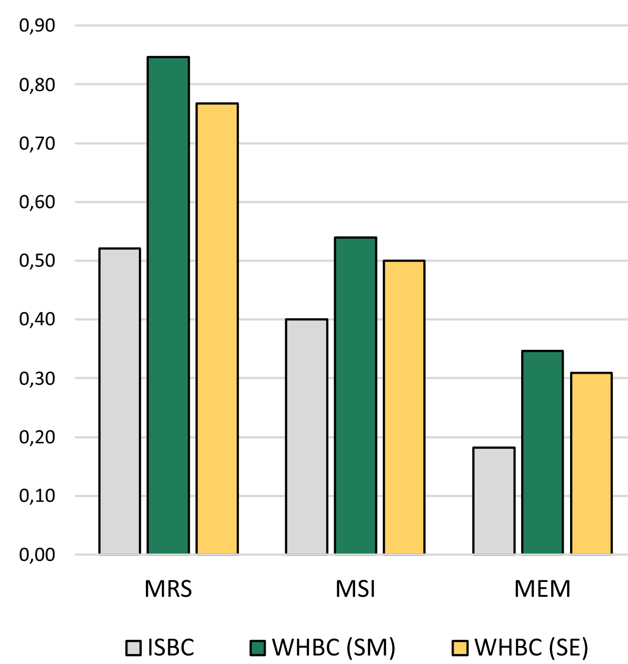

Fig. 8 Selected circularity indicators; a higher score indicates a better performance

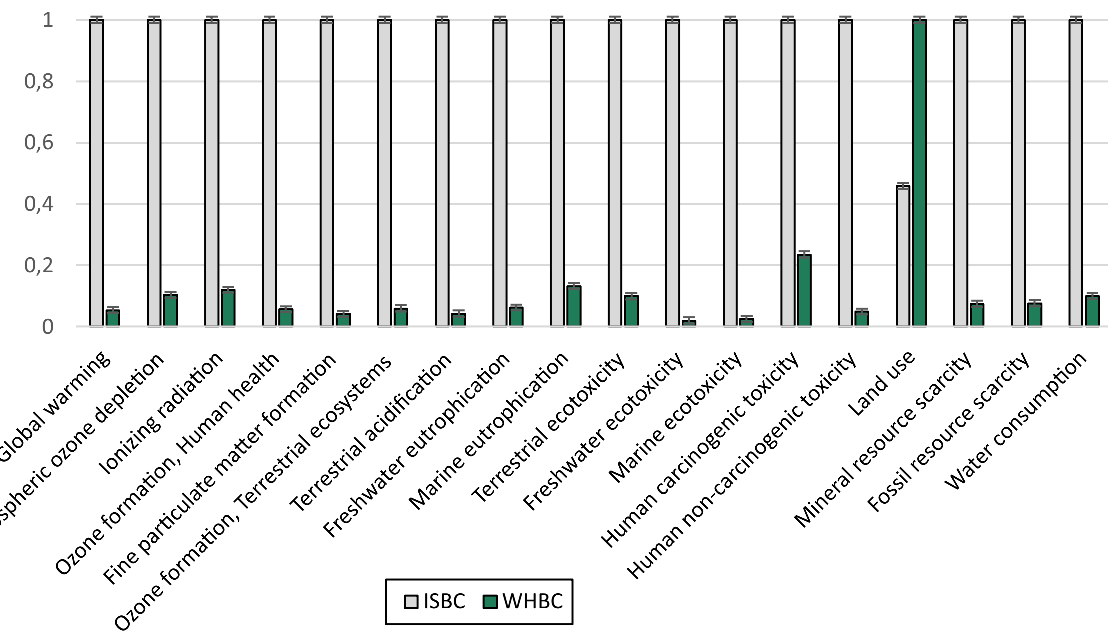

Fig. 9 Uncertainty analysis

4 Discussion

4.1 Environmental performance and hotspots

The assessment of the two battery compartments in this work revealed valuable insights into potential environmental advantages of an innovative battery compartment manufactured from renewable materials. It has been shown that the WHBC induces less environmental impact over its whole lifecycle compared to the ISBC. Especially in the resource extraction- and production phase, the WHBC bears a large reduction of environmental impact. In the use phase, due to the lightweight construction of the WHBC, less electricity is needed which also results in a reduced, albeit smaller, environmental impact. These results differ from the findings of another study which investigated engineered wood in automotive applications where the biggest reduction potential was identified in the use phase because of lightweight design and not because of the replacement of steel with wood [9]. Unlike in this study though, a combustion vehicle was examined that uses gasoline instead of electricity. Compared to electric vehicles, combustion vehicles typically have the most substantial impact in the use phase [90] and thus also benefit from a reduced vehicle weight. In the present study aluminium is replaced with a wood-based multi-material system where steel is used as part of the structural elements instead of aluminium. The higher reduction potential of the WHBC can be explained by the fact that aluminium relates to different environmental issues (e.g., GHG emissions, land use change or freshwater ecotoxicity) [91, 92] and forms a hotspot in different impact categories for the ISBC in the present study. Replacing aluminium with less harmful materials like wood, steel and cork increases the benefits from an environmental perspective. Looking also at the potential social impacts, the results of another study showed that the replacement of aluminium with a wood-hybrid alternative increases the social performance of the product system. This effect can be explained by the shift from globalized value chains to more regionalized value chains [25].

