Life Cycle Assessment as a Decision Tool in Material Development - Experiences from a Multi-year Carbon Fibre Composite Development

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ORIGINAL PAPER

Life Cycle Assessment as a Decision Tool in Material Development—Experiences from a Multi-year Carbon Fibre Composite Development Project

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Abstract
This paper describes what type of advice life cycle assessment can provide in different parts of a material development project. Based on experiences from a multi-year research project aiming to decrease the environmental impacts of carbon fibre composites, we aim to show and discuss what type of input we could provide the material developers at different times. The goal is to guide life cycle assessment practitioners and material developers on what role life cycle assessment can play in various project parts. Cradle-to-gate data collected at different points in time throughout the project are compiled and recalculated to the same functional unit. Assessment results from all stages clearly show that even if the carbon fibres constitute a minor share of the composite, they are the environmental hotspot with considerable potential for improvements. Depending on the timing of the project, advice ranges from being careful with the source of nitrogen in the production process to using microwave heating in carbon fibre production. We recommend material developers to include life cycle assessment as early as possible in the project. We also recommend life cycle assessment practitioners continuously work with material developers in updating the models and inventory. Additionally, we recommend that life cycle assessment practitioners add more details to the assessment and expand the study's foreground system as the project progresses. This could be done in combination with assessing the technology readiness level of the routes. By doing so, the life cycle assessment practitioner can provide material developers insight into potential routes worth developing. It also identifies the lowest-hanging fruits for reducing the materials' environmental impact.

Keywords Carbon fibre composites · Prospective · life cycle assessment

Introduction

One of the main benefits of using life cycle assessment (LCA) is identifying potential environmental improvements throughout a product's life cycle (Azapagic & Clift 1999). By taking inventory of flows (such as materials, energy, and emissions) entering and exiting the system under study, we can quantify how much their contribution is to, e.g. climate impact, acidification, or toxicity. While most easily done for a well-defined and known system, there is also a need to assess the environmental impact of technologies under development. This can help avoid unfavourable technology development routes leading to increased environmental impacts.

LCA's role as a decision tool is debated in the literature. Pryshlakivsky and Searcy (2021) claim that the LCA community is divided into two camps: one aligned with industry aiming to streamline and simplify LCA to support the decision-making about the needs of their organisation, and one group that seeks to expand and enhance the abilities of LCA concerning other fields such as economics and policies. They state that both groups must make trade-offs to achieve their desired results. This means that LCA practitioners within the industry need to keep the organisation's strategy and conditions in mind while considering the consequences of conducting simplified LCAs. On the other hand, academics have yet to motivate the benefits of expanding LCAs into areas other than the organisations' production system. Hetherington et al. (2014)

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describe how LCA can be used as a development tool in early research. They write that LCAs done in the early stages of product development are essential. This is because the potential to develop, e.g. a pilot plant for the considered technology, depends on verifying improved environmental impacts at, e.g. lab scale. As the stakeholders can vary from researchers, technology developers, and internal project managers to external project funders, the information provided by the LCA practitioner must correspond to the needs of each of these stakeholders.

The work presented in this paper was done within the LIBRE project (Lignin-based carbon fibres for composites), funded by the Bio-Based Industries Joint Undertaking under the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 720707. We were part of a work package that dealt with the environmental and economic performance of lignin-based carbon fibres for composites. Carbon fibre composites consist of carbon fibres providing mechanical strength and a polymer matrix distributing the load. The material is both stiff and light and is often used to substitute conventional materials for, e.g. lightweighting in vehicles (Tapper et al. 2020; Witik et al. 2011). However, due to the energy-intensive carbon fibre production process, substituting conventional materials does not always provide an environmental benefit throughout the product's life cycle (Witik et al. 2011). The intention of our role as LCA practitioners in the LIBRE project was to guide material developers in the project consortium in identifying routes for decreasing the environmental impact of carbon fibres by, e.g. using lignin as a precursor material.

