Life cycle assessment of lignin-based carbon fibres

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ABSTRACT

Lignin-based carbon fibres may replace both glass fibres and fossil-based carbon fibres. The objective of this study was to determine the environmental impact of the production of lignin-based carbon fibres using life cycle assessment. The life cycle assessment was done from cradle to gate and followed an attributional approach. The climate impact per kg of lignin-based carbon fibres produced was 1.50 kg $CO_{2,eq}$. In comparison to glass fibres, the climate impact was reduced by 32% and the climate impact of fossil-based carbon fibres was an order of magnitude higher. A prospective analysis, in which the background energy system was cleaner, showed that the environmental impact of lignin-based carbon fibres will decrease and outperform the glass fibres and fossil-based carbon fibres from a climate impact point-of-view. The constructed LCA model can be applied in further studies of products that consist of or use lignin-based carbon fibres.

KEYWORDS

Bio-based economy, Kraft lignin, lignin-based carbon fibres, life cycle assessment, prospective analysis, climate impact

INTRODUCTION

Forests and forest products can play a key role in combatting climate change and in the transformation to a bio-based economy. Technologies have been developed (or are in development) that use the cellulose and hemicellulose from forest biomass in order to produce, e.g. fuels, chemicals and bio-based materials. Lignin from forest biomass has so far mostly been used as a source of energy in, e.g. Kraft pulp mills, but it can also be used as a feedstock to produce value-added chemicals and materials [1].

Fossil-based carbon fibre is currently produced by carbonizing a precursor fibre made from poly-acrylonitrile (PAN). Besides its climate impact due to the use of fossil resources for the production of PAN, the production of PAN-based carbon fibre (PAN-CF) also leads to generation of hydrogen cyanide (HCN) during carbonization [2], a highly toxic substance whose emission needs to be minimized to avoid severe health impacts. This indicates that alternatives for carbon fibre production are of interest. Lignin-based carbon fibre (L-CF) production is an example of such an alternative, and L-CF has the potential to replace both glass and fossil-based carbon fibres. However, such future alternative processes and products need to be carefully assessed and life cycle assessment (LCA) is a method that can be applied in order to guide technology development [3].

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LCA considers the environmental impacts of a product or service during its life cycle, from raw material extraction until the end-of-life [4]. LCA has been applied to assess wood-based alternatives for fuels [5], chemicals [6] and materials [7]. However, literature on the production or use of L-CF is sparse. Das [8] considered the use of L-CF in carbon fibre reinforced polymers (CFRPs) and compared it with the use of PAN-CF. The author concluded that a 30% reduction in life cycle energy use could be obtained by switching from PAN-based to lignin-based fibre. However, it was assumed that lignin production did not lead to an environmental impact because it is a by-product of pulp or ethanol production. Furthermore, Meng et al. [9] assessed recycling technologies for carbon fibre composites and concluded that recycling of these materials is environmentally preferable over landfill and incineration options. This study however focused on materials containing fossil-based carbon fibres. These results indicate that an improved environmental performance can be achieved by moving away from fossil-based carbon fibre and by implementing recycling options for materials that contain such fibres. Lastly, Hermansson et al. [10] conducted a prospective study of lignin-based and recycled carbon fibres through a meta-analysis of LCAs. They concluded that energy use during carbonization of the precursor fibre is a main contributor to environmental impact, and that assessments of both lignin-based and recycled carbon fibre are subject to challenges regarding allocation of environmental impacts.

The current study aimed at determining the environmental impacts of the production of L-CF using LCA. The objectives of this study were: 1) to improve and/or optimize the L-CF production process from an environmental life cycle point-of-view; 2) to compare the environmental impact of the L-CF production process with the production of PAN-CF and of glass fibres; and 3) to help guide the further technology development of the L-CF production process by identifying the environmental hotspots, and by doing a prospective analysis to assess its performance in a future state. The results of the LCA are intended to be used by researchers (both academic and industrial), technology developers and industry decision makers in order to evaluate several paths that can be taken during the research and development of the L-CF production process.

