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Proceedings of the 20th European Conference on Composite Materials

COMPOSITES MEET SUSTAINABILITY

Vol 6 – Life Cycle Assessment

Editors : Anastasios P. Vassilopoulos, Véronique Michaud

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ESCM EUROPEAN SOCIETY FOR COMPOSITE MATERIALS

Proceedings of the 20th
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ECCM20
26-30 June 2022,
EPFL Lausanne Switzerland

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Prof. Anastasios P. Vassilopoulos, CCLab/EPFL
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Editorial

This collection gathers all the articles that were submitted and presented at the 20th European Conference on Composite Materials (ECCM20) which took place in Lausanne, Switzerland, June 26-30, 2022.

ECCM20 is the 20th edition of a conference series having its roots back in time, organized each two years by members of the European Society of Composite Materials (ESCM).

The ECCM20 event was organized by the Composite Construction laboratory (CCLab) and the Laboratory for Processing of Advanced Composites (LPAC) of the Ecole Polytechnique Fédérale de Lausanne (EPFL).

The Conference Theme this year was "Composites meet Sustainability". As a result, even if all topics related to composite processing, properties and applications have been covered, sustainability aspects were highlighted with specific lectures, roundtables and sessions on a range of topics, from bio-based composites to energy efficiency in materials production and use phases, as well as end-of-life scenarios and recycling.

More than 1000 participants shared their recent research results and participated to fruitful discussions during the five conference days, while they contributed more than 850 papers which form the six volumes of the conference proceedings. Each volume gathers contributions on specific topics:

Vol 1 – Materials

Vol 2 – Manufacturing

Vol 3 – Characterization

Vol 4 – Modeling and Prediction

Vol 5 – Applications and Structures

Vol 6 – Life Cycle Assessment

We enjoyed the event; we had the chance to meet each other in person again, shake hands, hold friendly talks and maintain our long-lasting collaborations. We appreciated the high level of the research presented at the conference and the quality of the submissions that are now collected in these six volumes. We hope that everyone interested in the status of the European Composites' research in 2022 will be fascinated by this publication.

The Conference Chairs

Anastasios P. Vassilopoulos, Véronique Michaud

Hosting Organizations

Composite Construction Laboratory (CCLab)
Laboratory for Processing of Advanced Composites (LPAC)
Ecole Polytechnique Fédérale de Lausanne (EPFL)

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And all those who helped, colleagues who reviewed abstracts and chaired sessions, and CCLab and LPAC students and collaborators who worked hard to make this conference a success.

Contents

GREEN CARBON / CARBON WITH CVI – POSSIBLE OR NOT?

Denny Schüppel[a], Florian Halter[b], Tobias Schneider[a], Dr. Lars Wietschel[b], Dr. Andrea Thorenz[b], Prof. Dr. Axel Tuma[b], Prof. Dr. Dietmar Koch[a]

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Abstract: *In recent decades, the development efforts on ceramic composites (CMC) have mainly focused on improving the mechanical, chemical, and thermal properties as well as on optimizing cost-effective production routes. Recently, more and more application areas for CMC have emerged outside of aerospace engineering, where environmental impacts and emissions are increasingly relevant. These impacts have hardly been studied so far but are attracting growing interest due to the increasing awareness of environmental impacts. The project team of the CU EcoCeramic joint research project is now focusing on these questions using C/C (carbon fiber reinforced carbon) as a generic example to show what the environmental footprint of C/C manufacturing looks like along the chemical vapor infiltration (CVI) route. On one hand, the key performance indicators (KPI) are considered. Secondly, realistic future scenarios are calculated, such as the use of regenerative process energy and the further development of manufacturing technology. Finally, current approaches and ideas are discussed as to what a holistic regenerative approach to C/C using CVI might look like when biobased carbon fibers and green process gases are used. The environmental impact is determined by a life cycle assessment (LCA).*

Keywords: CMC, CO_2-Footprint, CVI, Carbon/Carbon, LCA

1. Introduction

The present work and the associated research project CU EcoCeramic [1] deal with the life cycle assessment and economic evaluation of fiber-ceramic composite structures, so-called Ceramic Matrix Composites (CMC). The aim is to overcome existing obstacles in the use of CMC and to achieve a real closure of the recycling loops. The research objective is to consolidate and expand the acceptance of CMC. In doing so, a robust and transparent presentation of the current and future ecological footprint of CMC can help the broad SME sector to use this class of materials in the future as an "enabler" for necessary technological solutions in such ways that they can contribute to achieving the Paris 2050 climate targets [2].

