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The environmental benefits and challenges of a composite car with structural battery materials

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One way to reduce the environmental impact of an electric vehicle is to reduce the vehicle's mass. This can be done by substitution of conventional materials such as steel, aluminium, and plastics with carbon fibre composites, or possibly even with structural battery composite materials. In the latter case, another consequence is that the size of the vehicle battery is reduced as the structural battery composite not only provides structural integrity, but also stores energy. This study assesses the change in life cycle environmental impacts related to transitioning from a conventional battery electric vehicle to a vehicle with components made from either carbon fibre composites or structural battery composites, with the aim of identifying environmental challenges and opportunities for cars with a high share of composite materials. Results show that a transition to carbon fibre composites and structural battery composite materials today would (in most cases) increase the total environmental impact due to the energy intensive materials production processes. The two major contributors to the environmental impacts for the structural battery composite materials are energy intensive structural battery material manufacturing process and carbon fibre production process, both of which can be expected to decrease their energy consumption as the technology maturity level increases and other production and manufacturing processes are developed. For future assessments, more effort needs to be put on collecting primary data for large-scale structural battery composites production and on assessing different technology development routes.

1. Introduction

Around 30% of the total European greenhouse gas emissions in 2017 came from the transport sector, to which road transports contributed more than 70% [1]. To reduce these emissions, there needs to be a transition from fossil to renewable fuels, but also a reduction in fuel consumption. A reduction in fuel consumption can be accomplished by making vehicles lighter, for example by substituting conventional structural materials with lighter ones, such as composites. It has also been suggested for battery electrical vehicles (BEVs) that the heavy batteries are replaced by structural batteries (SBs) that would integrate energy storage into the structural components, and thereby would reduce weight even further by decreasing the size of the battery. A drawback with composite materials

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is however that they, in some cases, are very energy intensive to produce compared to conventional materials. Therefore, lightweighting does not always lead to a reduced environmental impact throughout a vehicle's life cycle [2].

This study assesses the possible environmental benefits from using composite materials in vehicles, both conventional carbon fibre composites and SBs. The aim is to investigate what possibilities a transition to multifunctional lightweight materials introduces in terms of reducing vehicle weight and, to identify future areas of research for reducing the environmental impact of structural battery composites.

2. Methodology

The methodology of this study is divided into two main parts: 1) the conceptual design of a composite vehicle with carbon fibre composites (also known as carbon fibre reinforced polymers, CFRPs) or SBs (Section 2.1), and 2) the cradle-to-grave environmental life cycle assessments (LCA) of these conceptual composite vehicles (Section 2.2). The purpose of the conceptual design was to demonstrate the potential mass-savings of the vehicle by using CFRPs and SBs while keeping or increasing the system performance. The result from the conceptual design functioned as input data for the inventory analysis of the LCA. The purpose of the LCA was to assess the influence the use of CFRPs and SBs could have on the environmental impact of electric vehicles as well as to identify areas that need further research for decreasing the environmental impact.

2.1 Design of a conceptual composite vehicle

Three different types of vehicles were considered: One conventional BEV, one vehicle where selected components are replaced with CFRPs, and one vehicle where the components are replaced with SBs.

The components of the conventional BEV that were being replaced with CFRPs and SBs are listed in Table 1. The components' material type and properties were obtained from Pradeep et al. [3], while the dimensions of the components were assumed after discussions with technical experts. The input data for the components in the conventional BEV are presented in Table 1 and are used to estimate the dimensions of the replacing composite components as well as the lightweighting of the vehicles.

Table 1: The components considered in this study and the input data for the assessment. Based on data from Pradeep et al. [3] and discussions with technical experts.