METHOD

System description and functional unit

The system under study was divided into three parts (see Figure 1):

1. Resource extraction and production of auxiliary raw material and energy (background system). This part of the system, which is located upstream of the L-CF production, includes the cultivation and harvesting of wood, the production of chemicals and other materials needed, and the production of fuel and electricity needed in these and the downstream processes.
2. Production of the L-CF and co-products (foreground system). The production of the L-CF includes the chemical (Kraft) pulping of the wood, the isolation and purification of the lignin using the Lignoboost process and the manufacturing of the L-CF. It is assumed that all these processes are co-located at the same site, a pulp mill in southern Sweden. The main product of this process is the pulp that is produced from the wood.
3. Transportation. This includes the transport of the wood and of the auxiliary chemicals to the pulp mill site.

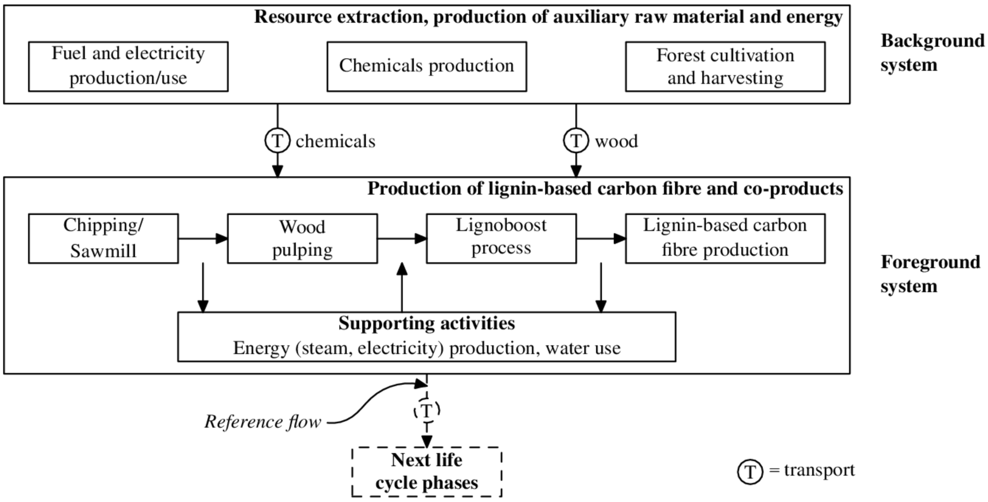

Figure 1. System boundaries of the life cycle assessment in this study. The dashed lines indicate the flows and processes that are not included in the scope of this life cycle assessment.

A simplified model of the L-CF production process is depicted in Figure 2. Wood is cultivated, harvested and transported to the pulp mill. The wood is debarked and chipped to produce wood chips. Wood chips from the sawmill that is co-located with the pulp mill is also used as a raw material. The main product of the pulp mill is pulp. The black liquor contains dissolved lignin which partly flows to the Lignoboost process. The Lignoboost process isolates and purifies (and possibly chemically alters) the lignin. Leaching purifies the lignin before the melt spinning process, where a 3K precursor carbon fibre (3K means that the carbon fibres consist of 3000 filaments) is formed by extrusion. The precursor fibre is then stabilized and carbonized to a L-CF with a carbon content of 95-98%. The pulp mill also produces steam and electricity for the L-CF production process. The steam production in the pulp mill and its use in other parts of the process has not explicitly been included in the LCA model. However, the process model does account for reduced amounts of electricity that can be sold on the market, due to its consumption in the L-CF production process. Other by-products from the pulp mill are tall oil and turpentine.

The system under study did not include the transportation of the L-CF to a site where it is further used. This is thus a cradle-to-gate system, from raw material cultivation and extraction (wood from the forest) to the carbon fibre product leaving the production site. Therefore, the function of the system that was studied was to produce L-CF. The functional unit was 1 kg of L-CF produced from softwood lignin. The reference flow, i.e. the quantity of L-CF to achieve the functional unit, was the same: 1 kg of L-CF leaving the production process.

