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Can carbon fiber composites have a lower environmental impact than fiberglass?

Frida Hermansson [a,*], Sara Heimersson [a], Matty Janssen [a], Magdalena Svanström [a]

[a] Division of Environmental Systems Analysis, Department of Technology Management and Economics, Chalmers University of Technology, Gothenburg, SE-412 96 Sweden

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ABSTRACT

Carbon fiber composites are increasingly used to decrease fuel consumption in the use phase of vehicles. However, due to the energy intensive production, the reduced fuel consumption may not lead to life cycle environmental savings as much as for other lightweighting materials, for example fiberglass. This study uses life cycle assessment methodology to assess how different future development routes including using bio-based raw materials, microwave technology, and recycling of composites with the recovery of fibers influence the environmental impact of both carbon fiber composites and fiberglass in vehicles. Results show that combining different development routes could lead to carbon fiber composites with a lower environmental impact than fiberglass composites in the future and that recycling of composites with recovery of fibers is the route that alone shows the greatest potential.

1. Introduction

Lightweighting of vehicles is an effective way to reduce fuel consumption during use. This can be done by substituting conventional materials, such as metals, with composites (see e.g. Overly et al. (2002) and Witik et al. (2011)). Two types of composites used in vehicles for the purpose of lightweighting are glass fiber reinforced polymers, GFRPs (also known as fiberglass), and carbon fiber reinforced polymers, CFRPs (also known as carbon fiber composites). Despite the fact that CFRPs are both lighter and stiffer than GFRPs (Witik et al. (2011) and Elanchezhian et al. (2014)), which leads to a higher fuel saving capacity, the use of CFRP instead of GFRP does not automatically lead to a lower environmental impact throughout the vehicle's life cycle. In fact, Hermansson et al. (2019) showed that the shift from GFRP to CFRP could increase the climate impact and energy use, primarily as a result of the energy intensive carbon fiber production process. Previous studies have suggested that the environmental impacts of CFRPs could be decreased by transitioning to a bio-based raw material in carbon fiber production (see e.g. Das (2011)) and by recycling the composites and recovering the fibers (see e.g. Meng et al. (2017)). Further, Lam et al. (2019) suggest that by using microwave heating when producing the fibers, the energy consumption can decrease significantly. Hermansson et al. (2019) looked into the environmental impacts of recycled carbon fibers and carbon fibers produced from lignin by means of a meta-analysis of life cycle assessment (LCA) results and found that both were promising routes for decreasing the environmental impacts of CFRP. Changes in environmental impacts for carbon fibers produced using microwave heating have, however, not been assessed previously.

This study assessed the future potential environmental impacts of future use of CFRPs and GFRPs in vehicles using LCA. None of the technology routes mentioned above have been implemented at an industrial scale today, which is why a future oriented LCA approach is needed. Such LCAs are often referred to as prospective LCAs. Arvidsson et al. (2018 p. 1287) define prospective LCAs as "studies of emerging technologies in early development stages, when there are still opportunities to use environmental guidance for major alterations". When conducting prospective LCAs, scenario methods can be used to develop plausible futures to be assessed (Pesonen et al., 2000). This can entail exploring not only various considered or conceivable technical changes that technology developers can engage in, i.e., the foreground system, but also changes to surrounding systems, such as energy systems and markets of different materials, i.e., the background system, separately or in combination.

The overall purpose of this study was to assess if and under which conditions the use of CFRP in vehicles could have a lower environmental impact than the conventional lightweighting material, GFRP. This was

* Corresponding author.
E-mail address: frida.hermansson@chalmers.se (F. Hermansson).

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done by assessing different technology development routes both separately and in combination, as some are likely to happen at the same time, by means of explorative scenarios in LCA. This study aims to explore windows of opportunity for decreasing the environmental impacts of CFRP and to assess which development routes seem the most promising. Other studies have previously used LCA to compare the environmental impacts from using CFRP or GFRP in vehicles: Witik et al. (2011) compared the environmental impacts from using different lightweight polymer composites to steel and magnesium in vehicles. They concluded that some materials with a larger lightweighting potential, such as CFRP and magnesium, can have increased burdens from the production phase which could make them undesirable from a life cycle perspective. Overly et al. (2002) compared the environmental impacts of different lightweight materials to steel in vehicles. Their results showed that CFRP is environmentally preferable in most categories, primarily because CFRP has the largest weight reduction potential. As the conclusions regarding the environmental performance of CFRP in vehicles differ between these studies, it illustrates the importance of further assessing the environmental impacts of these materials to explore under which conditions the use of CFRP is environmentally beneficial. This study does that and differs from previous LCAs by 1) having a prospective approach, using explorative scenarios to assess the future production of GFRP and CFRP following different development routes, and 2) by comparing the resulting environmental impact for different technology development routes to identify which one decreases the environmental impact of CFRP the most compared to that of GFRP. Note that the outcome of a prospective or future-oriented assessment should be seen primarily as a contribution to decision-making in technology development (Villares et al., 2017). Consequently, any results presented in this paper should merely be viewed as an indication about what could happen under different technological and societal developments and be used as guidance for, e.g., future material development studies.

2. Background

2.1. Fiber production and composite manufacturing

The production of glass fibers and carbon fibers differs significantly, both in terms of raw materials used and in terms of processing technology. Glass fibers are produced from glass that is melted in a furnace and then travels through a channel out to different forehearths after which the fibers are formed (Stickel and Nagarajan, 2012). Carbon fibers, on the other hand, are (usually) produced from polyacrylonitrile (PAN), a fossil-based polymer, where the polymer is first wet spun into a precursor fiber before being turned into a carbon fiber. The transformation to carbon fiber is then done in a series of steps including thermosetting in an oxidizing environment, carbonization in an inert environment, and, finally, treatment to give the fiber surface the right properties (Das, 2011).