The project, the interaction between us as LCA practitioners and material developers, and how the LCAs developed over time can essentially be seen as a living lab. In living labs, different stakeholders are brought together to generate new ideas. They are typically formed to solve societal challenges, especially for urban areas (Hossain et al. 2019). With this line of reasoning, we argue that by looking back at the project, we can learn from what challenges and possibilities LCA introduces when used in different parts of the project in an approach similar to the assessment of a living lab. Consequently, this paper disseminates the experiences of LCA practitioners in a multi-year material research project and provides accumulated and generalised knowledge on the environmental impacts of carbon fibre composite production. To our knowledge, there are no other studies that disseminate LCA results from different stages of such a research project available in the literature. However, there are studies on using LCAs as a material selection tool. One such is the study by Tapper et al. (2020), who evaluated the LCA framework and its abilities to determine the benefits of closed-loop composite recycling based on the different life cycle phases of carbon fibre composites. The aim was to guide future material selection for recycled carbon fibre composites. Our paper differs as we investigate the guidance LCA practitioners can provide at different stages of a material development project, which depends on the available data and guidance material developers seek.

Methodology

Three case studies from earlier work are selected and adapted for the context of this study: (1) a case study based on earlier LCA results found in available literature performed at the start of the project, (2) a case study based on primary data from the project performed when production specific data had been gathered, and (3) a prospective case study assessing the potential environmental impact of carbon fibre composites following different technology development routes performed during the last stage of the project. These case studies are built on data collected during the LIBRE project but are in this paper recalculated to the same functional unit. The aim is to shed light on what decision support the different LCAs provide to the material developers.

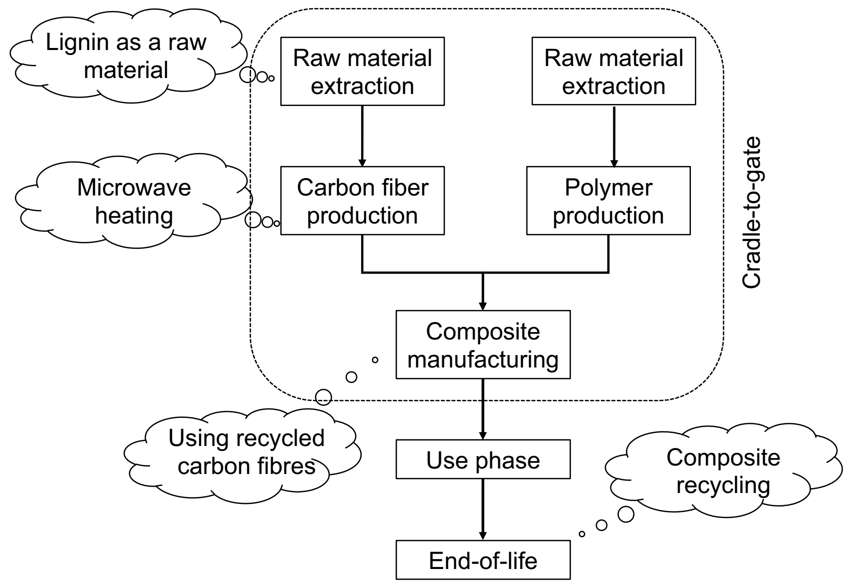
The functional unit of all three case studies is the manufacturing of 1 kg of carbon fibre composite to be used in any application, consisting of 20 wt% carbon fibres and 80 wt% polymers. The system boundaries include raw material extraction, materials production, and composite manufacturing, i.e. cradle-to-gate. The manufacturing for case studies 2 and 3 was assumed to take place in Germany, while for case study 1, the geographical boundaries are global because the study gathered average literature data. The basic outline for the composite life cycle, including the technology development routes considered, is outlined in Fig. 1.

The impact categories assessed are climate impact and energy use. In case study 1, assessment results derived from different methods for determining these impact categories were treated and compiled (see Hermansson et al. (2019)). For case studies 2 and 3, climate impact using (IPCC 2013) and cumulative energy demand (CED) provided by Ecoinvent 3.3 (Wernet et al. 2016) are used. The modelling for case studies 2 and 3 is done using Ecoinvent 3.3 APOS (Wernet et al. 2016) if nothing else is mentioned and implemented in the OpenLCA software.