Component	Material	ρ (kg/m)	E (GPa)	l (m)	w (m)	t (mm)	m (kg)
Outer door panels	Aluminium	2700	69	1.2	0.8	3	31.1
Roof	Steel	7800	206	2.2	1.1	0.8	15.1
Bumpers	Polypropylene	950	1.4	2	0.5	5	9.50
	CFRP	1310	50	2	0.5	2	5.24
A and B roof arches	Steel	7800	206	1.1	0.05	1	0.858
C roof arch	Steel	7800	206	1.1	0.05	5	2.15
Hood	Steel	7800	206	1.6	1.1	0.8	11.0
Dashboard	Polypropylene	950	1.4	1.8	0.5	2	1.71

(continued)

(continued)

Component	Material	ρ (kg/m)	E (GPa)	l (m)	w (m)	t (mm)	m (kg)
Inner door panels	Polypropylene	950	1.4	1	0.6	2	4.56
Luggage floor	Polypropylene	950	1.4	1	0.88	2	1.67
Luggage wall	Polypropylene	950	1.4	0.5	0.88	2	1.67

For the composite vehicles, the analysis included calculations of the CFRPs' and SBs' effective modulus of elasticity and energy density, to assess how much composite materials that would be needed to maintain the components' structural integrity. Input data for the calculation of the SBs' effective modulus of elasticity are presented in Table 2. The CFRP scenario followed the same methodology as for the SB scenario, but the energy density was not considered due to the CFRPs' monofunctional characteristics.

Table 2: Input data for calculations of the effective modulus of elasticity for the SBs, estimated based on current state-of-the-art [4].

Parameter	Metric	Unit
ν_{xy}	0.3	-
ν_{yx}	0.05	-
E_x	75	GPa
E_y	10	GPa
G_{xy}	5	GPa
d	60	μm/cell

The calculations of the effective modulus of elasticity were based on classical laminate theory and resulted in a value of 32.5 GPa. The calculations were based on a cell design with 6 laminates where the orientation code is $[0/60/60]_s$. Constitutive relationships for the fibre reinforced lamina was determined to express the reduced stiffness matrix where the fibre lamina was assumed to be in the plane stress state. The constitutive relationships were transformed from a fibre-oriented coordinate system to a global coordinate system by multiplying the reduced stiffness matrix with the stress transformation matrix as well as the strain transformation matrix. Midplane strains, plate curvatures and material properties were assumed to be the same within each lamina. The effective modulus of elasticity was obtained by summing the product of the transformed reduced stiffness matrix and the thickness for each lamina. The energy density of the SBs was set to 75 Wh/kg, and was based on the findings by Carlstedt and Asp [5]. For the CFRP case, the effective modulus of elasticity was assumed to be 50 GPa. The same type of analysis was applied for the CFRP case as for the SB case, but with the exception that, as earlier mentioned, the energy density was excluded.

To calculate the amount of composite material needed to replace the components in the conventional BEV, the input data in Table 1 were combined with the effective modulus of elasticity as well as the energy densities of SBs and CFRP to create a case with a vehicle with the components replaced by CFRP, and one case with a vehicle with the components replaced with SBs while still maintaining the components' structural integrity. The changes in mass of the components and the changes in size of the battery are found in Table 3 in Section 2.2.

2.2 Life cycle assessment

The goal of this LCA was to assess the influence a transition towards using CFRPs and SBs could have on the environmental impact of electric vehicles, as well as to identify main contributors to the environmental impact of CFRP and SBs to aid further material development. The LCA of the three different vehicles is based on the modelling done for the conceptual composite vehicle in Section 2.1, where the conventional BEV (i.e., the base case) is based on the data found in Table 1. The lightweighting potential of the CFRPs and SBs in the vehicles are found in Table 3. Note that this LCA builds on the modelling of the conceptual vehicle as described in Section 2.1, but processes in the vehicles' LCA build on literature and database data and, consequently, the results should be seen as an early screening LCA for hotspot identification. Figure 1 shows a simplified outline of the vehicles' life cycle (either conventional electric vehicle, vehicle with CFRP components, or a vehicle with SBs). The technical system is further described below.

