Dielectric heating of carbon precursors

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Life cycle assessment of carbon fibre production using microwave technology

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Abbrevations

PAN - Polyacrylonitrile

Bio-PU - Bio based polyurethane

1. Goal and scope

1.1 Goal

The goal of this assessment is to compare using microwave carbonization technology to conventional carbonization technology using furnaces for two types of fibres: One PAN-based and one lignin- and bio-polyurethane (bio-PU) based.

1.2 Scope definition

1.2.1 Scope

Functional unit: The functional unit of the study is 1kg of either PAN-based or lignin- and bio-PU carbon fibres at factory gate.

It is assumed that the resulting fibres have the same quality, and thereby can fulfil the same function in the final application. The lignin and bio-PU based fibres are assumed to be produced from 50% lignin and 50% bio-PU. The production of the fibres is assumed to be either by means of a traditional furnace or using microwave technology. The production of the fibres is assumed to take place in Germany.

As there is no large-scale production of carbon fibres produced using microwave technology nor lignin- and bio-PU, a prospective approach is needed in the assessment.

1.2.2 System boundaries

This study considers the cradle-to-gate activities of the carbon fibre production. This means that the extraction of raw materials, the processing of the materials and the production of the carbon fibre which leaves the system at the factory gate. The study does not include the manufacturing of a composite in which the carbon fibre is used, the use of the composite or any end-of-life treatment. These can however be assumed to be the same for the different types of fibres considered in this study.

1.2.3 Geographical boundaries

All activities are assumed to take place in Germany. For more information, see Section 2 (description of the technical system).

1.2.4 Temporal boundaries

The technologies assessed in this study are still not available in any larger or industrial scale. Therefore, a prospective approach is needed to assess the possible future environmental impact of the fibres.

1.2.5 Allocation

For the production of lignin, economic allocation has been chosen as an allocation method based on the arguments that the economic revenue of the process is the driver rather than any physical relationships, such as mass or energy (Huppes & Schneider, 1994). A drawback of using economics as a foundation for allocation in prospective assessments is that it is challenging to set an economic value on the future products as the supply and demand for lignin will likely change (see for example Hermansson et al. (2020)). In the specific case of lignin, the main question is if it can be considered a waste (giving lignin a very low allocation factor using economic allocation) or a product of great value in the future (which gives lignin a high allocation factor and a larger share of the burden)? As a response to this, the allocation approach *main product bears all burden* as described by Sandin et al. (2015) is used, reflecting a case where lignin is not the main product of the system (thus having an allocation factor of 0, i.e. not carrying any burden of the mill) and a case where lignin is the main product of the system (having an allocation factor of 1, i.e. carrying the entire burden of the mill). Therefore, the future environmental impact of lignin is very likely to be somewhere in that range.

1.2.6 Choice of impact assessment methods

This study will consider climate impact and energy use. These are chosen as they are among the most commonly used impact assessment methods. Also, consideration of the climate impact is motivated by the replacement of fossil based raw material (PAN) to bio-based raw material (lignin and bio-PU). It is also strongly linked to fossil fuel use in in e.g., electricity generation. The consideration of energy use is motivated by the fact that previous studies have shown that the carbonization of the fibre is highly energy intensive (see Hermansson et al. (2019)).

The climate impact was assessed using CML2001 and the energy use using cumulative energy demand as provided by Ecoinvent 3.3 (Wernet et al., 2016).

2. Detailed description of the studied system

The PAN and lignin and bio-PU based carbon fibres are produced in a series of steps. First, the lignin and the bio-PU are blended, compounded, and pelletized. In the case of PAN, the fibres are usually preceded by a solvent-based polymerization process (Overly et al., 2002). The lignin- and bio-PU based are then spun using melt spinning, whereas the PAN-based fibres often are spun using wet spinning (Das, 2011). Following this is the carbon fibre production which is the same for both the types of fibres. This includes the stabilization and the carbonization of the carbon fibres which in this study is done either by means of a conventional furnace or microwave technology and subsequent surface treatment and spooling. Figure 1 shows the outline for the production of lignin-based carbon fibres.