Case Study 1

The goal of case study 1 is to screen the carbon fibre composite cradle-to-gate life cycle for environmental hotspots. Based on the carbon fibre composite production meta-analysis, it aims to assess the prospective environmental impacts of transitioning to lignin-based and recycled carbon fibres presented in Hermansson et al. (2019). Case study 1 uses cradle-to-gate data collected from Das (2011), La Rosa et al. (2016), Maxineasa et al. (2015), Suzuki and Takahashi

Fig. 1 The basic outline of the life cycle of carbon fibre composites with considered technology development routes included



(2005), Zhou (2013), and Meng et al. (2017). All data used in the calculations are found in Hermansson et al. (2019). The different environmental impacts are normalised to values representing 20 wt% of carbon fibres and 80 wt% other materials (polymers and fillers). Note that various LCA studies have different system boundaries and present results in different ways, meaning that there is likely a double counting of impacts, primarily related to composite manufacturing processes (such as injection moulding) and transportation for some cases.

Case Study 2

The goal of case study 2 is to assess the environmental impact of manufacturing carbon fibre composites in the specific way planned in the material development project. It is based on data presented in Hermansson et al. (2022b). The aim is to provide material developers with critical parameters that could decrease the environmental impact related to the manufacturing of carbon fibre composites when some data are available from lab experiments and similar processes. The data for the carbon fibre production was collected within the LIBRE project (inventory data are found in Stróżyk et al. (2023)), and the PAN precursor fibre dataset is provided by Fazio and Pennington (2005) in the European reference life cycle database (ELCD). The latter was adapted to fit the terminology of Ecoinvent; see Hermansson et al. (2022a) for details on the adaptation.

Case Study 3

The goal of case study 3 is to assess the possible future environmental impact of manufacturing carbon fibre composites following the implementation of three different technology development routes: producing the carbon fibres from lignin (in fact, 50% lignin and 50% biopolyurethane, the latter to reduce brittleness (Collins et al. 2019)), and using microwave heating in the carbon fibre production, as well as using recovered carbon fibres (produced using the two former routes), Fig. 1 outlines the life cycle and in which part each development route influences. The aim of case study 3 is to provide material developers with information on the possible future environmental impacts of carbon fibre composites if implementing these routes.

The study is based on the findings in Hermansson et al. (2022b) (inventory data for carbon fibre production are found in Stróżyk et al. (2023)). However, some adaptations were made. They used economic allocation to partition the impacts of the Organosolv mill between the co-products. In this study, we instead opt for mass allocation to partition the impacts from the Organosolv,[1,2] mill (as lignin is always the product of a multi-output process). This choice is based on the argument that this approach is less sensitive to market situations and/or changes in demand, both of which are hard to predict (Coelho et al. 2022). Additionally, the earlier study did not assess the use of recovered carbon fibres as a part of changes to the foreground system. We here assume that the recycled carbon fibre content is 82 wt%, which is used in Hermansson et al. (2022b) as a proxy that captures the need to compensate recycled carbon fibres of reduced quality with primary fibres. To allocate benefits and burdens, we use the cut-off approach crediting the composite for using recycled carbon fibres, meaning that a credit is provided for

[1] Resulting in an allocation factor of 0.34 for lignin.

[2] The input of enzymes to the Organosolv mill is excluded due to lack of data in Ecoinvent 3.3.