Type of LCA and allocation

An attributional approach was taken to carry out the LCA. Allocation of the environmental burden to the different products (and by-products) of the system was applied. Such allocations were needed in the cases of the sawmill process, the pulping process and the leaching process (see Figure 2). Allocation was done based on economic value of the product and by-product flows except for the sawmill process, where the allocation was done on a mass basis. Sensitivity analysis was done to determine how market pulp and lignin prices affect the results of the LCA.

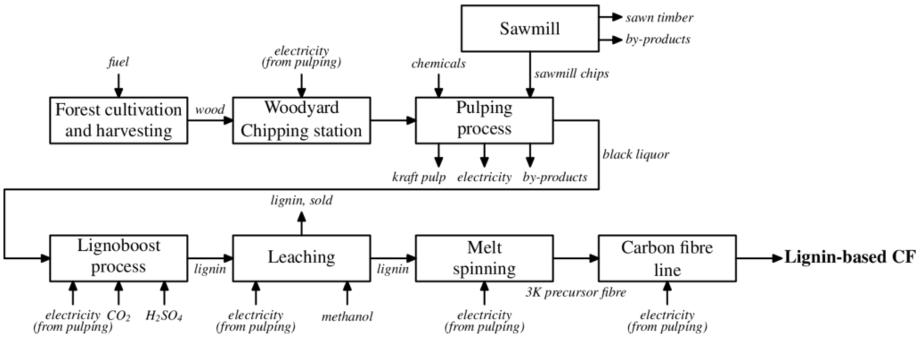

Figure 2. Flow chart of the lignin-based carbon fibre production process. The by-products of the pulping process are electricity, tall oil and turpentine. The black liquor contains the lignin needed for carbon fibre production.

Data acquisition

Several sources of data were used to describe the system:

1. Forest industry data
2. Simulation of the L-CF production process using the software WinGEMS 5.0 (see Figure 2)
3. Ecoinvent database, version 3.4 [11]. For the comparison of glass fibre with L-CF, the ecoinvent process 'glass fibre production, RER' was used.
4. Literature sources. For the comparison of L-CF and PAN-CF, a dataset for PAN-CF production was found in [2].

The LCA software openLCA version 1.7.4 [12] was used to model the complete L-CF production system according to Figure 1 (both the foreground and background systems), to compile the acquired data, and to calculate the environmental impacts.

Environmental impact categories

The life cycle impact assessment was carried out using the CML impact method [13]. This is a midpoint assessment method and is based on the ISO standards related to LCA. Of the list of midpoint impact categories that are described in the CML method, the following were selected for the evaluation of the L-CF production system:

- Global warming potential (GWP). One of the main goals of replacing fossil-based carbon fibre with L-CF is to reduce climate impact. GWP is measured in fossil carbon dioxide equivalents ($CO_{2,eq}$).
- Acidification potential (AP). The combustion of biomass and fossil fuels can lead to increased acidification due to emissions of SO_2, NH_3 and NO_x. AP is measured in kg sulphur dioxide equivalents ($SO_{2,eq}$).
- Eutrophication potential (EP). Depending on forest management, fertilizers may be used which can lead to increased eutrophication. EP is measured in kg phosphate equivalents ($PO_{4,eq}$).
- Photochemical ozone creation potential (POCP). The combustion of biomass and fossil fuels can lead to increased photochemical ozone creation due to emissions of volatile organic compounds (VOCs), CO and NO_x. POCP is measured in kg ethylene equivalents ($ethylene_{eq}$).
- Human toxicity potential (HTP). The production of fossil-based carbon fibre may lead to harmful emissions that impact human health. It should however be noted that the CML

method does not contain a characterization factor for HCN. HTP is measured in kg 1,4 dichlorobenzene equivalents (1,4-DCB_{eq}).

The renewable and non-renewable energy use (REU and NREU, respectively) were calculated using the Cumulative Energy Demand (CED) method [14]. The impacts considered above are often caused using either type of energy, and the extent of the use of REU and NREU may thus be a proxy for these impacts.