After the fibers have been produced, the composites can be manufactured. This is done by arranging the fibers in an application-specific way and adding a polymer matrix. The composites are then formed using e.g., injection molding, compression molding, or resin transfer molding.

2.2. Technology development routes

This study was part of the Lignin Based Carbon Fibres for Composites project (LIBRE, 2016). The goals of the project included to develop lignin-based carbon fibers for composites and to reduce the energy consumption and associated emissions by using microwave heating technologies, which is why these routes were chosen to be included in this study. Moreover, Hermansson et al. (2019) found that the recycling of composites and the subsequent recovery of the fibers is a promising route for decreasing the environmental impacts of CFRP, and therefore this route was also included. In addition to these three technology development routes, which are described in more detail in Sections 2.2.1-2.2.3, factors in the surrounding world that could influence the future environmental impact of the composites were also explored, as further described in Section 3.1.

2.2.1. Using bio-based raw materials in fiber production

An alternative raw material to PAN in carbon fiber production is lignin. Lignin is the world's most abundant aromatic polymer and is found in most terrestrial plants. It is estimated that 15% to 40% of the plants' dry weight is constituted by lignin, where it provides structural integrity (Ragauskas et al., 2014). Today, lignin is mainly used for internal energy use in pulp mills and biorefineries. However, there are possibilities for extracting lignin also for other uses (see e.g. Modahl et al. (2015) and Culbertson et al. (2016)). One such potential use is for producing carbon fibers (see e.g. the LIBRE (2016) project). The production of lignin-based carbon fibers roughly follows the same production process as described for PAN-based carbon fibers in Section 2.1. There are, however, two major differences in the processing: 1) lignin can sometimes be blended with another polymer before being spun into a precursor fiber (Das, 2011) to reduce brittleness and to improve thermoplastic behavior (Collins et al., 2019) which is not required for PAN; and 2) the PAN precursor fiber is spun by means of wet spinning, which requires solvents, while the lignin-based precursor fiber can be spun by means of melt spinning (Das, 2011). The use of lignin instead of the traditional raw material PAN does not only provide a renewable raw material source, but the lignin also has some other inherent properties that, in theory, make it suitable for carbon fiber production: the large content of aromatic compounds and the oxygenated nature of lignin may reduce energy use in the carbonization and stabilization steps compared to PAN (see e.g. Das (2011)). Using lignin as a raw material has previously been shown to be a possibility for decreasing the environmental impact of carbon fibers and carbon fiber composites (see e.g. Das (2011), Janssen et al. (2019), and Hermansson (2020)).

2.2.2. Microwave heating

One way to decrease energy consumption during carbon fiber production is the use of microwave technology instead of traditional furnaces. As an example, Lam et al. (2019) used microwave pyrolysis to turn bamboo into carbon fibers. They claim that the use of microwave technology could lower the energy use in the carbon fiber production from bamboo fibers by more than 90% compared to conventional pyrolysis using furnaces due to a faster heating rate and a shorter processing time.

2.2.3. Recycling of composites with the recovery of fibers

The third technical route for decreased environmental impacts is the recycling of the composites with the recovery and reuse of the fibers. There are three main types of recycling methods for fiber reinforced plastics: mechanical recycling, thermal recycling, and chemical recycling (Yang et al., 2012). The mechanical recycling method is the most mature composite recycling method and involves milling the composite into a powder. The recovered material can then be used as, for example, a filler (Zhang et al., 2020). In thermal recycling, high temperatures are used to separate the polymer from the fibers, and the materials are degraded and recovered to a varying degree depending on the specific method used (Yang et al., 2012). The chemical recycling method removes the polymer matrix by using organic or inorganic solvents to liberate the fibers (Yang et al., 2012), and generally produces clean and long fibers (Zhang et al., 2020). Often in LCAs, the higher the quality of recovered material, the better the environmental impact, as this can offset the production of high quality materials in the next life cycle (Hermansson et al., 2019). This means that thermal and chemical recycling would likely be the most beneficial from an environmental life cycle perspective, depending on the magnitude of impacts from the recycling process. Note, however, that recycling can be modelled in different ways in LCA; this is further discussed in Section 3.1.

3. Methodology

3.1. Life cycle assessment goal and scope

The goal of this study was to assess the potential impacts of the future use of CFRP and GFRP in vehicles with the overall intention of exploring if, and under what conditions, CFRP can outcompete GFRP environmentally. Data were as much as possible collected within the LIBRE (2016) project and supplemented with literature data when needed. Calculations and details for the modeling can be found in the Supplementary material.

The functional unit employed in this study was the service provided by one car component with low structural integrity requirements, represented by a pair of car mirror brackets. The car component was assumed to be used over 100 000 km distance driven regardless of being made of GFRP or CFRP. The weight of the pair of GFRP car mirror brackets was 0.24 kg and the material composition was 40% fibers and 60% polyamide (PA). The weight of the pair of CFRP car mirror brackets was 0.19 kg and the material composition was 20% fiber and 80% PA. With further development of the design and of the material, the weight of the CFRP car mirror bracket could possibly be decreased further, which was therefore assessed in a sensitivity analysis.

All modeling was done using OpenLCA v1.10, and Ecoinvent APOS 3.3 (Wernet et al., 2016) was used as a data source if nothing else is stated. All production, use, and end-of-life treatment was assumed to take place in Germany and all transportation of materials has been excluded from the assessment. Fig. 1 shows the basic outline of the technical system under assessment. The main difference between the GFRP and the CFRP manufacturing processes is the fiber production, as described in Section 2.1.