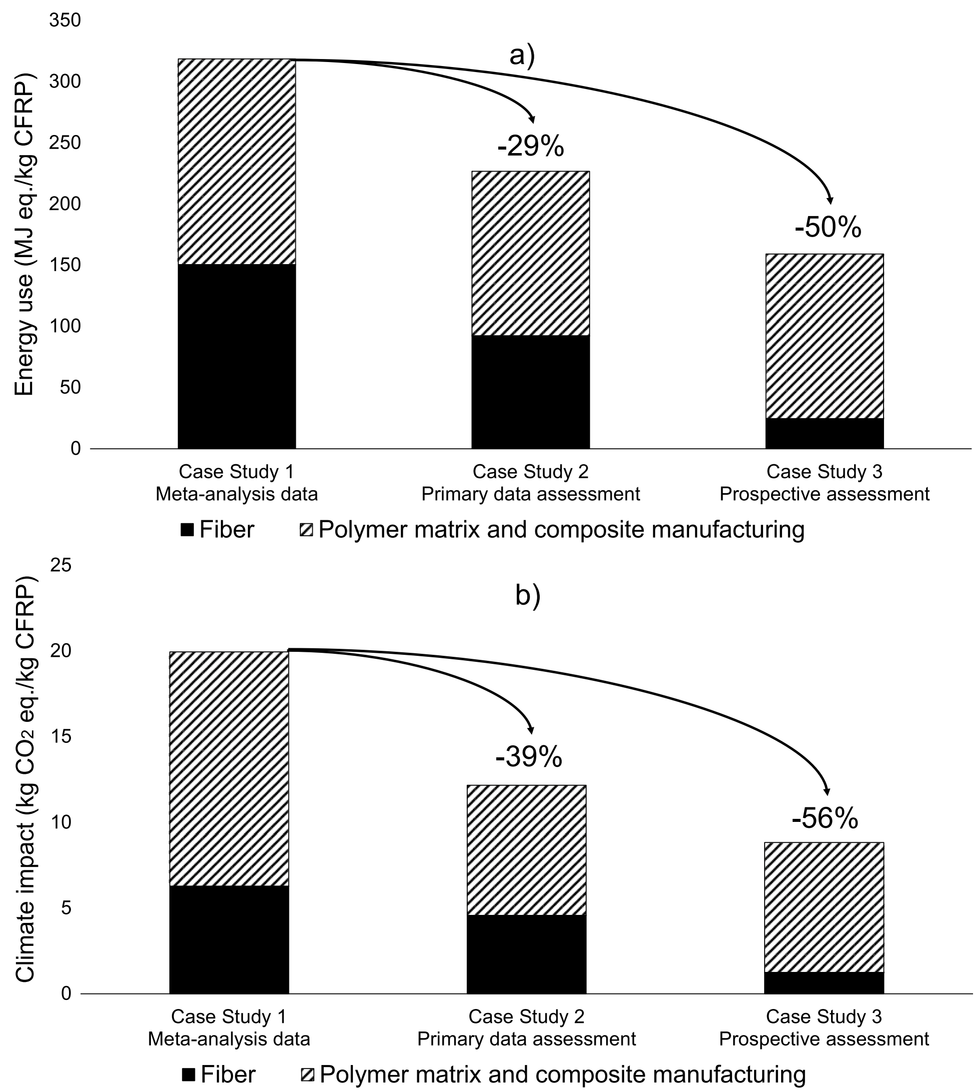


Fig. 2 The (**a**) energy use and (**b**) climate impact for producing 1 kg of carbon fibre composite. Case study 1 is based on treated literature data; case study 2 is based on primary data from the project; and case study 3 explores the influence of changes that could be made in the production process in a future-oriented analysis based on a mix of project and literature data as well as estimates

using recycled materials. We assume the carbon fibres originate from a composite with the same composition recycled through pyrolysis (assuming 30 MJ/kg energy needed (Witik et al. 2013)). We apply the redefined cut-off approach suggested by Hermansson et al. (2022a) to allocate the impacts of the pyrolysis process between the fibres and polymer.

Results and Discussion

The results from the three case studies described in the 'Methodology' section are found in Fig. 2.

Figure 2 shows that the energy use and climate impact for case study 1 are significantly higher than the results from case studies 2 and 3. However, the higher impact compared to the results of case study 2 is mainly connected to the polymer matrix and other composite manufacturing. Differences in polymers and composite manufacturing methods may partly explain this. Note that system boundary differences between the studies likely contribute to the higher impact. Another possible explanation is that impact assessment methods were partially equivalent. This is especially true for how the energy use has been accounted for, where the impact assessment method used varied more than for climate impact (Hermansson et al. 2019). For more information on different energy use indicators and their role in LCA, see Arvidsson and Svanström (2016).