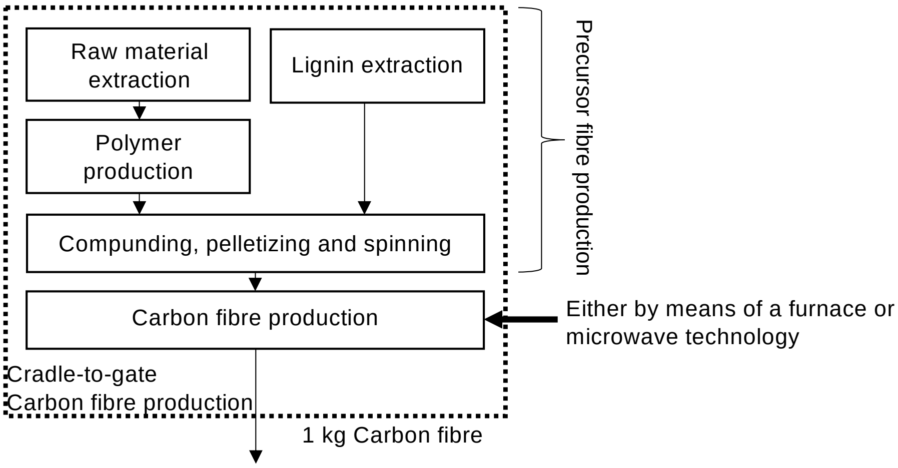

Figure 1: The simplified outline of the lignin- and bio-PU based carbon fibre production system.

3. Inventory

This section includes a description of the data collection, including the data quality, and assumptions made.

All modelling was done in OpenLCA. When ecoinvent processes are referred to below, it refers to Ecoinvent database 3.3 (Wernet et al., 2016) and when ELCD processes are referred to, it refers to the database provided by European Platform on Life Cycle Assessment (2018).

3.1 Lignin and bio-PU based carbon fibres

The inventory for the lignin and bio-PU based carbon fibres is based on primary data collected within the LIBRE project. Data for Organosolv lignin production is taken from Moncada et al. (2018) and bio-PU production is based on a polyurethane data set available in Ecoinvent 3.3, where the polyols have been replaced with bio-based polyols based on data from Fridrihsone-Girone (2015).

When needed and possible, literature data have been used to upscale production processes within the LIBRE project from for example pilot-scale to industrial scale (such as for the spinning process, where the processing electricity for the extrusion is approximated by 0.1 kWh/kg as suggested by Das (2011)). Note that other energy and material inputs related to heating and cleaning are still based on pilot scale data due to data availability. The carbon fibre production data using a conventional furnace are provided within the project for industrial scale for production of PAN-based carbon fibres. However, due to lignin's inherent properties, there are indications that the energy consumption in carbon fibre production is around 25% lower than for PAN (Das, 2011). Therefore, a reduction in 25% of the energy used for oxidation, carbonization, and stabilization using furnace is assumed. Note that the blending with the bio-PU could influence this reduction, but to what extent is still unknown.

The available data for carbonization using microwave technology are for lab scale. For the purpose of this life cycle assessment, approximations and assumptions were made. The data provided within the project suggests that the microwave carbonization needs only 6.8% of the energy used for carbon fibre production using a furnace. Therefore, the energy use for the microwave oxidation, stabilization, and carbonization of the lignin and bio-PU based carbon fibre production is assumed to be 6.8% of the energy use when using a furnace. The material yield in the oxidation, stabilization, and carbonization process is measured to be 40%. Note that the order of magnitude for this reduction is in line with what is suggested by Lam et al. (2019), who used microwave pyrolysis to produce carbon fibers from bamboo. The reduction only applies to stabilization, oxidation and carbonization of the carbon fibres and not to processes such as spooling or any surface treatment or the carbon fibre.