The biggest potential in further reducing the environmental impact is in the resource extraction- and production phase. Therefore, it would be necessary to reduce the overall quantities of used materials or substitute materials with a specifically large impact. On the one hand, steel and glued laminated timber have a large contribution on the impact but are structurally bearing components, so a reduction from a technical point view is challenging. Epoxy resin on the other hand, which is used as a thermoplastic in the cell holders, could be replaced by a more sustainable alternative. Epoxy resin is currently mainly synthesized from bisphenol A, which is derived from fossil resources and is a harmful and toxic chemical for human health and the environment [93]. Epoxy resins based on lignin, which are currently under research, could be a more environmentally friendly alternative [94]. Another large contributor to the environmental impact is the use of glass fibers in the cell holders: Since the recycling of glass fibers has yet to mature to deliver high quality fibers [72], a substitution with biobased fibers would potentially lessen the impact [95]. In the resource extraction- and production phase the cork composite also bears a larger part of the environmental burden. The cork composite though was developed to be reused again after its initial life cycle and thus considering the whole life cycle, the contribution of the cork composite may not be crucial. By reducing materials for the production of the WHBC, the weight may be also reduced leading to a further reduction of energy consumption in the use phase.

Investigating both EoL scenarios, SM and SE, highlighted the benefits of material reuse instead of thermal recovery. However, the material utilization of waste wood sourced from the WHBC at its EoL is not realizable due to current policies in Austria [66]. Practical reasoning behind this legislation may be that modified woods cannot be easily identified: There are many ways to modify wood and when using chemicals in the process they may not always be traceable. However, this may be a crucial information for recycling companies handling waste wood. Therefore, a transparent value chain and labelling of wood engineered products may be helpful in enabling better separation and recycling technologies [96].

4.2 Land use and resource efficiency

In the category land use the scenario SE for the WHBC performs relatively worse compared to the ISBC which agrees with other studies comparing biobased- to non-biobased products [9, 97]. A substantial share of materials in the WHBC are biobased materials which need land area to be cultivated and thus the WHBC, with only energetic utilization at its EoL, has the largest impact in the category land use. In the scenario SM for the WHBC the performance is vastly better due to the avoided burden through producing lower grade wooden products from waste wood.

The comparatively worse performance in the SE for the WHBC still highlights the need to discuss the land use category. In comparison to the ongoing debate on biofuels and land use [98, 99], where the cultivation of energy crops on farms transforms whole landscapes, the issue with sourcing wood from sustainably managed forests is a bit more precarious. When wood is being harvested, it does not imply the eradication of whole forests: logging companies carefully remove selected trees in order to not damage the forest ecosystem so that they can source high quality wood for years to come. By harvesting limited quantities of wood, ecosystems are not directly destroyed and thus the measurement unit of the land use category (relative species loss for a land use type [100]) could be improved upon [101]. It can be argued though that the ecosystem and the wildlife may be disturbed by ongoing logging activities.

The results regarding the land use indicator may also suggest that material utilization is more desirable from the perspective of resource efficiency. Naturally, less land is needed when virgin materials are being reused in another product lifecycle. However, this conclusion cannot be drawn directly from these results, since the category land use refers to the relative species loss caused by a specific land use type [100]. Ongoing debates on the assessment of biodiversity impacts of land use, specifically regarding forests [102] call for additional consideration of specific resource efficiency- and circularity indicators. Due to this, three additional indicators were assessed within this work.

The indicators deliver consistent results since they are relatively similar in their nature of evaluation. Surprisingly, even though the ISBC is composed mainly of metals, which are easily recyclable, the WHBC, in both EoL scenarios, still performs better. Although the MRS and MSI assess the intrinsic recyclability of materials, which is very high with metals such as steel or aluminium, the actual recycled content in the product is weighted more heavily in the calculation of the indicators. The ISBC is mainly composed of aluminium, steel and aluminium complex alloy. Whereas the former two have a good recyclability, the aluminium complex alloy has a comparatively worse recyclability, being composed of many different metals which complicates the recycling process. The WHBC, which does not utilize any aluminium or aluminium complex alloy, is mainly composed of steel and wood. Since steel has a recycling quote of 90% and accounts for about 60% of the mass of the WHBC, it is evaluated even better than the ISBC. The ISBC is composed of about 70% of aluminium and aluminium complex alloy which have considerably lower recycling quotes (74% and 20%). Other materials besides steel (wood, cork composite or glues) only contribute on a minor scale to the results of the indicators. Since the MEM considers only the share of virgin- and recycled material, both battery compartments have their worst performance in this indicator. However, the properties and quality of recycled metals need to be considered as well before reusing them in structurally important components [103]. The CFF was also attempted to be calculated, however the depth of details needed for the assessment of this indicator was not given at this early development stage of the WHBC.