The production, processing, and use of CMC for new applications are predominantly carried out by SMEs in Germany [3]. High material costs combined with ignorance of eco-efficiency and sustainability lead to a reluctance to use CMC, which hinders innovation. While large companies are increasingly preparing their own life cycle assessments and employ specialists in environmental management, research and development or other central areas of the company, SMEs in particular are unable to keep pace. The results achieved in this project thus enable SMEs

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in the long term to market their products quickly and in an ecologically or economically sensible manner.

In the medium term, it can be assumed that new materials will only become widely established if they meet minimum requirements in terms of ecological compatibility and recyclability. In addition, solutions must be identified to enable the landscape to sequestrate carbon dioxide from the earth's atmosphere on a large scale, store it and bind it permanently in carbon sinks.

Ceramic matrix composites based on carbon fibers with a carbon matrix seem to be an option for the future. Initial research activities are being conducted into carbon fibers made from green hydrogen. At the same time, green process gases for the CVI process are also being researched. Accordingly, the guiding or research question of this article is: Is it worth thinking about "sustainable" carbon/carbon materials (see also figure 1) from an ecological point of view, or does the energy-intensive manufacturing process obscure the benefits of the materials used?

It also remains to be seen, weather the environmental benefits of novel applications enabled by carbon/carbon materials (see also figure 1) outweigh the environmental impacts caused the energy-intensive manufacturing process of CMCs.

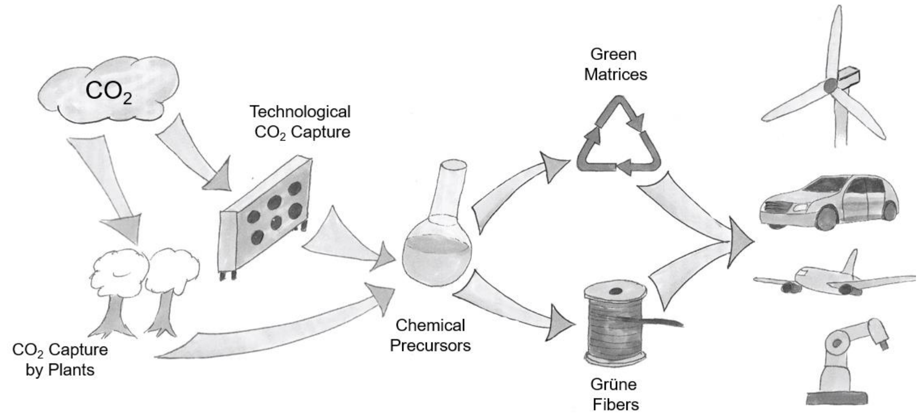


Figure 1: Generic sustainable production route for sustainable ceramic matrix composites, source: Ceramic Compoistes, Composite United e. V.

Ceramic matrix composites with a carbon fiber and a carbon matrix (C/C) are the most common CMC in terms of production volume. In aircraft alone, approx. 10,000 to 20,000 tons of brake discs are installed annually [4]. Most of these materials are produced by the chemical vapor infiltration (CVI) process route. In this process, an alkane, e.g., methane, flows around a "dry" carbon fiber preform in a furnace. Under highly specialized processing conditions, the carbon atoms of the alkane are deposited on the preform and thereby build up the matrix.

The build-up of a carbon matrix depends on many success factors: Gas flow rate, total pressures, partial pressures, gas composition, carrier gas mixtures, duration of gas flow, furnace temperature and many more. CVI is a highly complex process that only a few companies worldwide have mastered so far. However, if successful, high temperature resistant high-performance components can be produced, see figure 2.