The oxidation, stabilization and carbonization are done in an inert environment using nitrogen produced from compressed air. Note that data on the amount of nitrogen used is taken from a process that is not industrial scale which will have influence on the results, as the consumption can be expected to decrease in the future.

3.2 PAN-based carbon fibre production

The dataset "Polyacrylonitrile fibres (PAN), production mix, at plant, from acrylonitrile and methacrylate, PAN without additives" (Fazio & Pennington, 2005) from the the ELCD database (European Platform on Life Cycle Assessment, 2018) is used to model the PAN-precursor fibre. PAN based carbon fibre production is based on data provided within the LIBRE project. Just as for the lignin- and bio-PU based carbon fibres, the energy consumption when using microwave technology is assumed to be reduced to 6.8% of the energy consumption using furnaces, and the processes are assumed to use the same amount of nitrogen produced from compressed air. The yield in the PAN-based carbon fibre production has been measured to be 50%.

4. Results

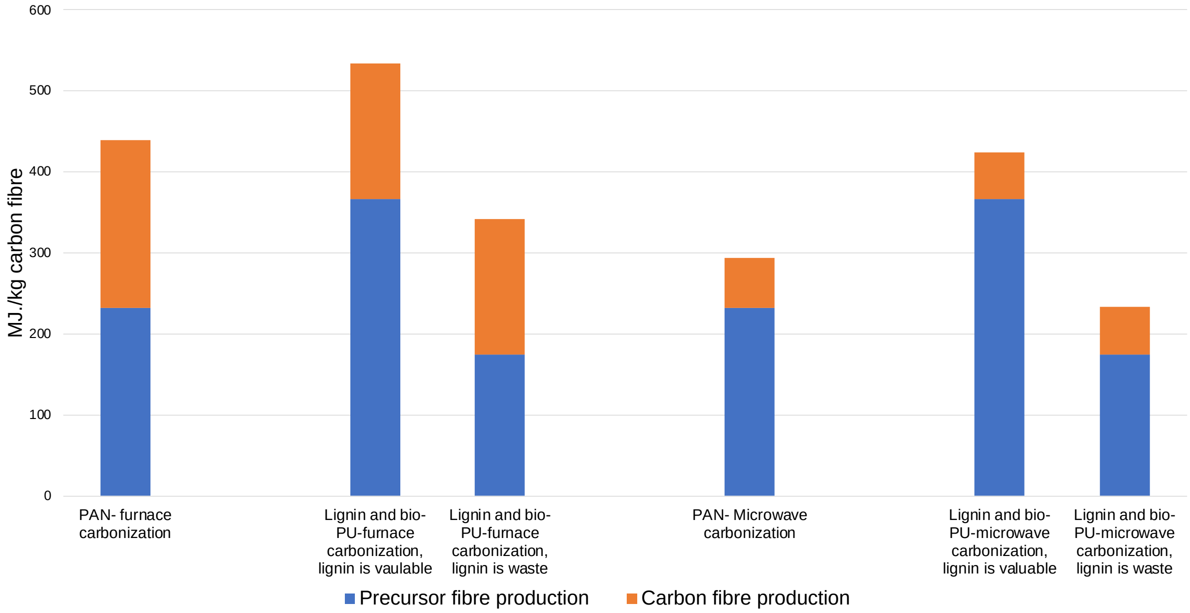

Figure 2: The cumulative energy demand of 1 kg produced fibres using different raw materials, allocation factors, and carbonization technologies.

The results for the cumulative energy demand for the production of 1 kg of carbon fibres in Figure 2 shows that the case of bio-based carbon fibres where lignin is seen as a valuable product has the highest energy use. This is strongly connected to the use of biomass as an energy resource at the

Organosolv mill (connected to the precursor fibre production), as the allocation method used in lignin production in this case allocate all impacts of the Organosolv mill to the lignin. In the case where lignin is seen as a waste, the energy use is much lower, as no impacts of the Organosolv mill is allocated to the lignin.