This study assesses climate impact using the IPCC 2013 methodology and energy use using the cumulative energy demand (CED) methodology as provided by Ecoinvent 3.3 (Wernet et al., 2016), as well as resource depletion using the crustal scarcity indicator (CSI) method developed by Arvidsson et al. (2020). Climate impact was chosen as it is strongly connected to the emissions from the energy used in the carbon fiber production, but also since it correlates well with several other

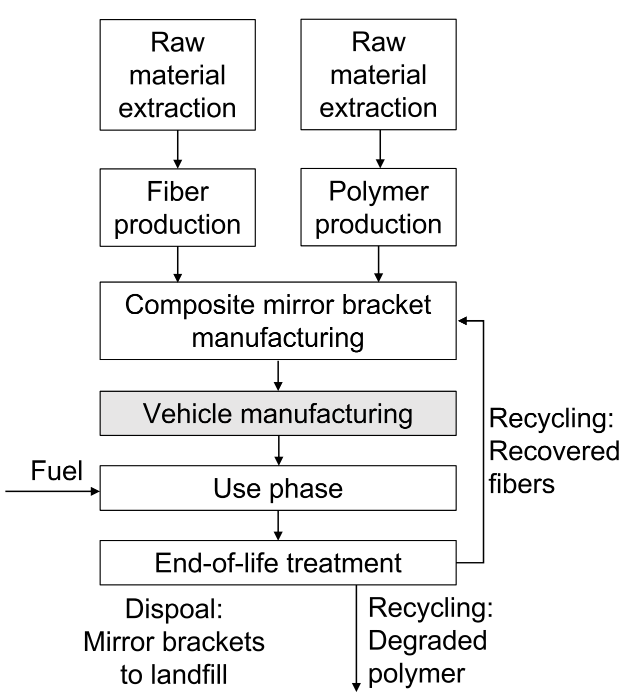

Fig. 1. The conceptual flowchart of the technical system. The vehicle manufacturing (gray box) is assumed to be the same for both the CFRP and the GFRP brackets and is therefore not further considered.

impact categories, such as eutrophication, acidification, and photochemical ozone creation potential (Janssen et al., 2016). Energy use is an important parameter in most production processes and vehicle use phases and is often the reason for lightweighting efforts. The resource depletion was considered because both glass fibers and PAN-based carbon fibers are produced using fossil raw materials, and this is one way to shed light on resource related challenges.

In this assessment, we explore different development routes for CFRP and GFRP in vehicles and compare these to a base case of GFRP and CFRP produced using today's available technology. We explore three development routes related to fiber production and composite manufacturing: 1) using bio-based raw materials (lignin) in carbon fiber production, 2) using microwave heating in carbon fiber production, and 3) recycling of composites with recovery of fibers (for both glass and carbon fibers). In addition, some possible changes to the background system were explored. Hermansson (2020) identified the demand for lignin (and hence, price of lignin) as well as the energy mix in the energy system as influential for the climate impact of carbon fiber production, which is why these two factors were considered. Additionally, this study explores the shift from vehicles with internal combustion engines (ICE) to battery electric vehicles (BEV).

The PAN-based carbon fiber production is based on a version of the PAN-precursor fiber production dataset provided by European Platform on Life Cycle Assessment (2018) which was modified to be compatible with the impact assessment methods of this study (see Hermansson et al. (2022) for details) and data collected within the LIBRE (2016) project. The bio-based carbon fiber production is based on an updated version of what was published in Hermansson (2020), and we assume that the lignin-based and PAN-based carbon fibers have the same quality. The lignin-based fibers are assumed to be produced from 50% bio-based polyurethane (bio-PU) and 50% Organosolv lignin (see Culebras et al. (2018) for the properties of different fibers produced from lignin and bio-PU blends). The bio-PU production was approximated by combining polyol production based on data from Fridrihsone-Girone (2015) with a modified Ecoinvent dataset on polyurethane production. The lignin production data were based on data for an Organosolv mill provided by Moncada et al. (2018).

Lignin is always the product of a multi-output process, which means that the impacts of the lignin-generating mill need to be allocated between the outputs, and the prospective nature of this study makes the choice of allocation basis challenging (see Hermansson et al. (2020) for more information on how lignin's climate impact could change over time). In this study, we chose to allocate the impacts of the Organosolv mill on an economic basis. A possible future development is that the demand for lignin increases, and thus also its price in comparison to that of other co-products from the mill. To illustrate such a situation, the main-product-bears-all-burden approach of Sandin et al. (2015) was used to represent a situation where the lignin price is high compared to other co-products of the biorefinery. This extreme assumption can be seen as a worst-case scenario to test the importance of lignin's market development for the CFRPs' environmental impact.

The material yield in the stabilization and carbonization is assumed to be 50% for the bio-based carbon fibers which is in line with what is suggested by Das (2011). Note that the blending with bio-PU can influence the material yield to become lower than that (see Culebras et al. (2018)). It is also assumed that the material yield in stabilization and carbonization is 50% also for the PAN-based carbon fibers. The energy carrier in the fiber stabilization and carbonization is assumed to be electricity and nitrogen is used to create an inert environment. Carbon fibers are traditionally produced using furnaces but could be produced by means of microwave heating. In this study, we assume that the use of microwave heating can reduce the energy consumption for the stabilization and carbonization by 93.5% compared to using conventional furnaces. This value is based on the average difference in energy consumption between using a furnace and microwave pyrolysis for transforming a bamboo fiber to a carbon fiber as reported by Lam et al.

(2019). It is assumed that the nitrogen consumption and material yield stay the same regardless of carbon fiber production method.