Figure 2: Exemplary components made of C/C, produced with CVI. Source: CV-Technology GmbH.

Here you can see only a few examples of C/C components. In Europe, there are ten companies that operate a CVI commercially while four of them are located in Germany. The process differs within these companies as there is no "standard" CVI process. The entire setup changes when components and, above all, geometries change. For example, small components can be flowed through well while the flow through large components is more difficult. Depending on the availability of the plant, the geometry of the components and the component requirements, other plant configurations result, which has to be considered for the life cycle assessment. According to this, it is generally not possible to speak of a C/C component that has been manufactured using CVI.

2. Approach

Through a systematic variation of relevant material, process and production parameters, the range of decision variables as well as the corresponding interactions are demonstrated, and the most important levers are elaborated. To display the variety of applications despite the lack of a standard C/C component, several component types were analyzed. Assumptions and scenarios must help to describe the reality abstractly and generically on the one hand, but well-founded and resilient on the other. For this reason, generic structures of different degrees of complexity have been defined in the present work, see also Fig. 3. A basic distinction can be made between "profile-shaped" and "shell-shaped" structures. Profile-shaped components can, for example, be manufactured by means of braiding processes. Shell-shaped components are produced by weaving, among other methods. Five different levels of complexity have been defined for this purpose: Starting from complexity level 1: plane plate or plane tube up to complexity level 5: multiple curved shell or skeletal structure.

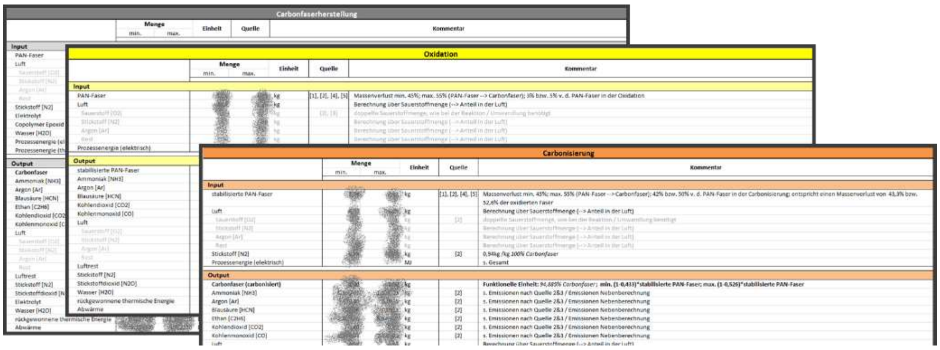
Figure 3: Illustration of the different levels of complexity. Here: complexity level 1 for a plane plate and 3 of a shell structure.

Expert panels were held for all generic geometries to discuss realistic process parameters. The discussed parameters serve as a database for the subsequent Life Cycle Inventory. Based on these values, the global warming potential was calculated for eight different scenarios. 1) State of the art (average) 2) Realistic favourable [slightly thinner, smaller, less complex] 3) Realistic unfavourable [slightly thicker, larger, more complex] 4) Gas recovery 5) Gas flow optimized 6) Production in Austria 7) Production in Norway 8) Realistic favourable 2030.

There is already a whole series of scientific publications from the world of carbon fibre-reinforced plastics on which this work bases. Hohmann et al. for example, have published several papers that take a generic look at the environmental footprint of carbon fibre and the preforming process, as described above [5-7]. These point out, that the ecological footprint of carbon fibre alone varies greatly. In addition, the production margins and general conditions vary greatly. Some fibre manufacturers use a more electricity driven energy input for oxidation and carbonization, while others use a more gaseous energy input [5-7].

In the preceding research study MAI Enviro [5], a generic HT fiber was determined using SGL Carbon and (at that time) Toho Tenax. Furthermore, life cycle assessments were performed for all other production processes of CFRP [5][6]. The values determined in this study are used as input for this present work.