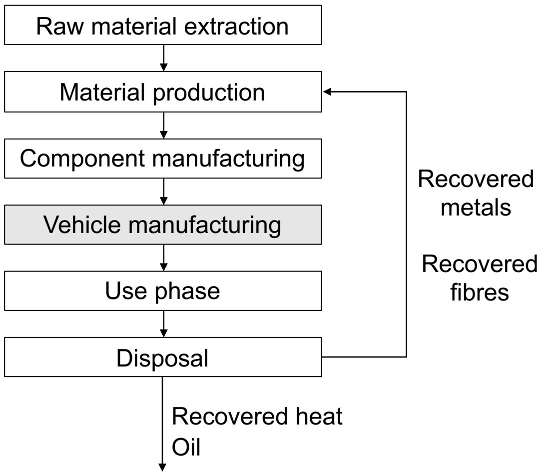

Figure 1: The basic outline of the product life cycle. The grey box is outside the scope of this study and is not included in the assessment.

The functional unit of the study was defined to include the function of the vehicle components listed in Table 1, as well as the battery of the electric vehicle. This was needed to consider the multiple functions of the SBs. The study assesses three different cases as defined in the previous section: a base case considering a conventional BEV with parts made from materials specified in Table 1, one vehicle where these parts are replaced with mono-functional composites (CFRP), and one vehicle where the parts are replaced with multifunctional composites (SBs). The study is cradle-to-grave which means it includes the raw material extraction, composite and structural batteries production, the use phase as well as the end-of-life treatment. It was assumed that the vehicle was driven for 200 000 km before being discarded, which is in line with other studies for composite vehicles, but with internal combustion engines (see for example Duflou et al. [6] and Das [7]). The production, use, and disposal of the composites is assumed to take place in Germany, using German or European specific data as far as possible.

All LCA modelling was done using OpenLCA. If not stated otherwise, the Ecoinvent APOS database version 3.3 [8] was used. The materials of the components in the conventional BEV are listed in Table 1. All CFRPs were assumed to consist of 60% carbon fibres and 40% epoxy. The modelling of the carbon fibre production was based on a life cycle inventory by Romaniw [9][1] and the polyacrylonitrile (a fossil based polymer usually used for carbon fibre production) precursor fibre production data were provided by Fazio and Pennington [10] and was found in the ELCD database [11]. The composites are assumed to be produced by means of resin transfer moulding (RTM), which requires 12.8 MJ/kg [12] and it is assumed that all energy used in the RTM process is electricity. Models for the SBs were based on data provided by Zackrisson et al. [13], where the polyvinylidene fluoride was excluded due to data availability. Data for $LiFePO_4$ (used to coat the fibres in the SB positive electrode) production was taken from Zackrisson et al. [14] and Dunn et al. [15], and data for diammonium production (used to produce $LiFePO_4$) from Manjare and Mohite [16]. The

[1] See Table C4 in Romaniw [9]

electrolyte used in the structural batteries was approximated to be equivalent to an electrolyte used in the production of NiMH batteries. The battery of the electric vehicle was assumed to be a Li-ion battery that could be used for the mechanical drive of an electric vehicle.

The vehicle components are assumed to be fully recycled after use, and the recycling is modelled using system expansion by substitution, where a credit for avoided production is given to the system. The metals used in the base case vehicle are assumed to be collected and reused again in secondary applications (however any collection and treatment has been excluded due to uncertainties as these are very case specific), and the polymer parts are assumed to be incinerated, and the heat recovered and given as a credit to the system. It was assumed that polypropylene had an energy content of 45 MJ/kg (the calculated net combustion heat for polypropylene according to Ioelovich [17]) which was assumed to be turned fully into heat. The CFRPs are assumed to be recycled by means of pyrolysis, which requires 30 MJ electricity per kg CFRP [18]. Note that the pyrolysis process in this study does not include any emissions, other than emissions related to the energy input. It is also assumed that the structural batteries can be recycled via pyrolysis to recover the carbon and glass fibres; this is however something that is not done today and needs more research. The recovered carbon fibres are assumed to have lost 18% of their tensile strength [19] and the glass fibres are assumed to have a tensile strength degradation of 50% [20] (both tensile strength reduction values are originally used for fluidized bed recycling, but are used as a proxy for pyrolysis in this study), and the credit given is for avoided production is adjusted in line with these values using a quality correction factor. It is assumed that the polymer is degraded to an oil during pyrolysis (see for example Cunliffe et al. [21]) with the corresponding impact/function as petroleum, and is thus given a credit for avoided petroleum production. In this study we assume that the polymer is degraded to 100% oil, in reality this value is probably lower. Any recycling or end-of-life treatment of the Li-ion battery has been left out of this study due to lack of data.