The fibers are considered to be chopped before being added into the thermoplastic polymer matrix (any impacts related to chopping and mixing have been excluded as they are deemed to be negligible). The mirror brackets are finally formed by means of injection molding. The resulting composite is assumed to be of relatively low structural integrity, thus suitable for car components with lower requirements such as car mirror brackets.

When using CFRP mirror brackets instead of GFRP mirror brackets, the vehicle becomes lighter. This results in a lower fuel consumption over the vehicle's life cycle. This was calculated using the rationale used by Del Pero et al. (2017). The fuel savings from the lightweighting of the car when switching from a car mirror bracket produced from GFRP to one from CFRP corresponds to 0.092 liters in an ICE vehicle and 0.345 kWh in a BEV throughout the mirror brackets' life cycle (i.e., 100 000 km).

The end-of-life for the composites was in the base case assumed to be a landfill as this is the option that is currently practiced. When recycled, it is assumed that the composite is sent to pyrolysis, which uses 30 MJ/kg CFRP composite (Witik et al., 2013), and we assume the same value for GFRP. Note that there are some emissions (of for example carbon dioxide) from the pyrolysis process, but due to lack of data, only emissions associated with the energy needed for the process were included in this study. The pyrolysis process is assumed to result in carbon fibers with a tensile strength reduction of 18% compared to primary fibers (Pickering et al., 2015), which is approximately in line with what is reported by Irisawa et al. (2021), and depends on process conditions such as temperature and time. The tensile strength of the glass fibers was assumed to be reduced by 50% (Pickering, 2006), which is slightly less than reported in Rahimizadeh et al. (2020). Both values for tensile strength reduction used in this study are for the recovery of fibers from composites using fluidized beds but are here used as a proxy value for a general pyrolysis process. It is assumed that the polymer is recovered as an oil from the pyrolysis process (Cunliffe et al., 2003). This oil is assumed to be equivalent in function and impacts to petroleum and it is assumed that the whole polymer matrix is fully degraded to an oil.

When the composite mirror brackets are recycled, another allocation problem will arise, and burdens (such as from primary material production) and benefits (such as from recovered fibers and oil) from recycling need to be distributed between the life cycles of the first and second products. In this study, we use two different allocation approaches to distribute the environmental impacts between the products: the end-of-life recycling approach and the cut-off approach, both adapted for composite recycling as suggested by Hermansson et al. (2022) and using a mass basis for allocating the impacts from the composite recycling process between the fibers and the polymer. The inclusion of both allocation approaches was done to capture the extremes in common approaches (Hermansson et al., 2022). The end-of-life recycling approach, on the one hand, considers the amount of material being recycled. In this study, we assumed that the composites are fully recycled after use, meaning the recycling rate of the materials leaving the system is 100%. The recovered materials substitute the production of primary materials, and the composite is therefore given a credit for the avoided production of fibers and polymer. The credit for the fibers is adjusted using a quality correction factor based on the relative tensile strength reduction (as suggested by Hermansson et al. (2022), and the polymer is given a credit for the avoided production of petroleum, as it is degraded to a comparable oil during pyrolysis. The cut-off approach, on the other hand, considers the amount of recycled material being used in the production. Using recycled fibers in composite production today is very rare. However, as composite recycling technology matures, this is likely to change. For the recycling options in this study, it was assumed that 50% of the incoming glass fibers and 82% of the incoming carbon fibers were from recycled material and that these come from composites recycled by means of pyrolysis. These values were chosen to account for the difference in need of adding primary materials to compensate for quality losses. It was assumed that the polymer used in the composite production is 100% primary material. It is possible that the polymers recycled from the composites are used as an input in a second composite in the same way as we assume for the fibers, but due to lack of data for any processing needed for the pyrolysis oil to become a comparable polymer again, this was not considered.

To test the robustness of the assumptions made, sensitivity analyses were done for: recycling rates, the fibers' tensile strength reduction in recycling, the energy consumption during pyrolysis, the energy consumption for microwave heating, as well as additional lightweighting of the CFRP mirror brackets compared to GFRP mirror brackets. The results of the sensitivity analysis are discussed in Section 4.3.

3.2. Generating future scenarios

The technology development routes described in Section 3.1 can also be combined into consistent scenarios. This was done by following the method used by Langkau and Erdmann (2021) who assessed the environmental impacts of the future supply of rare earth metals. In short, sub-scenarios were created based on different variations in the life cycle inventory corresponding to the different development routes (now the varied inventory data will be called parameters). To limit the number of possible combinations of sub-scenarios, the interrelationships between these were assessed and only the sub-scenarios most likely to be strongly connected were combined into future scenarios and assessed further.

The parameters used in the scenario development were divided into parameters influencing the foreground system or the background system and are found in the Supplementary material. The parameters for the allocation-related variations were all based on changes in the background system: The parameter related to the demand of lignin will influence the allocation of impacts between the products of the lignin-generating process. The environmental legislation parameter accounts for that different recycling allocation approaches (here, the cut-off and the end-of-life recycling approaches) provide different incentives (Hermansson et al., 2022) and therefore reflect different norms and values (Ekvall and Tillman, 1997; Frischknecht, 2010).

To map how the different parameters, and consequently the sub-scenarios, interrelate, a causal loop diagram (De Vries, 2012) was made. Based on these interrelationships, the sub-scenarios were subject to a cross consistency check (the basics of such a procedure are for example described in Ritchey (2018)) in order to reduce the amount of possible combinations to only the most plausible ones. Both the causal loop diagram and the cross-consistency check can be found in the Supplementary material.