Case study 1 shows that, despite possible double counting in the polymer and composite manufacturing phase, carbon fibre production is a hotspot in the cradle-to-gate life cycle of carbon fibre composites. Especially when it accounts for only 20 wt% of the composite, this illustrates the usefulness of using this kind of meta-analysis as an early screening tool, aiding material developers in understanding where to focus when aiming to reduce the environmental impact of carbon fibre composites. This approach is thus a way to fulfil the suggestions by Ott et al. (2022), who discuss the need for simplified evaluation approaches for identifying key development opportunities and hotspots. The approach, however, requires that parts of the system have been assessed, alone or as parts of larger systems, using LCA before. While not illustrated here, case study 1 was also useful for identifying methodological challenges for assessing technology development routes. Two challenges identified are the importance of the allocation approach in recycling and the choice of allocation approach in lignin production. These methodological choices could significantly influence the result (Hermansson et al. 2019).

Case study 2 shows carbon fibre is a hotspot for the composite life cycle. One major hotspot in the carbon fibre production process is energy consumption, meaning that material developers should aim to decrease the energy consumption in stabilisation and carbonisation. Another aspect, perhaps more easily addressed by material developers, is connected to the nitrogen needed to create an inert environment for the carbon fibre production phase. Janssen et al. (2019) point out that liquid nitrogen is a hotspot in carbon fibre production. Reusing nitrogen in a closed-loop could be an option. Another option could be using nitrogen produced through pressure swing absorption. This could significantly reduce the specific electrical power used (Schulte-Schulze-Berndt & Krabiell 1993). In case study 2, nitrogen is assumed to be produced using compressed air and a minor share of carbon fibre production's climate impact and cumulative energy demand. However, as mentioned above, other nitrogen sources can significantly contribute more. In hindsight, case study 2 confirms the function of the meta-analysis used in case study 1 as a screening tool for identifying hotspots since both case studies highlight the carbon fibre production process as a primary contributor to the environmental impact of carbon fibre composite manufacturing.

Case study 3 shows the environmental impact when three different technology development routes have been simultaneously considered in the carbon fibre production process: producing carbon fibres from lignin, using microwave heating in carbonisation and stabilisation, and using recycled carbon fibres. The results show that implementing these three routes could significantly lower carbon fibres' environmental impact, so it is no longer the primary hotspot of carbon fibre composite manufacturing.

The resulting quality and processability of lignin-based carbon fibres are debated. Groetsch et al. (2023) acknowledge the environmental advantages of cellulose-lignin-based carbon fibres but identify significant shortcomings regarding processability and material properties. If the lignin-based carbon fibres achieve good quality, the environmental impact is lower than that of PAN-based carbon fibres (Hermansson 2020; Janssen et al. 2019). However, as was mentioned concerning case study 1, the influence of the allocation approach in lignin production can be significant, depending on the system boundaries of the study. The climate impact of lignin production was examined by Hermansson et al. (2020), who found that the results varied significantly depending on the allocation approach used, as well as the temporal boundaries of the study.

Singh et al. (2023) suggest that microwave heating can be used in materials processing to decrease energy consumption by allowing a lower temperature and shorter processing time. In line with this, Stróżyk et al. (2023) show that the environmental impact of carbon fibres prepared via microwave heating is significantly lower than those produced via conventional furnaces. They also find that the mechanical performance of the carbon fibres produced via microwave heating is on par with those produced using conventional furnaces. This conforms what is reported by Lam et al. (2019), who showed that using microwave heating in pyrolysis of bamboo fibres to carbon fibres decreased the energy consumption by as much as 90% compared to conventional furnaces, primarily because of a higher heating rate and a faster processing time.