Prospective analysis

The development of the materials in which the L-CF is applied and the development of the technology to produce L-CF is currently ongoing. The production of L-CF is therefore not yet at an industrial scale, and this needs to be considered in the LCA. The purpose of doing a prospective LCA, is to study "emerging technologies in early development stages, when there are still opportunities to use environmental guidance for major alterations". The system under study is therefore situated at a certain time in the future in order to capture the potential future environmental impacts. The methodological choices made, and analysis of the results needed to reflect this [3]. In this study, the focus was on a future energy background system within which the production process would operate.

The assumption was made that the energy system will evolve towards a decreasing use of fossil resources to produce the energy by 2025. The LCA model was adjusted in openLCA in order to reflect such a future energy background system, using the following steps:

1. The processes that were selected for adjustment contributed with more than 1% to the climate impact of the base case of the production system (Figures 1 and 2). The 'base case' refers to the system using the current energy background.
2. The providers of energy-related inventory flows in these processes were replaced with a cleaner provider, if available. A provider in this case is a process that produces the energy-related inventory flow. The inventory flows that were replaced were electricity (low and medium voltage), heat and fuel (diesel) flows.
3. As a proxy for a cleaner provider, the provider (i.e. the production process for an energy-related inventory flow) was assumed to be located in Sweden. It should be noted that another geographical location with a relatively clean energy system may be chosen.
4. If there was no Swedish provider available in the ecoinvent database for the targeted inventory flow, then the next aim was a provider located in Europe (based on an average process).
5. The provider was replaced in the openLCA software using the 'Bulk replace' function. This means that this provider was replaced everywhere in the LCA model.

RESULTS AND DISCUSSION

Environmental impacts of the lignin-based carbon fibre production process

The climate impact of the base case process is 1.50 kg $CO_{2,eq}$/kg of L-CF produced (see Figure 3). The main contributors to this impact are the Lignoboost process (37%), the carbon fibre line (23%), the leaching process (22%) and the pulping process (12%). The climate impact is mainly due to the use of chemicals and electricity in the different parts of the process. In total, the production and use of chemicals contributes with 66% to the total climate impact of the production system. Important chemicals are carbon dioxide (CO_2) in the Lignoboost process, methanol in the leaching process, and sodium hydroxide (NaOH) and sodium chlorate ($NaClO_3$) in the pulping process. The electricity generated in the pulping process has a low climate impact, however the amount needed, especially for the carbon fibre line, is significant. The remaining process steps (melt spinning, sawmill operations, wood yard, chipping station and forest operations) contribute with 6% in total to the GWP of the production process. Most of this impact is due to fuel production and use (close to 4%, both fossil-based and bio-based diesel) in the forest operations and electricity use (1%) in the melt spinning process.

The prospective analysis (see Figure 3) shows that a cleaner energy background system leads to a reduction of the climate impact by 0.46 kg $CO_{2,eq}$ to 1.04 kg $CO_{2,eq}$/kg of L-CF produced (or a 31% reduction). The reductions are due to a cleaner production of chemicals used in the leaching, Lignoboost and pulping processes, and due to cleaner electricity generated by the pulping process. The prospective analysis also shows that the environmental hotspots are the same when compared to the base case.

The REU in the base case is 76 MJ_{eq}/kg of L-CF, and the NREU is 39 MJ_{eq}/kg of L-CF. The REU is mostly due to the use of wood as a raw material (approximately 70 MJ_{eq}/kg L-CF) in the production system. The NREU is mainly due to the use of fossil and nuclear resources (34 MJ_{eq}/kg L-CF and 4 MJ_{eq}/kg L-CF, respectively). Evolving to a cleaner energy background system leads to a slight increase of the REU to 78 MJ_{eq}/kg L-CF and a more significant decrease of the NREU to 35 MJ_{eq}/kg L-CF. In the case of REU, the increase is mostly due to an increase of hydroelectricity which is due to the choice of using the Swedish electricity production as a proxy for a cleaner electricity provider in the prospective LCA model. In the case of the NREU, on the one hand, the decrease in NREU is mainly due to a decrease in fossil energy use by approx. 5 MJ_{eq}/kg L-CF. On the other hand, nuclear energy use increases by approx. 1 MJ_{eq}/kg L-CF, again due to using Swedish electricity production as a proxy for clean electricity production.