In the area of data collection, this paper therefore deals primarily with all process steps that have not been covered in MAI Enviro - here using the CVI process as an example. All secondary processes (provision of gases, heat, cooling, other mass flows) were balanced individually, see also Figure 4. In addition to each individual input and output stream, realistic minimum and maximum values were parameterized in such a way that the estimation of the CO_2 footprint can be made as a function of the degree of complexity.



Carbonfaserherstellung

	Menge min.	Menge max.	Einheit	Quelle	Kommentar
Input					
PAN-Faser					
Luft					
Sauerstoff [O2]					
Stickstoff [N2]					
Argon [Ar]					
Rest					
Stickstoff [N2]					
Elektrolyt					
Copolymer Epoxid					
Wasser [H2O]					
Output					
Carbonfaser					
Ammoniak [NH3]					
Argon [Ar]					
Blausäure [HCN]					
Ethan [C2H6]					
Luft					
Sauerstoff [O2]					
Stickstoff [N2]					
Argon [Ar]					
Rest					
Luftrest					
Stickstoff [N2]					
Elektrolyt					
Wasser [H2O]					
rückgewonnene thermische Energie	[redacted]	[redacted]			
Abwärme					

Oxidation

	Menge min.	Menge max.	Einheit	Quelle	Kommentar
Input					
PAN-Faser	[redacted]	[redacted]	kg	[1], [2], [4], [5]	Massenverlust min. 45%; max. 55% (PAN-Faser --> Carbonfaser); 3% bzw. 5% v. d. PAN-Faser in der Oxidation
Luft	[redacted]	[redacted]	kg		Berechnung über Sauerstoffmenge (--> Anteil in der Luft)
Sauerstoff [O2]	[redacted]	[redacted]	kg	[2], [3]	doppelte Sauerstoffmenge, wie bei der Reaktion / Umwandlung benötigt
Stickstoff [N2]	[redacted]	[redacted]	kg		Berechnung über Sauerstoffmenge (--> Anteil in der Luft)
Argon [Ar]	[redacted]	[redacted]	kg		Berechnung über Sauerstoffmenge (--> Anteil in der Luft)
Rest	[redacted]	[redacted]	kg		Berechnung über Sauerstoffmenge (--> Anteil in der Luft)
Prozessenergie (elektrisch)					
Output					
stabilisierte PAN-Faser					
Ammoniak [NH3]					
Argon [Ar]					
Blausäure [HCN]					
Kohlendioxid [CO2]					
Kohlenmonoxid [CO]					
Luft					
Sauerstoff [O2]					
Stickstoff [N2]					
Argon [Ar]					
Rest					
Luftrest					
Stickstoff [N2]					
Stickstoffdioxid [N2O]					
Wasser [H2O]					
rückgewonnene thermische Energie					
Abwärme					