In the cases where the material substitution leads to a lighter weight of the vehicles, the fuel consumption of the vehicle will be reduced [22]. The change in fuel consumption can be calculated using Eq. 1 [23].

$$\Delta FC = \Delta m * FRV \tag{1}$$

Where ΔFC=fuel consumption, Δm=difference in mass between the original vehicle and the conceptual vehicle and FRV=fuel reduction value. In this study, the fuel reduction value is assumed to be 0.069 Wh/kg/km (Forell et al. (2016) as cited in Johannisson et al. [24]).

The fuel reduction over the vehicle's lifetime of 200 000 km is then calculated using the ΔFC as calculated using Eq. 1 for each conceptual vehicle, by multiplying the resulting value by the milage. The fuel saved is then given as a credit for the avoided energy use. The mass savings and fuel savings are found in Table 3.

Table 3: The mass reductions, changes in fuel consumptions and the total amount of fuel saved throughout the vehicle's life cycle.

	Δm (kg) Material substitution	Δm (kg) Battery size	Δm(kg) Total	Fuel saved (kWh)
Conventional BEV	n/a	n/a	n/a	n/a
CFRP vehicle	-37.6	0	-37.6	-519
SB vehicle	+3.68	-42.0	-38.4	-529

In the case of SBs, the mass of the vehicle changes due to a transition from conventional materials to SBs, as well as due to a reduction in the size of the battery, as the SBs store some of the energy. This means that the SB vehicle could be given both a credit or a burden for the total change of mass, which leads to a changed fuel consumption in the use phase, as well as credits related to the avoided production of parts of the battery.

This study considers climate impact using the CML2001 assessment method as provided by Ecoinvent 3.3 [8] and the crustal scarcity indicator developed by Arvidsson et al. [25]. Climate impact is included as it is a widely recognized environmental issue, that is strongly connected to energy use in production processes and vehicle use phases. The crustal scarcity indicator is chosen to account for minerals used in the electric vehicle batteries and other parts of the vehicle.

3. Results and discussion

Figures 2a and Figure 2b show the climate impact and crustal scarcity impact of the three different vehicles.