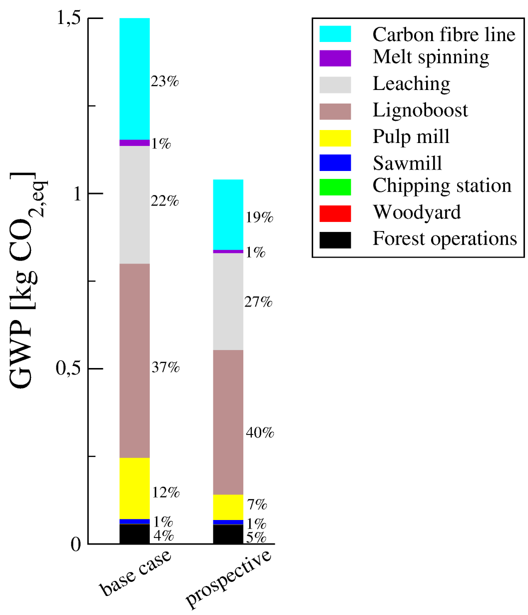

Figure 3. Climate impact to produce 1 kg of lignin-based carbon fibres with the base case and the prospective production system. The percentages next to the bars are the relative contributions of the process steps (note that those of the wood yard and chipping station are not given (both are <<1%)).

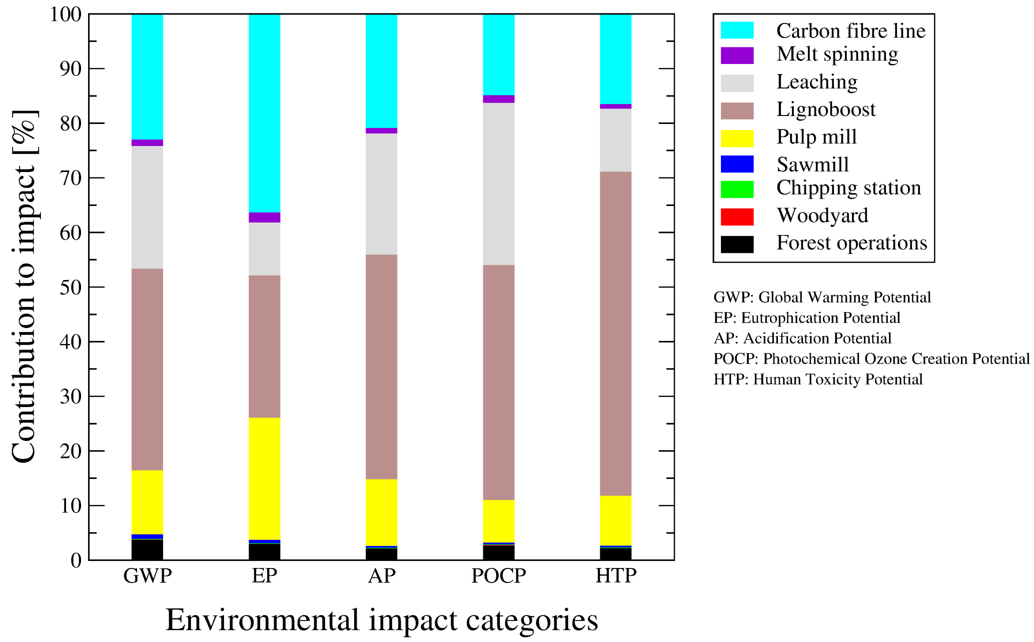

Figure 4. Contribution analysis for the considered environmental impact categories for the base case lignin-based carbon fibre production system.

A contribution analysis for the environmental impact categories that were considered in this study showed that the different process steps contribute similarly to the climate impact, AP and POCP (see Figure 4). This means that it is likely that changes in the process to lower GWP will also lead to a decrease in AP and POCP, e.g. by a reduction in the use of chemicals or by evolving to a cleaner energy background system. In the case of EP, the contributions of the carbon fibre line and the pulping processes are larger than in the other impact categories. The pulping process emits phosphorus (P) to water and nitrogen oxides (NO_x) to air, both substances causing eutrophication. The Lignoboost process contributes significantly more to the HTP when compared to the other impact categories. This is due to an increased contribution of the liquid CO_2 production. The contributions of the processes to the different impact categories are largely unaffected by the change to a cleaner energy background system (as is shown for climate impact in Figure 3).