Carbonisierung

	Menge min.	Menge max.	Einheit	Quelle	Kommentar
Input					
stabilisierte PAN-Faser	[redacted]	[redacted]	kg	[1], [2], [4], [5]	Massenverlust min. 45%; max. 55% (PAN-Faser --> Carbonfaser); 42% bzw. 50% v. d. PAN-Faser in der Carbonisierung; entspricht einen Massenverlust von 43,3% bzw. 52,6% der oxidierten Faser
Luft	[redacted]	[redacted]	kg		Berechnung über Sauerstoffmenge (--> Anteil in der Luft)
Sauerstoff [O2]	[redacted]	[redacted]	kg	[2]	doppelte Sauerstoffmenge, wie bei der Reaktion / Umwandlung benötigt
Stickstoff [N2]	[redacted]	[redacted]	kg		Berechnung über Sauerstoffmenge (--> Anteil in der Luft)
Argon [Ar]	[redacted]	[redacted]	kg		Berechnung über Sauerstoffmenge (--> Anteil in der Luft)
Rest	[redacted]	[redacted]	kg		Berechnung über Sauerstoffmenge (--> Anteil in der Luft)
Stickstoff [N2]	[redacted]	[redacted]	kg	[2]	0,94kg /kg 100% *Carbonfaser*
Prozessenergie (elektrisch)	[redacted]	[redacted]	MJ		s. Gesamt
Output					
Carbonfaser (carbonisiert)	[redacted]	[redacted]	kg		**Funktionelle Einheit:** *94,889% Carbonfaser*; **min. (1-0,433)*stabilisierte PAN-Faser; max. (1-0,526)*stabilisierte PAN-Faser**
Ammoniak [NH3]	[redacted]	[redacted]	kg	[2]	s. Emissionen nach Quelle 2&3 / Emissionen Nebenberechnung
Argon [Ar]	[redacted]	[redacted]	kg	[2]	s. Emissionen nach Quelle 2&3 / Emissionen Nebenberechnung
Blausäure [HCN]	[redacted]	[redacted]	kg	[2]	s. Emissionen nach Quelle 2&3 / Emissionen Nebenberechnung
Ethan [C2H6]	[redacted]	[redacted]	kg	[2]	s. Emissionen nach Quelle 2&3 / Emissionen Nebenberechnung
Kohlendioxid [CO2]	[redacted]	[redacted]	kg	[2]	s. Emissionen nach Quelle 2&3 / Emissionen Nebenberechnung
Kohlenmonoxid [CO]	[redacted]	[redacted]	kg	[2]	s. Emissionen nach Quelle 2&3 / Emissionen Nebenberechnung
Luft	[redacted]	[redacted]	kg		Berechnung über Sauerstoffmenge (--> Anteil in der Luft)

Figure 4: Sample data collection for various missing processes along CVI process route

Furthermore, central boundary and framework conditions were defined for the subsequent CO_2 analysis. It is always important to note that the figures presented here are based on series production. However, there are also CVI plants that are primarily used for research and development. For research and development, however, the furnaces are often oversized, which leads to a biased environmental assessment. In addition, sometimes several prototypes must be produced for one component. All these development steps are neglected in the present work.

3. Results

Figure 5 shows an average state-of-the-art process of series components in the left bar. The complexity level is three and the surface type is shell-shaped. The number of pieces is rather high compared to the CVI process with approx. 500 pieces per year. It can be seen that the carbon fiber accounts for only a very small share of the GWP of this generic component at 2.1% (orange). Preforming and other logistical processes, in this case nonwoven production (gray), account for another 0.27%. The main share of the ecological footprint here is accounted for by the CVI process and all its secondary processes. In particular 69.5 % of the GWP is attributable to use of electricity for the CVI process. (German electricity mix 2021). In addition, alkanes, such as methane, ethane, etc., which are used to build up the matrix account for 20%. The remaining part of the GWP is made up of carrier and other gases with approx. 8 %. These include: Nitrogen for purging, the use of inert gases such as argon, or gases to adjust the partial pressure, e.g. hydrogen. Neglected here: The reprocessing of CVI systems. Especially in series production, CVI systems have to be maintained frequently. However, these maintenance intervals are massively dependent on the manufactured product and can therefore not be considered in such an approach.