Meng et al. (2017) compared the use of recycled carbon fibres to the use of primary carbon fibres. They found that using recycled carbon fibres is a viable route for decreasing the environmental impact of composites, which is confirmed by Hermansson et al. (2022b). Hermansson et al. (2022a) add another challenge to assessing the recycling of composites, specifically that the components of the composite may have different recycling rates as well as different quality degradation in the recycling process and should therefore not be considered as a single material in the context of recycling. They suggest that the recycling process in these cases should be seen as a multi-output separation process, where the impacts of the separation should be divided between the components and between the product sent to the recycling and the products using recycled materials. Tapper et al. (2020) also point out that without appropriate remanufacturing technologies, any benefits from the recovered carbon fibres are not utilised.

The production of carbon fibres from lignin or using microwave heating is still not (in 2023) industrially implemented. Producing carbon fibres from lignin has, in recent years, started to approach pilot scale production (see, for example the press release on the production of lignin-based carbon fibres by Deutsche Institute für Textil- und Faserforschung (2023)). Microwave heating in carbon fibre production is still on a relatively low technology readiness level (TRL) and is primarily done in academic or research environments (see, for example Lam et al. (2019)). This means that these two routes are, in combination, less likely to happen soon. Recycling the composite and recovering the fibres through pyrolysis is a technology with a relatively high TRL (Rybicka et al. 2016). It is thus the most likely development route to happen in the near future. However, the recycling of lignin-based carbon fibres produced using microwave technology and the quality of these recycled fibres are yet to be researched. Since the recycling of carbon fibre composites and recovery of fibres already has a relatively high TRL, this might be the lowest-hanging fruit for material developers who wish to decrease the environmental impact of carbon fibre composites.

A more consistent inclusion of TRL levels in the future-oriented LCA would be beneficial, as this would help identify the route most helpful for decreasing the environmental impact of products and which route is likely more straightforward to implement in terms of technology development. A drawback with our future-oriented approach in this paper is that while the results look promising, it is impossible to weigh options against each other regarding the likelihood of happening soon. This could mean that the material developers are presented with results of combinations with technologies based on a lab scale that outperforms the results of technologies based on a pilot scale. In such a situation, a slightly less environmentally beneficial route may be deselected over a route requiring years of development. The technology route might not even perform as well as first thought or be too costly to realise. Future LCA methodology developments in terms of weighting factors based on the TRL of the assessed development routes would be a helpful contribution to future-oriented LCAs to mitigate this issue and to provide another dimension to the decision support. Arguably, this could be a compromise between the two LCA camps defined by Pryshlakivsky and Searcy (2021), which means that the LCA practitioner can expand the study to identify the most beneficial route/combination of routes in an exploratory and unconditionally manner. They can also determine the most feasible route for the organisation to implement.

Conclusions and Recommendations

This paper describes a multi-year effort to assess carbon fibre composites' life cycle environmental impact. We saw that LCA can be useful throughout the project, providing different inputs depending on data availability and demand from material developers and other stakeholders.

Overall, results show that the hotspot in carbon fibre composite manufacturing is the production of carbon fibres, but there is a great potential for reductions. One suggestion is to be careful when choosing the nitrogen source to create an inert environment. More extensive routes include using lignin as a precursor material, using microwave heating in carbon fibre production, or recycling the composites and recovering the fibres. The latter route has the highest TRL and is thus the lowest hanging fruit for material developers but does require that the techniques for manufacturing carbon fibre composites from recycled materials are improved and implemented.

We recommend LCA practitioners to collaborate with the material developers throughout the project, continuously updating the data and expanding the study to meet the needs of the project consortium. We recommend that material developers implement LCA early in a material development project. This can help the material developers identify the lowest hanging fruits to decrease the material's environmental impacts early on, making material development more efficient.

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Data Availability All data generated or analysed during this study are included in this published article.

Declarations

Competing Interests The authors declare no competing interests.