Using microwave technology for carbon fibre production shows great potential to decrease the cumulative energy demand for both PAN- and lignin and bio-PU based fibres, but that if the lignin- and bio-PU based carbon fibres perform better is dependent on the value of lignin. Note that the energy use for the PAN-fibres produced using microwave technology consists of approximately 4% renewables, whereas the amount of renewable energy sources used when producing the lignin- and bio-PU fibres using microwave technology is between 10% and 40%, depending on if lignin is considered a waste or a valuable product.

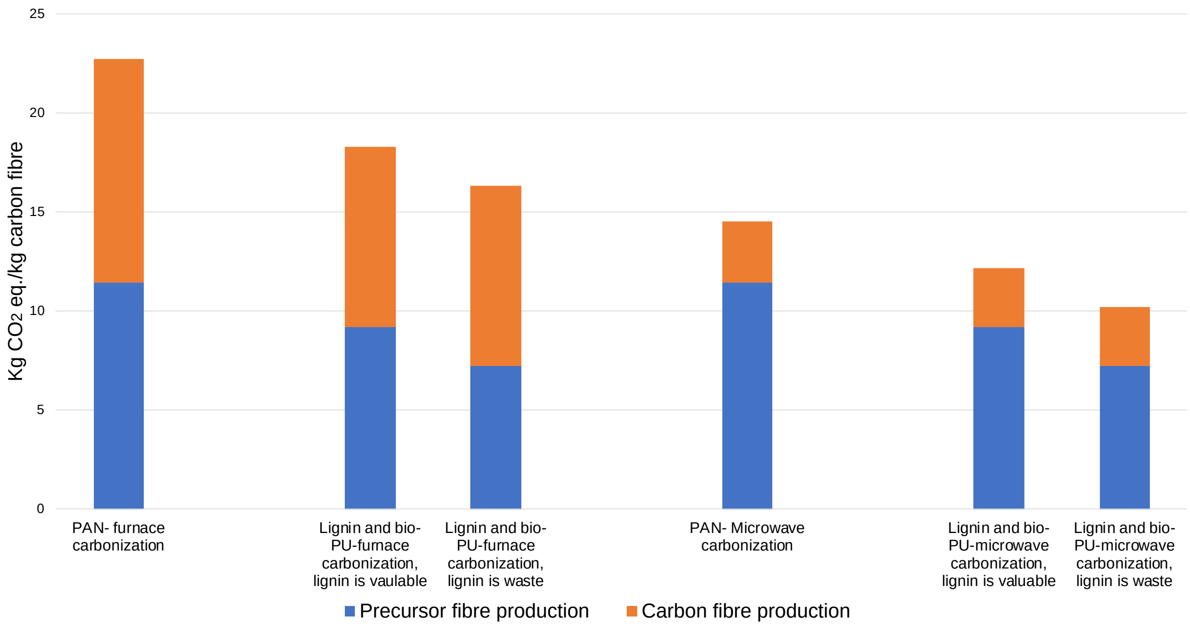

Figure 3: The climate impact of 1 kg produced fibres using different raw materials, allocation factors, and carbonization technologies.

Results in Figure 3 show that the climate impact of the carbon fibres produced using a conventional furnace is significantly higher for the PAN-based fibres than the lignin- and bio-PU based fibres. The reason for this is because of the lower climate impact of the precursor fibre (in spite of the lower material yield in carbon fibre production, meaning that 2.5 kg of lignin- and bio-PU based precursor fibres are needed for the production of 1 kg of carbon fibres. This can be compared to the 2 kg of PAN-based precursor fibres needed for the production of 1 kg of carbon fibres). It is also because lignin's inherent properties in theory reduce the energy consumption in the carbon fibre production step by 25% (and thus lower the related greenhouse gas emissions). Using microwave technology reduces the climate impact of both types of carbon fibres, however, in contrast to the results for the cumulative energy demand in Figure 2, Figure 3 shows that lignin- and bio-PU based carbon fibres always has a lower climate impact than the PAN-based carbon fibres, regardless if lignin is seen as a waste or a valuable product.

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