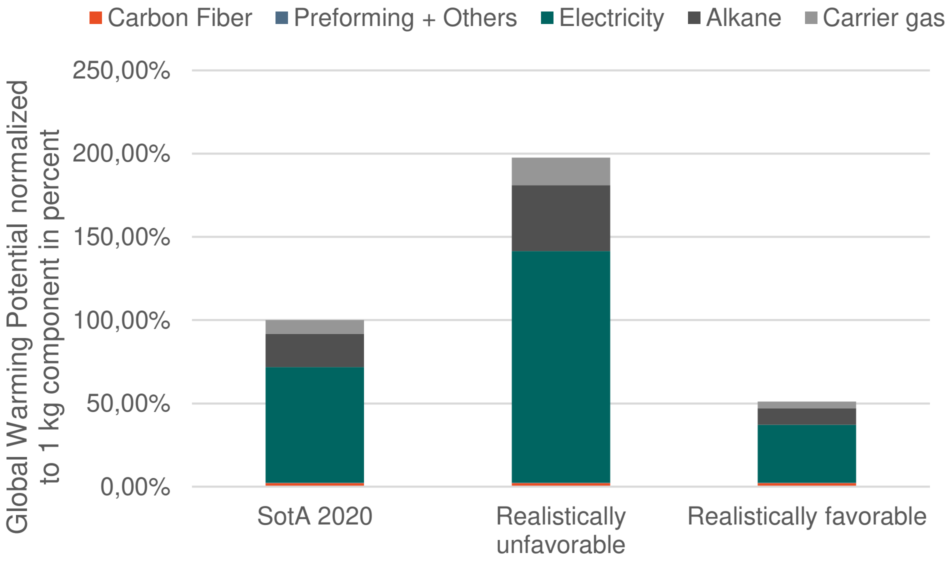


Figure 5: Normalized GWP - State of the Art Process and Realistically Unfavorable / Favorable

As described in chapter 2: GWP is strongly dependent on the processes used and the manufactured components. In Figure 5, the geometries of the manufactured generic semi-finished products were simulated unfavorably and favorably using the example of the middle and right bars. Component thickness (slightly thicker, slightly thinner), component size (slightly larger, slightly smaller) and component complexity (five and 1) were simulated. For this purpose, the thermal furnace load was reduced and increased by 20 % respectively (to approx. 90 % of the maximum load). The results imply that marginal and general conditions of the manufacturing process have a very significant influence. This is why it is not possible to speak of a generalized CVI, but why the marginal and general conditions should always be included. Therefore, the component type and the furnace utilization are decisive for the CO_2 emissions.

Knowing the significant ecological variation of the different boundary and framework conditions shown in Figure 5, further investigations of the ecological factors influencing a C/C via the LSI route were done and illustrated in Figure 6. The left bar shows the state of the art values from Figure 5. Based on this, different scenarios were considered.

First of all, the influence of Gas treatment or gas recovery is determined. In the CVI process, significant amounts of alkanes are passed through the textile preform at high temperatures. These can be different alkanes. Taking methane (CH4) as an example, only a single-digit percentage of the methane introduced is converted in the reactor to carbon, which builds up the matrix, and additionally hydrogen. More than 90 % of the methane leaves the CVI process unreacted, enriched with alkanes of higher carbon content. The state of the art process assumes that all exhaust gases go to controlled combustion and are emited to the environment. In contrast, in Scenario 2 "Gas Recovery" it is assumed that a functioning methanizer exists at the gas outlet, which proportionally captures the outflowing hydrogen, enriches it with CO2 and produces methane. This methane is to be fed back into the process as recycled feedstock. This additional gas treatment step requires approx. 1 % - 3 % more electricity, but saves up to 81 % alkane. Thus, this step alone reduces the CO2 emissions of the entire production process by 16 %.

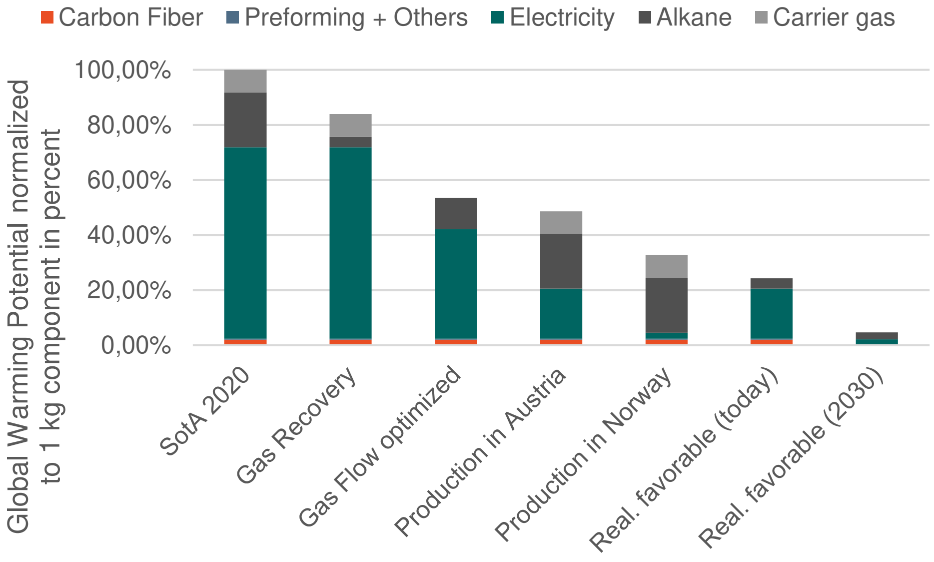


Figure 6: Ecological optimization potentials in comparison to the State of the Art 2020