References

Arvidsson R, Svanström M (2016) A framework for energy use indicators and their reporting in life cycle assessment. Integr Environ Assess Manag 12(3):429–436. https://doi.org/10.1002/ieam.1735

Azapagic A, Clift R (1999) The application of life cycle assessment to process optimisation. Comput Chem Eng 23(10):1509–1526. https://doi.org/10.1016/S0098-1354(99)00308-7

Coelho, CRV, Peters, G, Zhang, J, Hong, B, Abdollahi, M, Undeland, I (2022) A comparative life cycle assessment of cross-processing herring side streams with fruit pomace or seaweed into a stable food protein ingredient. Future Foods, 100194. https://doi.org/10.1016/j.fufo.2022.100194

Collins MN, Nechifor M, Tanasă F, Zănoagă M, McLoughlin A, Stróżyk MA, Culebras M, Teacă C-A (2019) Valorization of lignin in polymer and composite systems for advanced engineering applications–a review. Int J Biol Macromol. https://doi.org/10.1016/j.ijbiomac.2019.03.069

Das S (2011) Life cycle assessment of carbon fiber-reinforced polymer composites. Int J Life Cycle Assess 16(3):268–282. https://doi.org/10.1007/s11367-011-0264-z
Deutsche Institute für Textil- und Faserforschung. (2023). Carbon fibers from lignin - a new peocess for economical production [Press release]. Retrieved from https://www.ditf.de/en/index/current/press-releases.html. Accessed 3 Apr 2023
Fazio, S, Pennington, D (2005) Polyacrylonitrile fibres (PAN); from acrylonitrile and methacrylate; production mix, at plant; PAN without additives (location: EU-27). European Commission, Joint Research Centre (JRC). Retrieved from: https://data.jrc.ec.europa.eu/dataset/jrc-eplca-db00901a-338f-11dd-bd11-0800200c9a66
Groetsch T, Maghe M, Creighton C, Varley RJ (2023) Economic and environmental effects of precursor variation in a continuous carbon fibre manufacturing process. J Ind Eng Chem 127:554–566. https://doi.org/10.1016/j.jiec.2023.07.041
Hermansson F, Janssen M, Svanström M (2019) Prospective study of lignin-based and recycled carbon fibers in composites through meta-analysis of life cycle assessments. J Clean Prod 223:946–956. https://doi.org/10.1016/j.jclepro.2019.03.022
Hermansson F, Ekvall T, Janssen M, Svanström M (2022a) Allocation in recycling of composites - the case of life cycle assessment of products from carbon fiber composites. Int J Life Cycle Assess 27(3):419–432. https://doi.org/10.1007/s11367-022-02039-8
Hermansson F, Heimersson S, Janssen M, Svanström M (2022b) Can carbon fiber composites have a lower environmental impact than fiberglass? Resour Conserv Recycl 181:106234. https://doi.org/10.1016/j.resconrec.2022.106234
Hermansson, F, Janssen, M, Svanström, M (2020) Allocation in life cycle assessment of lignin. Int J Life Cycle Assess https://doi.org/10.1007/s11367-020-01770-4
Hermansson F (2020) Assessing the future environmental impact of lignin-based and recycled carbon fibres in composites using life cycle assessment. Chalmers Tekniska Hogskola (Sweden). Retrieved from: https://research.chalmers.se/en/publication/518432
Hetherington AC, Borrion AL, Griffiths OG, McManus MC (2014) Use of LCA as a development tool within early research: challenges and issues across different sectors. Int J Life Cycle Assess 19(1):130–143. https://doi.org/10.1007/s11367-013-0627-8
Hossain M, Leminen S, Westerlund M (2019) A systematic review of living lab literature. J Clean Prod 213:976–988. https://doi.org/10.1016/j.jclepro.2018.12.257
Janssen, M, Gustafsson, E, Echardt, L, Wallinder, J, Wolf, J (2019) Life cycle assessment of lignin-based carbon fibres. Paper presented at the 14th Conference on sustainable development of energy, water and environment systems (SDEWES), 1–6 October 2019, Dubrovnik. Retrieved from: https://www.divaportal.org/smash/get/diva2:1371258/FULLTEXT01.pdf