One the one hand, it is clear that the results of LCAs benefit from the additional information of such circularity indicators in this work, so an implementation to the general LCA framework may seem beneficial. On the other hand, LCAs are already a robust scientific- and standardized method, thus it may be challenging to modify them by implementing additional indicators without interfering too much with the existing framework.

4.3 Limitations

The assessment in this paper faces a few limitations due to data unavailability, not yet developed manufacturing processes as well as future regulatory uncertainties. Data limitations restrict the results of this work in a few ways: For some materials, approximations had to be used since the originally intended materials were not available in the used database. This, however, can lead to inaccuracies when modeling the environmental impact of the respective battery compartments. Another limitation is the not-yet-existent manufacturing process of the WHBC: In this work only the environmental impacts of utilizing the materials given in Table 1 have been assessed. However, the manufacturing process may have energy- and electricity requirements which alter the overall impact of the WHBC. Thus, the manufacturing was not considered for any of the battery compartments, but when included, it may influence the results.

An uncertainty analysis backs up the assessment results here which indicate that they are not prone to variability due to variations in the LCI. However, it must be noted though that only the quantities of materials used in the resource extraction- and production phase have been subject to variation. The results may change if an uncertainty analysis is conducted on the selected unit processes from ecoinvent, the characterization models and factors implemented in the chosen impact assessment method, or on assumptions in the use- or EoL phase. Since the resource extraction- and production phase is connected with the highest impacts, only the uncertainties of this phase were assessed to confirm the results. However, it must be noted that, due to lack of knowledge in early product design with limited data availability, the uncertainties are higher which might shift the results to another direction [104, 105].

The findings have important implications for the industry and policymakers. The adoption of novel hybrid battery compartments, such as the WHBC, and structures from renewable materials in general could help the automotive industry to achieve environmental targets by lowering the impact and improving the sustainability of electric vehicles. Legislators should incentivize the use of renewable resources in the production of electric vehicles and enable a material utilization of engineered wood products compared to just an energetic utilization. Therefore, research and development on recycling- and separation technologies should be facilitated to cope with structural components manufactured from hybrid materials. To put the results into a larger perspective, it can be assumed that the transport sector in the year of 2022 was responsible for the emission of 3.53 billion tons of CO2-Eq [106]. In the same year 18 million electric vehicles were in operation around the world and under the assumption that 10% percent of these vehicles utilize a WHBC, a potential saving of roughly 1 million tons of CO2-Eq may be achievable. The results show that battery compartments manufactured from wood and steel have benefits on a larger scale compared to the industry standard (Fig. 9).

5 Conclusion

Two battery compartments for electric vehicles were assessed in an environmental assessment through a comprehensive LCA, a novel wooden hybrid battery compartment (WHBC) manufactured from wood and steel, and an industry standard battery compartment (ISBC). Two EoL scenarios have been assessed for the WHBC to account for a material- or energetic utilization. The key findings suggest that the WHBC presents a substantial reduction in environmental impact across its entire life cycle, especially in the resource extraction- and production phase. Epoxy resin and glass fibers were identified as materials with a relatively high impact in the WHBC. Due to its reduced weight, the WHBC also induces less environmental impact in the use phase. Additionally, a material utilization of the WHBC should be preferred over energetic utilization to further reduce the environmental impact. The assessment with circularity indicators identifies the WHBC as the more circular and resource efficient solution compared to the ISBC.

Future research on the WHBC should focus on the substitution of materials with a high impact such as epoxy resin or glass fibers or on the reduction of used low alloyed steel. The separation of materials at the EoL needs to be further investigated, especially for the purpose of reusing, re- or downcycling wood engineered products. The design and collection of data on manufacturing processes for the WHBC or other wood engineered products is another possible lead for further research. The development of national policies in Austria for the future regulation of the utilization of waste wood in the EoL phase would also be sensible. The methodology of the category land use could be further refined to enhance our understanding of environmental impacts of wood or wood engineered products.

Based on the results it can be argued that the production of a hybrid wood battery compartment proves the point that more functional and structurally important components of automotive vehicles can be manufactured from engineered wood products. In the design process the findings of this study should be considered: The environmental benefits of substituting hotspot materials in the resource extraction- and production phase outweigh the reduced impact in the use phase due to weight reducing measures.

In conclusion, the transition to using engineered wood in battery compartments for electric vehicles presents a way for the automotive industry to lower their environmental impact. The findings provide a basis for additional research to contribute to the sustainability goals in this sector.

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Data availability The dataset used in this study is available from the corresponding author on request.

Declarations

Competing interests The authors declare no competing interests.

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