The most plausible combinations of sub-scenarios were then combined into overall scenarios. The cross-consistency check resulted in three different overall scenarios which are found in Table 1. In essence, Scenario 1 would mirror a future with a strong focus on the bioeconomy (focusing on decreasing emissions throughout the system and using bio-based materials), Scenario 2 would have a strong focus on a circular economy (focusing on recycling and reusing materials and decreasing waste generation), and Scenario 3 would be a combination of the two first - a future with a strong focus on a 'circular bioeconomy'. Note that these classifications are rough and based on the groupings of which sub-scenarios that were deemed to correlate the most with each other.

We made the choice to consider only the most extreme situation for all scenarios. This choice was based on the argument that the balance between technologies is hard to predict, so for clarity reasons, when presenting the results, this assessment is binary in the sense that it is either 100% or 0% of the different sub-scenarios. This means, e.g., that there is 100% of bio-based carbon fibers that are only used in BEVs in Scenario 1, that all carbon fibers are PAN-based and used only in conventional vehicles and fully recycled in Scenario 2, and that 100% of the carbon fibers are bio-based, used in only BEVs and completely recycled in Scenario 3. In the future, there would of course be a mix, with some

Table 1
The three constructed scenarios for the assessment. *) only influences carbon fiber reinforced polymers (CFRPs); all other developments influence both CFRPs and glass fiber reinforced polymers (GFRPs).

	Parameter settings in foreground system	Parameter settings in background system
Scenario 1: Bioeconomy	- Fibers are produced from bio-based raw materials* - Fibers are produced using microwave heating* - Composites are sent to landfill	- Price of lignin increases* - Energy mix transitions towards being fossil-carbon lean - Composites are used in a BEV[1] - There is legislation to reduce extraction of fossils from the ecosphere
Scenario 2: Circular economy	-Fibers are produced using fossil-based raw materials - Fibersare produced using conventional technologies - Composites are recycled and materials recovered	- Price of lignin remains the same* - Energy mix stays constant - Composites are used in vehicle with ICE[2] - Thereis legislation to promote recycling and recovery of materials; end-of-life recycling approach
Scenario 3: Circular bioeconomy	- Fibers are produced using bio-based raw materials* - Fibers are produced using microwave heating* - Composites are recycled and materials recovered	- Price of lignin increases* - Energy mix transitions towards being fossil-carbon lean - Composites are used in a BEV[1] - There is legislation to reduce extraction of fossils from the ecosphere; cut-off allocation approach

[1]Battery electric vehicle.
[2]Internal combustion engine.

sub-scenarios dominating.

4. The future environmental impacts of composites in vehicles

4.1. What would it take for CFRP to have a lower environmental impact than GFRP in vehicles?

Fig. 2 shows the influence the considered development routes could have on climate impact, energy use, and resource depletion of car mirror brackets made from GFRP or CFRP as described in Section 3.1, if implemented separately.

Results show that GFRP mirror brackets always have a lower climate impact than CFRP mirror brackets except for when the composites are being recycled or when a fossil-carbon lean energy mix is assumed. The generally higher climate impact of the CFRP car mirror brackets is primarily due to the very energy intensive carbon fiber production process. When using our modeling approach, the use of gasoline in an ICE vehicle results in a credit for lightweighting corresponding to approximately the impacts of manufacturing the composite which reduces the climate impact of the CFRP mirror brackets to some extent, but generally not enough for it to be competitive to GFRP. The lightweighting credit becomes even smaller when the brackets are used in a BEV, indicating that lightweighting of electric vehicles by means of CFRP would be less useful for decreasing the life cycle climate impact. The lower climate impact of CFRP mirror brackets compared to GFRP mirror brackets in Fig. 2a) are primarily dependent on some modeling choices, namely the allocation approach used in the recycling modeling and the substituted products, as well as the way the future fossil-carbon lean energy mix for the PAN-fibers was modelled (see the Supplementary material for details).

Fig. 2b) shows that the life cycle energy use is only lower for CFRP mirror brackets when the composites are being recycled as the energy use is not influenced to the same extent by a transition to a fossil-carbon lean energy mix. The main reason for this is, just as for climate impact, the carbon fiber production process. The energy use of CFRP mirror brackets is also higher than for GFRP mirror brackets even if the fibers are produced from biobased raw materials, regardless of the price of lignin or the introduction of microwave heating in fiber production. The lightweighting credit offsets some of the higher energy use of the CFRP mirror brackets compared to GFRP mirror brackets. However, unlike for the climate impact, switching from using the brackets in a BEV instead of a vehicle with ICE does not influence the net energy use significantly.

Fig. 2c) shows that the resource depletion is significantly lower for the CFRP mirror brackets than for the GFRP mirror brackets for all development routes. This is because of the glass fiber production, where the production of boric acid used in the glass fiber production is responsible for almost 70% of the total resource depletion of the GFRP mirror brackets, which is primarily caused by a flow of colemanite. Colemanite is one of four major borate minerals that in total account for 90% of the global industry use of borate minerals, and more than 75% of the global consumption is for ceramics, detergents, fertilizers, and glass (U.S. Geological Survey, 2021). As glass is already a major application for borate minerals, and with an increased global interest in lightweighting of vehicles, this indicates that the resource depletion may be a major problem related to the future manufacturing of fiberglass.

4.2. What could happen in different futures?

Fig. 3 shows the resulting climate impact, energy use, and resource depletion for a pair of car mirror brackets produced from either GFRP or CFRP for the base case (representing today) and in three different scenarios representing three different futures: bioeconomy, circular economy, and circular bioeconomy (see descriptions in Section 3.2).