The 3rd bar from the left, shows the optimization potential of an optimized gas flow. There are a lot of possibilities to optimize the gas flow. However, this optimization is also dependent on the geometries of the components and thus the degrees of complexity. In order to remain comparable with the state of the art, optimization potentials in complexity level 3 were presented for flat semi-finished products. This representation differs in other degrees of complexity. Optimized gas flow can be achieved by means of gas flow aids in the reactor, adjustment of the partial pressures and temperature setting. The composition of the alkane is also decisive. If methane is used, for example, a certain purity of well over 90 % must be available depending on the process. As Figure six shows the optimized gas flow causes the matrix to build up faster in this example. As a result, the process can be run for a shorter time (43 % less

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electricity required), less alkane (-42 %) is needed and carrier gases can be completely omitted. This reduces the CO_2 footprint by 47 % compared to the state of the art.

Bars 4 and 5 show the ecological optimization potential for production cities (meaning exclusively the CVI process) outside of Germany (state of the art, left bar), but in Austria (electricity mix 2021) or Norway (electricity mix 2021). Due to the comparatively more ecologically sensible electricity mixes (more electricity from hydropower/wind power, less electricity from coal and gas), significant reduction potentials based on location alone can be found: Austria - 51% and Norway - 67% compared to Germany.

Many companies that want to launch semi-finished products or finished products on the market are already being asked about the carbon footprint of their products. As a result, many companies are already active in this area. In addition to reducing costs and increasing component performance, the ecological production margins and framework conditions are becoming increasingly relevant. Together with the project consortium [1], a possible generic C/C production was defined, which reflects the state of the art today as reasonably as possible as shown in Figure 5, realistically favorable today. This scenario is state of the art for some manufacturing companies. The second bar from the right shows the state of the art if the following conditions are also met (compared to the left bar): Vapor recovery, optimized gas flow, no carrier gas, Austrian electricity mix. Individual companies thus already achieve a CO_2 reduction potential of 76% compared to other companies.

The last Scenario determined the “Realistically Favorable in the year 2030”. In the past, it has become established in the forerunner projects to also define realistic assumptions for the future. For example, it can be assumed that the use of biogases (methane) instead of natural gases will become established. This will only lead to minimal adjustments to the process and can be implemented technologically or is already being investigated today due to the political unrest in Eastern Europe. In addition, the European electricity mixes will change until 2030. Furthermore, process optimizations of 20% (faster) have been assumed as well as the use of a bio-based carbon fiber [7]. It can therefore be assumed that the ecological optimization potential can once again drop by approx. 80 % compared to the favorable scenario today.

4. Conclusion

The main influencing factor for a generic CO_2 investigation of the CVI process is, that the scope must be clearly defined as Fig. 5 shows. To this end, it can be pointed out, that compared to other materials such as steel, aluminum, titanium, plastics or CFRP, C/C has a higher average CO_2 footprint via the CVI route. However, if the process is optimized in a technically clever way, almost 40% of greenhouse gas emissions can be avoided, compare Figure 7, left. However, the leverage of the production site is the highest due to the underlying electricity mix. Germany does not have a particularly favorable electricity mix in 2021. Austria or the European pioneer country Norway, on the other hand, do. The location alone has an influence of around 50% on CO_2 emissions in production. Green precursors, especially biogas compared to natural gas, have just under 20% influence on the CO_2 footprint of C/C products via the CVI route.