Sensitivity analyses

Sensitivity analysis showed that changes in market pulp and lignin prices lead to the greatest changes in environmental impact (results not shown here). The production and use of chemicals in the production of L-CF contributes significantly to all environmental impacts considered in this study. The use of electricity also contributes significantly to the environmental impact of the production system, in particular the electricity use during the carbonization process in the carbon fibre line. Compared to the sensitivity of the impacts with regards to the market prices of pulp and lignin, the sensitivity is modest due to changes in chemicals and electricity use. However, these are process variables that can be optimized by the technology developers, contrary to market prices, and should therefore not be neglected.

Comparison with other types of fibres

The ecoinvent database contains a dataset to produce glass fibre in Europe. An analysis showed that this production causes a climate impact of 1.98 kg $CO_{2,eq}$/kg of glass fibre produced, and thus is approximately 32% higher than the climate impact of L-CF (see Figure 5a and Table 1). This is likely due to a higher use of fossil-based energy, e.g. natural gas, in the glass fibre production. The HTP of the glass fibre production shows a similar difference with the L-CF production as for the climate impact. The impact of glass fibre production on human toxicity is mainly due to emissions of cadmium (Cd), antimony (Sb) and hydrogen fluoride (HF). The POCP of L-CF production is higher than the POCP of glass fibre production (by 37%) which is due to a greater use of chemicals in L-CF production. Furthermore, there is a small difference between the EP and AP of the production of the two fibre types, although it should be noticed that the AP of L-CF production is slightly higher than the AP of glass fibre production.

Romaniw [2] provides a dataset for the production of PAN-CF. An analysis based on this dataset shows that the climate impact of the production of PAN-CF is one order of magnitude greater than the production of L-CF and glass fibres at 38.9 kg $CO_{2,eq}$/kg (see Figure 5b and Table 1). The main contributors are the production of PAN-CF, and electricity and liquid nitrogen production and use. The main reason for this high climate impact when compared to L-CF and glass fibre is energy use.

Both glass and PAN-CF show reduced environmental impacts when the energy background system evolves to a cleaner one (see Figure 5 and Table 2). Although the climate impact of PAN-CF is reduced significantly from 38.9 kg $CO_{2,eq}$ to 19.3 kg $CO_{2,eq}$ per kg, it is still an order of magnitude higher than for the L-CF and glass fibre production (1.04 and 1.21 kg $CO_{2,eq}$ per kg of produced fibre, respectively). The other impacts due to PAN-CF production are also reduced, but they remain significantly higher than for the glass fibres and L-CF.