In Scenario 1, with a focus on bioeconomy, the climate impact of the GFRP and CFRP brackets is approximately the same. This is primarily a consequence of the energy background system. Any reduction in electricity use in the carbon fiber production from using microwave heating in a fossil carbon-lean energy mix will have less of an influence than a reduction in a system with a fossil carbon-rich energy mix. For the same reason, the effect of lightweighting in a future with a fossil carbon-lean energy mix and electric vehicles will also be significantly smaller. The life cycle energy use of the CFRP brackets, on the other hand, is significantly higher than for the GFRP brackets in Scenario 1. In fact, the difference in energy use between the two materials is even higher than for the today's scenario. This is because the considered price increase for lignin leads to it being allocated all the impacts of the mill. Note that the employed energy use assessment method does not differentiate between renewables and non-renewables in the energy system. Consequently, the shift to biobased fibers will not reward e.g. the lignin production process for having a high share of renewables (about 90%). This highlights the need in some contexts for assessing renewable and non-renewable energy use separately to avoid the risk of generating misleading results, especially in cases and for materials where the energy use is the dominating contributor to impacts. The resource depletion, on the other hand, is significantly lower for the CFRP mirror brackets than for the GFRP brackets. This is, again, connected to the use of boric acid in the glass fiber production (see Section 4.1) which is not influenced by changes in the background system.

In Scenario 2, which has a circular economy focus, the CFRP mirror brackets have a lower net climate impact, energy use, and resource depletion than the GFRP mirror brackets. The lower resource depletion of CFRP is still connected to the use of boric acid in the glass fiber production. The lower climate impact and energy use are primarily dependent on the recycling, and how it was modelled; the end-of-life recycling approach includes credits for the avoided production in the next life cycle. This credit is higher for carbon fibers than for glass fibers,

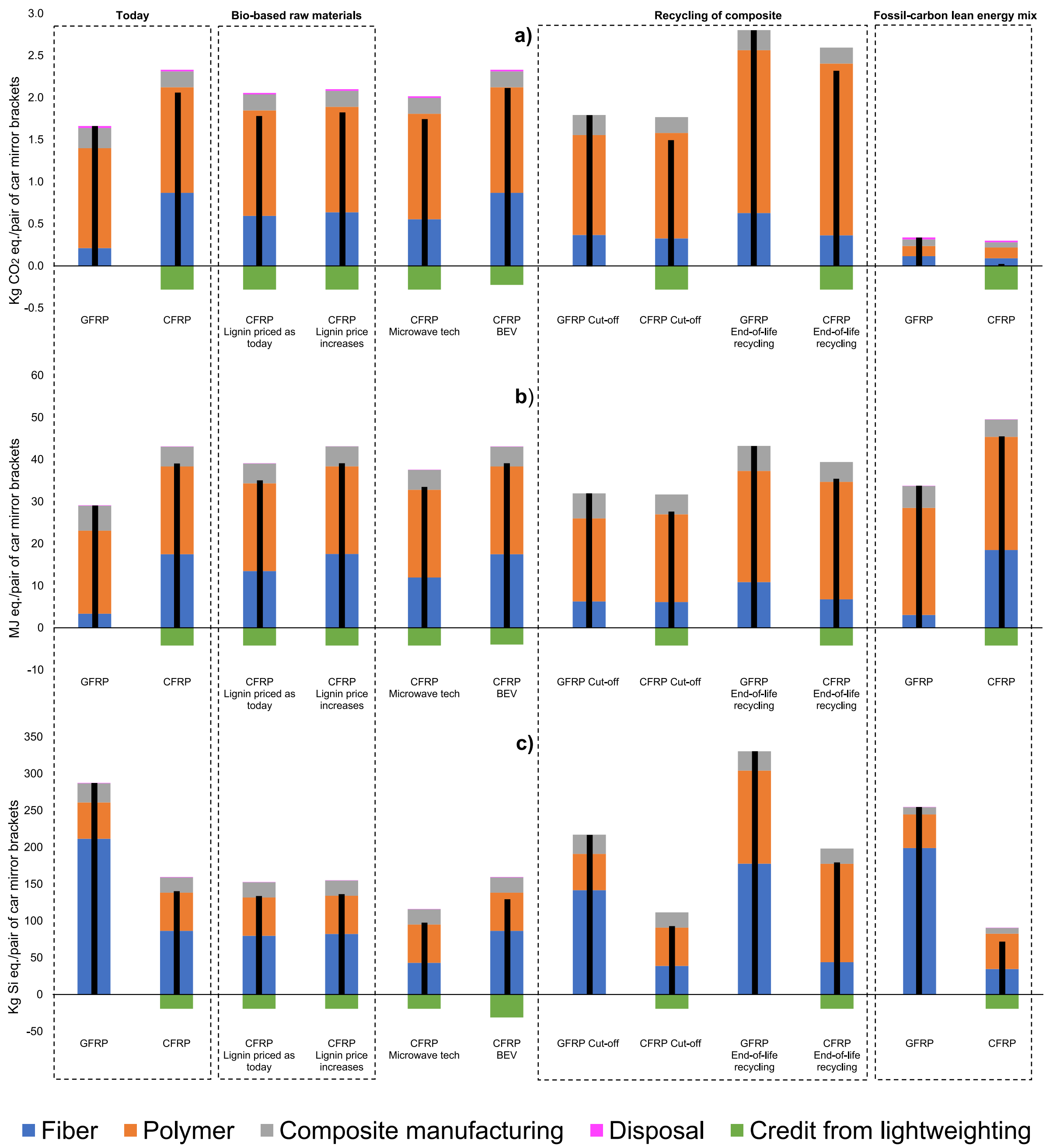

Fig. 2. The influence of the considered development routes described in Section 3.1 on the a) climate impact, b) energy use, and c) resource depletion of a pair of car mirror brackets produced from carbon fiber reinforced polymers (CFRP) or glass fiber reinforced polymers (GFRP). The black bar indicates the net impact and BEV is short for battery electric vehicle.

partly because the impacts of producing primary carbon fibers is higher, but also because the carbon fibers are assumed to retain a higher rate of tensile strength than the glass fibers. In addition to this, this is the scenario where the car mirror brackets are still considered to be used in conventional vehicles with ICEs, meaning that the lightweighting credit given to the CFRP car mirror brackets for the avoided use of petroleum-based fuel consumption is large.