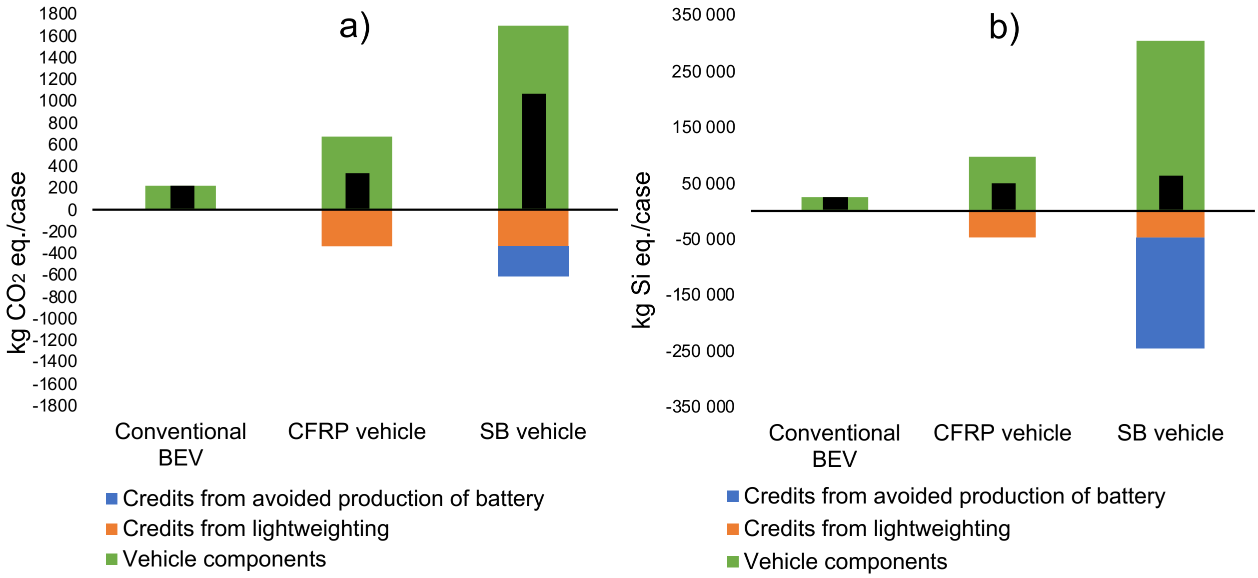

Figure 2: The a) climate impact and b) crustal scarcity impact of the three vehicles in the study. The black bar shows the net impact.

Figure 2a) shows that the net climate impact is almost the same for the conventional BEV and the CFRP vehicle (slightly higher for the CFRP vehicle), even as the lightweighting of the composite vehicles provides a benefit in the use phase. This is due to the very energy intensive carbon fibre production process, which is not weighed up for by the fuel saved in the use phase. It is also related to that a high recycling rate and recovery quality is expected for the metals (in fact, it is assumed that the parts are reused) while the fibres in the composite materials are degraded, and the polymer matrix is recovered as an oil corresponding to petroleum (which production process has a relatively low climate impact). The vehicle with the SBs has the highest climate impact of the three cases, even considering the lightweighting and the avoided Li-ion battery production. This is related to the energy intensive carbon fibre production process (used as electrodes in SBs), but also to the fact that the structural batteries themselves are very energy intensive to manufacture. It should be mentioned that the technology maturity level is very different between the three cases, where the conventional vehicle is having the highest technology maturity level and the SB vehicle the lowest, which means that the impact of the SB vehicle can be expected to decrease as manufacturing technology matures and the energy needed in manufacturing decreases. As an example, the SB manufacturing process has a cumulative energy demand that is almost 9 times higher than for the RTM process used in the CFRP manufacturing process. It is not unlikely that the energy consumption in the SB manufacturing process will approach the RTM energy consumption as technology is further developed. In addition to this, carbon fibre production can be made more energy efficient, which would decrease the impact of both CFRPs and SBs, for example by the use of bio-based raw materials (see for example: Das [7], Janssen et al. [26] and Hermansson [27]), and the use of microwave technology in carbon fibre production (see for example Lam et al. [28]).

Figure 2b) shows the crustal scarcity impact for the different cases. Here, the conventional vehicle also has the lowest impact, which is partly related to the high recycling and recovery rate of the metals. For this impact category, the SB vehicle is more competitive than for the climate impact. This is partly because of the avoided use of energy consumption in the use phase, but mostly because of the avoided production of part of the Li-ion battery, where the avoided production of the battery cell and the integrated circuit offsets most of the impacts. However, also for this impact category, the high energy use in the SB manufacturing phase and the carbon fibre production contributes significantly. In addition to this, the production of the $LiFePO_4$ (used to coat the carbon fibres in positive electrode production) also contributes significantly, where the main contributor is the lithium carbonate production. A development in SB manufacturing and carbon fibre production would therefore also benefit this impact category.

4. Conclusions

CFRPs and SBs show great potential to decrease the weight of electrical vehicles. However, the very energy intensive carbon fibre production process and structural batteries manufacturing process counteract the environmental benefits from lighweighting and, for the SBs, reduced battery size. While the results in this paper show that the CFRPs and SBs do not automatically provide an environmental benefit over conventional materials today, results indicate that the use of composites in vehicles could very well decrease the impacts compared to conventional vehicles if the energy use in the manufacturing phase, as well as in the carbon fibre production, is decreased.

More efforts need to be put into modelling the vehicle components, especially for structural batteries, using primary data. Modelling of different technology development routes are seen as particularly important to identify which route would have the largest influence on reducing the CFRPs and SBs environmental impact.

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