La Rosa A, Banatao D, Pastine S, Latteri A, Cicala G (2016) Recycling treatment of carbon fibre/epoxy composites: materials recovery and characterization and environmental impacts through life cycle assessment. Compos B 104:17–25. https://doi.org/10.1016/j.compositesb.2016.08.015
Lam SS, Azwar E, Peng W, Tsang YF, Ma NL, Liu Z, Park Y-K, Kwon EE (2019) Cleaner conversion of bamboo into carbon fibre with favourable physicochemical and capacitive properties via microwave pyrolysis combining with solvent extraction and chemical impregnation. J Clean Prod 236:117692. https://doi.org/10.1016/j.jclepro.2019.117692
Maxineasa SG, Taranu N, Bejan L, Isopescu D, Banu OM (2015) Environmental impact of carbon fibre-reinforced polymer flexural strengthening solutions of reinforced concrete beams. Int J Life Cycle Assess 20(10):1343–1358. https://doi.org/10.1007/s11367-015-0940-5
Meng F, McKechnie J, Turner T, Pickering SJ (2017) Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres. Compos A 100:206–214. https://doi.org/10.1016/j.compositesa.2017.05.008
Ott, D, Goyal, S, Reuss, R, Gutzeit, HO, Liebscher, J, Dautz, J, Degieter, M, de Steur, H, Zannini, E (2022) LCA as decision support tool in the food and feed sector: evidence from R&D case studies. Environment Systems and Decisions, 1–13. https://doi.org/10.1007/s10669-022-09874-y
Pryshlakivsky J, Searcy C (2021) Life cycle assessment as a decision-making tool: practitioner and managerial considerations. J Clean Prod 309:127344. https://doi.org/10.1016/j.jclepro.2021.127344
Rybicka J, Tiwari A, Leeke GA (2016) Technology readiness level assessment of composites recycling technologies. J Clean Prod 112:1001–1012. https://doi.org/10.1016/j.jclepro.2015.08.104
Schulte-Schulze-Berndt A, Krabiell K (1993) Nitrogen generation by pressure swing adsorption based on carbon molecular sieves. Gas Sep Purif 7(4):253–257. https://doi.org/10.1016/0950-4214(93)80026-S
Singh C, Khanna V, Singh S (2023) Sustainability of microwave heating in materials processing technologies. Mater Today Proceed 73:241–248. https://doi.org/10.1016/j.matpr.2022.07.216
Stróżyk, MA, Muddasar, M, Conroy, TJ, Hermansson, F, Janssen, M, Svanström, M, Frank, E, Culebras, M, Collins, MN (2023) Decreasing the environmental impact of carbon fibre production via microwave carbonisation enabled by self-assembled nanostructured coatings Preprint. Research Square. Retrieved from https://doi.org/10.21203/rs.3.rs-3121560/v1
Suzuki, T, Takahashi, J (2005) LCA of lightweight vehicles by using CFRP for mass-produced vehicles. In Fifteenth International Conference on Composite Materials, Durban, South Africa (pp. 1-4), Retrieved from: https://jt.o.oo7.jp/publications/050627TS.pdf
Tapper RJ, Longana ML, Norton A, Potter KD, Hamerton I (2020) An evaluation of life cycle assessment and its application to the closed-loop recycling of carbon fibre reinforced polymers. Compos B 184:107665. https://doi.org/10.1016/j.compositesb.2019.107665
Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21(9):1218–1230. https://doi.org/10.1007/s11367-016-1087-8
Witik RA, Payet J, Michaud V, Ludwig C, Manson JAE (2011) Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Compos A 42(11):1694–1709. https://doi.org/10.1016/j.compositesa.2011.07.024
Witik R, Teuscher R, Michaud V, Ludwig C, Månson J-AE (2013) Carbon fibre reinforced composite waste: an environmental assessment of recycling, energy recovery and landfilling. Compos A 49:89–99. https://doi.org/10.1016/j.compositesa.2013.02.009
Zhou, H (2013) The comparative life cycle assessment of structural retrofit techniques. Retrieved from https://core.ac.uk/download/pdf/79566288.pdf