In Scenario 3 (circular bioeconomy focus), the climate impacts of the CFRP and GFRP car mirror brackets are practically the same, whereas the energy use for the CFRP brackets is slightly lower than for the GFRP brackets. The reason for this is the same as for Scenario 1, that the climate impact for the car mirror brackets is strongly connected to the energy mix. When the energy system has transitioned towards being fossil carbon lean, the difference in climate impact between the GFRP and CFRP brackets is decreased significantly regardless of there being a large difference in energy use or not. In addition to this, the credit for avoided fuel use is decreased due to the fossil carbon lean energy mix. The difference in life cycle energy use between the brackets is primarily related to the recycling, where the input of recycled material is higher for CFRP than for GFRP. The resource depletion remains higher for the GFRP car mirror brackets for the same reason as before: the colemanite flow in the boric acid production. This is however decreased to some extent compared to for Scenario 1 due to avoided production of some of the glass fibers when the composite is being recycled.

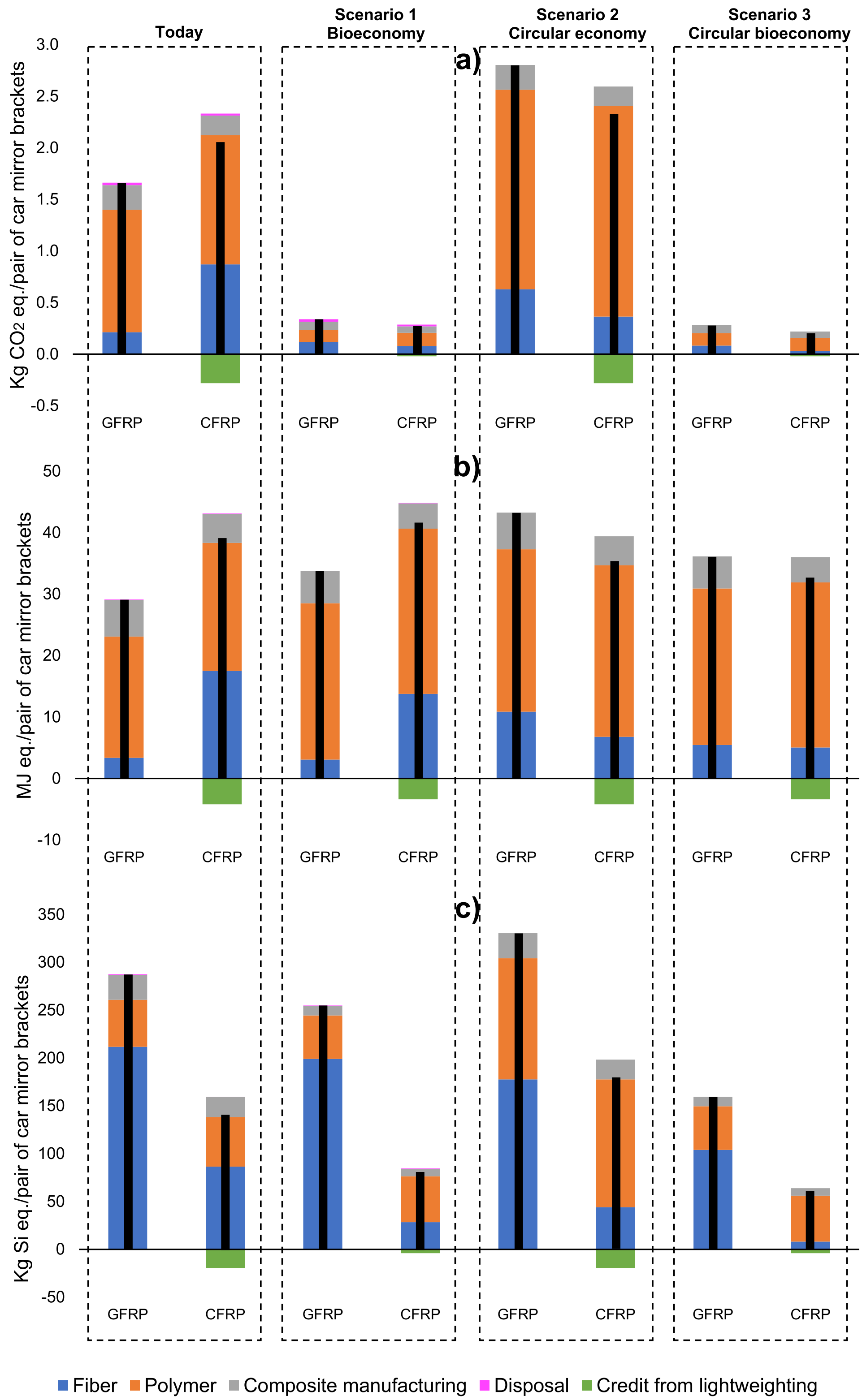

Fig. 3. The a) climate impact, b) energy use, and c) resource depletion of a pair of car mirror brackets produced from either carbon fiber reinforced polymers (CFRP) or glass fiber reinforced polymers (GFRP) today and in three different futures. The black bar indicates the net impact.