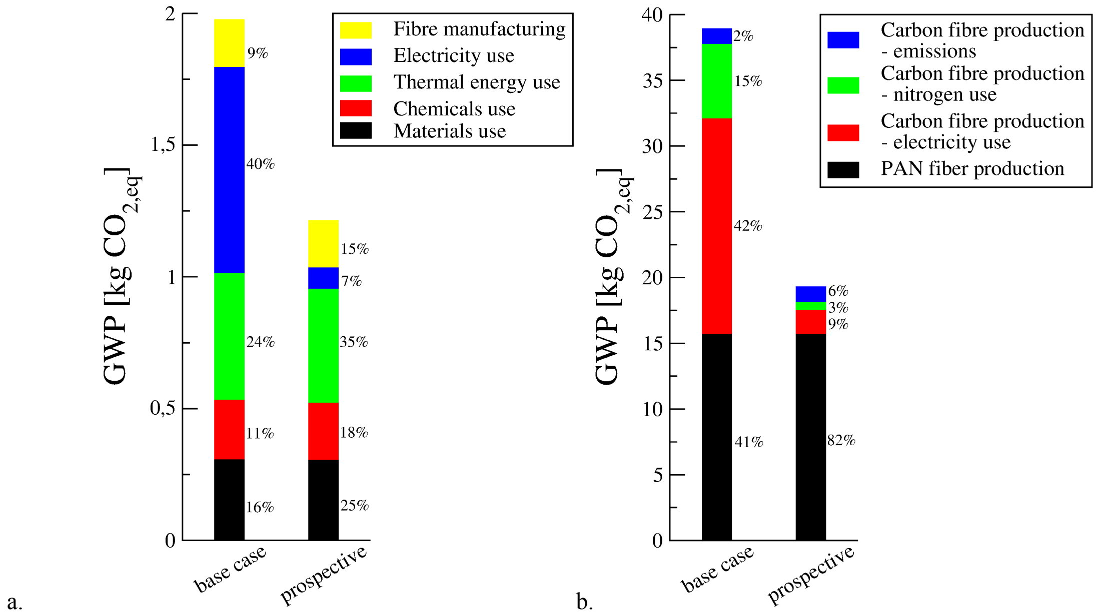

Figure 5: Climate impact (measured using global warming potential (GWP)) to produce: a. 1 kg of glass fibre and b. 1 kg of poly-acrylonitrile-based carbon fibre, for the base case and prospective production systems.

Table 1. Comparison of the total impacts to produce 1 kg of lignin-based carbon fibres (L-CF), 1 kg of glass fibres and 1 kg of poly-acrylonitrile-based carbon fibres (PAN-CF) in the current energy background system.

Impact categories	GWP [kg $CO_{2,eq}$]	EP [kg $PO_{4,eq}$]	AP [kg $SO_{2,eq}$]	POCP [kg $ethylene_{eq}$]	HTP [kg 1,4-DCB_{eq}]
L-CF	1.50	$3.72 \cdot 10^{-3}$	$1.59 \cdot 10^{-2}$	$7.4 \cdot 10^{-4}$	1.47
Glass fibre	1.98	$3.96 \cdot 10^{-3}$	$1.46 \cdot 10^{-2}$	$5.4 \cdot 10^{-5}$	2.02
PAN-CF	38.9	0.10	0.30	$6.7 \cdot 10^{-3}$	11.0

Table 2. Comparison of the total impacts to produce 1 kg of lignin-based carbon fibres (L-CF), 1 kg of glass fibres and 1 kg of poly-acrylonitrile-based carbon fibres (PAN-CF) in the prospective energy background system.

Impact categories	GWP [kg $CO_{2,eq}$]	EP [kg $PO_{4,eq}$]	AP [kg $SO_{2,eq}$]	POCP [kg $ethylene_{eq}$]	HTP [kg 1,4-DCB_{eq}]
L-CF	1.04	$2.42 \cdot 10^{-3}$	$1.34 \cdot 10^{-2}$	$6.3 \cdot 10^{-4}$	1.30
Glass fibre	1.21	$1.68 \cdot 10^{-3}$	$1.07 \cdot 10^{-2}$	$3.7 \cdot 10^{-4}$	1.75
PAN-CF	19.3	0.041	0.21	$2.7 \cdot 10^{-3}$	3.94

CONCLUSION

An attributional, cradle-to-gate LCA of the production of L-CF was carried out. The climate impact of the production of L-CF was 1.50 kg $CO_{2,eq}$/kg L-CF produced, and is competitive with the production of glass fibre whose climate impact is approximately 32% higher. L-CF production also outperforms PAN-CF production whose climate impact is an order of magnitude higher at 38.9 kg $CO_{2,eq}$/kg PAN-CF produced. The environmental impact allocated to the L-CF depends significantly on the market prices of pulp and lignin.

The comparison with glass fibre production still needs to be interpreted with caution, because the data for this production may not accurately reflect current practices. An effort should be made to collect primary data from glass fibre manufacturers in order to improve quality of the data that describes this process. The dataset to produce PAN-CF is based on a detailed production model but may also need further verification.

The prospective LCA shows that the production of carbon fibre using the proposed production system is beneficial from a climate perspective when assuming that the background energy system has become cleaner at the time of its implementation at an industrial scale. The L-CF also still outperforms the PAN-CF and glass fibre.

The constructed LCA model can be applied in further studies of products that consist of or use L-CF produced with the process described in this paper.

ACKNOWLEDGMENT

This project has received funding from the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 667501.

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