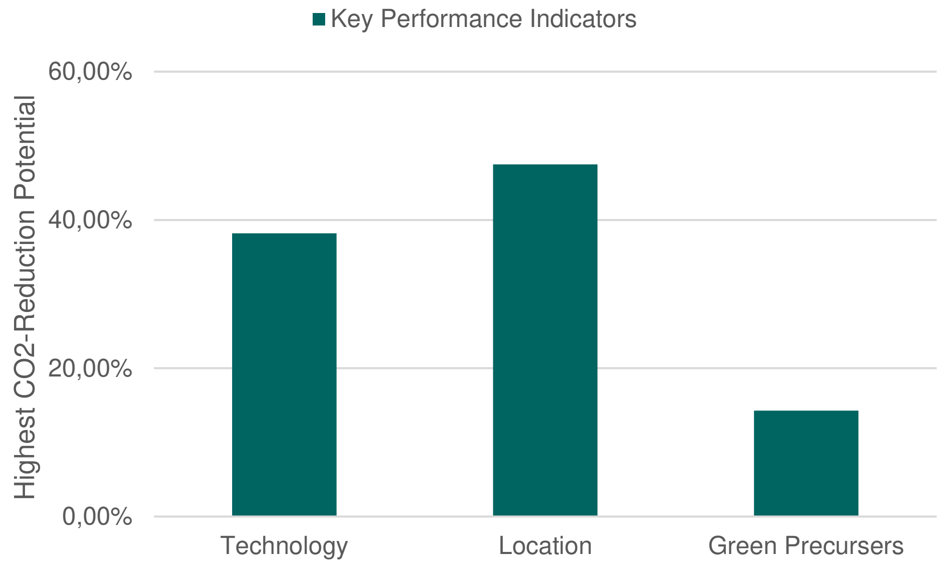

Figure 7 : Key Performance Indicators

The answer to the question, "Possible or not?" with respect to "Green C/C" is: yes, but. Yes, it is possible, but it strongly depends on which components are manufactured, how and where. Furthermore, it is crucial how innovative the manufacturing companies are and how advanced the production processes are already today.

5. Outlook

The next steps are to corroborate these collected life cycle inventory data sets by the broader industry. The absolute figures are then to be published. A rough shift of the relative proportions is not to be expected. However, a slight absolute adjustment may still happen, depending on the common understanding of the state of the art. In addition, correlations between ecological and economic footprint or ecological footprint and component performance will be established. Finally, some German companies are already working on the production of "own" methane, from hydrogen from the CVI process and CO_2 from the environment. Powered by renewable electricity, the question arises: will we even achieve a CO_2 sink one day?

6. References

1. Website of CU EcoCeramic (2020): https://composites-united.com/projects/cmc-enviro/
2. Paris 2050 climate targets (2016): https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_bf.pdf
3. List of members of the Network of Ceramic Composites (2020): https://composites-united.com/cluster/ceramic-composites/
4. Composited United Market Report (2021), M. Sauer, D. Schüppel; https://composites-united.com/cfk-marktberichte-des-cu/

5. MAI Enviro: Vorstudie zur Lebenszyklusanalyse mit ökobilanzieller Bewertung relevanter Fertigungsprozessketten für CFK-Strukturen (2015): A. Hohmann, B. Schwab, D. Wehner, S. Albrecht, R. Ilg, D. Schüppel, T. v. Reden; ISBN: 978-3-8396-0929-3
6. Recommendations for resource efficient and environmentally responsible manufacturing of CFRP products. Results of the Research Study MAI Enviro 2.0.(2017): A. Hohmann, S. Albrecht, J. P. Lindner, D. Wehner, M. Kugler, T. Prenzel, T. Pitschke, M. Seitz, D. Schüppel, S, Kreibe, T. von Reden; Buch des Spitzenclusters MAI Carbon; ISBN: 978-3-9818900-0-6
7. Nachhaltige Verbundwerkstoffe für Hochleistungsfasern, Abschätzung der Umweltwirkungen und Möglicher Reduktionspotentiale; A. Hohmann, Technologietag Leichtbau, 09. November 2021