Of all scenarios and indicators used in this study, it is only Scenario 1 (Bioeconomy) for energy use that does not create a situation that gives an advantage to the CFRP over GFRP. This means that CFRPs are quite likely to become more environmentally competitive to GFRPs in the future and, in particular, if recycling technologies for composites are implemented.

4.3. Assessing the environmental impacts of the future use of composites in vehicles using life cycle assessment

In this paper we explore different routes that the development of carbon fiber composite manufacturing could take. These routes are explored with a focus on plausible futures, rather than trying to predict the actual future impacts of CFRPs. This is done to identify which technology development routes are more promising than others and to identify any windows of opportunity for future material development. While our results seen individually may not be realistic, we argue that environmental impacts will likely end up somewhere in the range of the results presented in Figs. 2 and 3, and in particular if technology developers allow themselves to be guided by the conclusions.

It is important to consider that all results presented in this paper are highly dependent on the methodological choices made, primarily those connected to the choice of allocation approaches in lignin production and composite recycling. Hermansson et al. (2020) showed that the choice of allocation approach for lignin production has a significant effect on the resulting impact for lignin, and consequently also for lignin-based products. In this study, we used the main-product-bears-all-burden approach to approximate a future where lignin is the dominating and/or most expensive product of the Organosolv mills in Scenarios 1 and 3. However, it should be noted that using another allocation approach would change the environmental impacts of the bio-based fibers. Further, the recycling of the composites is handled by the end-of-life recycling approach in Scenario 2 and the cut-off approach in Scenario 3. Scenario 1 did not include any recycling, which is why no allocation between primary and secondary products was needed. The recycling allocation approaches suggested by Hermansson et al. (2022) include allocation of the pyrolysis' impacts between the fibers and the polymer. In this study, this is done on a mass basis; another basis, such as economic, would have given other results. An economic allocation basis is however challenging to use in prospective studies (Hermansson et al., 2020) which is why a mass basis was chosen.

As the end-of-life recycling approach provides incentives to recycle and provide recycled materials with high quality (as further discussed by Hermansson et al. (2022) we deemed it suitable in a context with strong focus on circular economy, such as in Scenario 2. In Scenario 3, the focus is both on circular economy and on bioeconomy, thus likely decreasing the extraction of fossils from the ecosphere. In this situation, the cut-off approach was instead considered more representative, as it is in line with the 'strong sustainability' idea, or the unwillingness to trade off resource extraction from the ecosphere for other values (see Frischknecht (2010) for how different allocation approaches relate to different views on sustainability). We suggest that the choice of allocation approach should be a part of the scenario development, where different allocation approaches are connected to different environmental concerns and future market developments. This can be done by more consciously considering how allocation approaches depend on how the background system develops when constructing the scenarios.

A currently unavoidable weakness in this LCA is the fact that the modeling of the future routes is based on assumptions and literature data. The results of the sensitivity analysis are summarized in Table 2 and are found in detail in the Supplementary material. Table 2 shows that the results are the most sensitive to the assumptions on energy consumption in the pyrolysis process and the microwave heating process. Table 2 also shows that the results are the least sensitive to assumptions on recycling rate and the quality degradation of the fibers in pyrolysis. The results of the sensitivity analysis also highlight the importance of not only substituting GFRP with CFRP on a one-to-one basis, but to also take advantage of any superior mechanical properties of the carbon fibers and to carefully assess the possible development of the design of the component.

Another limitation in this assessment of the future environmental impact of composites in vehicles is that the transition to a low carbon energy system in Scenarios 1 and 3 is done by approximations and not in a fully consistent way. This is primarily due to limitations in the modeling software used, the way some datasets are constructed, and the low data availability. However, it is unlikely that the outcomes of the study would change significantly with more consistent background modeling than described in the Supplementary material, as the main impacts are primarily related to direct energy use. Other software with better accommodation for changing the background system could be beneficial to use in future studies (see for example Joyce and Björklund (2021) and Steubing et al. (2020)). Further, more (transparent) data on, for example, bio-polymer production would also improve the trustworthiness of the results.

Table 2
The impact the parameters varied in the sensitivity analysis have on the results. Low impact indicates a maximum deviation of less than 10%, medium impact indicates a maximum deviation of between 10 and 30%, and high impact indicates a maximum deviation of more than 30%.

Parameter	Impact on LCA result		
	Climate impact	Energy use	Resource depletion
Recycling rate changes	Low	Low	Low
Quality of recovered fibers	Low	Low	Low
Pyrolysis energy consumption	Medium	Medium	High
Microwave heating energy consumption	Medium	Medium	High
Further mass reductions	Medium	Medium	Medium

5. Conclusions

This paper assesses the potential life cycle climate impact, energy use, and resource depletion of future GFRP and CFRP use in vehicles, to shed light on if CFRP could have a lower impact than GFRP. This was done by assessing different technology routes separately, but also grouped into different future scenarios. Results show that the most promising individual route for decreasing the relative environmental impact of CFRP car mirror brackets includes recycling of the composites with recovery of the fibers. Further, CFRP shows great potential to have a lower environmental impact than GFRP in all three different futures assessed, but this is highly dependent on assumed developments in the background system such as a high price of lignin, increased incentives for recycling, and increased incentives for reducing extraction from the eco-sphere. If the considered scenarios represent the future, we can conclude that CFRPs are likely to have a lower environmental impact than GFRPs in these kinds of applications in the future.

CRediT authorship contribution statement

Frida Hermansson: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Sara Heimersson:** Methodology, Investigation, Writing – review & editing. **Matty Janssen:** Methodology, Supervision, Writing – review & editing. **Magdalena Svanström:** Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Data availability statement

The authors declare that primary data for carbon fiber production cannot be shared due to confidentiality. Data supporting all other results can either be found in the article or in the supplementary material.

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Supplementary materials

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