

Green carbon / carbon with CVI - possible or not?

**Denny Schüppel, Florian Halter, T. Schneider, Lars Wietschel,
Andrea Thorenz, Alex Tuma, Dietmar Koch**

Angaben zur Veröffentlichung / Publication details:

Schüppel, Denny, Florian Halter, T. Schneider, Lars Wietschel, Andrea Thorenz, Alex Tuma, and Dietmar Koch. 2022. "Green carbon / carbon with CVI - possible or not?" In ECCM 2022 - Proceedings of the 20th European Conference on Composite Materials: Composites Meet Sustainability, volume 6 - Life Cycle Assessment, edited by Anastasios P. Vassilopoulos and Véronique Michaud, 314-22. Lausanne: EPFL Lausanne, Composite Construction Laboratory.
https://doi.org/10.5075/epfl-298799_978-2-9701614-0-0.

ECCM

20

26-30 JUNE

2022

LAUSANNE
SWITZERLAND



Proceedings of the 20th European Conference on Composite Materials

COMPOSITES MEET SUSTAINABILITY

Vol 6 – Life Cycle Assessment

Editors : Anastasios P. Vassilopoulos, Véronique Michaud

Organized by :

EPFL

Under the patronage of :

CCLAB
Composite
Construction
Laboratory

LPAC
Laboratory for Processing
of Advanced Composites

ESCM
EUROPEAN SOCIETY
FOR COMPOSITE MATERIALS

**Proceedings of the 20th
European Conference on Composite Materials
ECCM20
26-30 June 2022,
EPFL Lausanne Switzerland**

Edited By :

Prof. Anastasios P. Vassilopoulos, CCLab/EPFL
Prof. Véronique Michaud, LPAC/EPFL

Organized by:

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

ISBN: 978-2-9701614-0-0

DOI: http://dx.doi.org/10.5075/epfl-298799_978-2-9701614-0-0

Published by :

Composite Construction Laboratory (CCLab)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
BP 2225 (Bâtiment BP), Station 16
1015, Lausanne, Switzerland

<https://cclab.epfl.ch>

Laboratory for Processing of Advanced Composites (LPAC)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
MXG 139 (Bâtiment MXG), Station 12
1015, Lausanne, Switzerland

<https://lpac.epfl.ch>

Cover:

Swiss Tech Convention Center
© Edouard Venceslau - CompuWeb SA

Cover Design:

Composite Construction Laboratory (CCLab)
Ecole Polytechnique Fédérale de Lausanne (EPFL)
Lausanne, Switzerland

©2022 ECCM20/The publishers

The Proceedings are published under the CC BY-NC 4.0 license in electronic format only, by the Publishers.

The CC BY-NC 4.0 license permits non-commercial reuse, transformation, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial reuse, please contact the authors. For further details please read the full legal code at <http://creativecommons.org/licenses/by-nc/4.0/legalcode>

The Authors retain every other right, including the right to publish or republish the article, in all forms and media, to reuse all or part of the article in future works of their own, such as lectures, press releases, reviews, and books for both commercial and non-commercial purposes.

Disclaimer:

The ECCM20 organizing committee and the Editors of these proceedings assume no responsibility or liability for the content, statements and opinions expressed by the authors in their corresponding publication.

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)

Venue

Swiss Tech Convention Center (<https://www.stcc.ch>)

Conference Chairs

Chair : Prof. Anastasios P. Vassilopoulos, EPFL, Switzerland
Co-Chair: Prof Véronique Michaud, EPFL, Switzerland

International Scientific Committee

Prof. Malin Åkermo SE	Prof. Theodoros Loutas GR
Dr. Emmanuel Baranger FR	Prof. Veronique Michaud CH
Prof. Christophe Binetruy FR	Prof. Alessandro Pegoretti IT
Prof. Pedro Camanho PT	Prof. Joao Ramoa Correia PT
Prof. Konstantinos Dassios GR	Prof. Jose Sena-Cruz PT
Prof. Brian Falzon UK	Prof. Antonio T. Marques PT
Prof. Kristofer Gamstedt SE	Prof. Thanasis Triantafillou GR
Prof. Sotiris Grammatikos NO	Prof. Albert Turon ES
Prof. Christian Hochard FR	Prof. Anastasios P. Vassilopoulos CH
Prof. Marcin Kozłowski PL	Prof. Martin Fagerström SE
Prof. Stepan Lomov BE	Dr. Alexandros Antoniou DE
Dr. David May DE	Prof. Lars Berglund SE
Prof. Stephen Ogin UK	Prof. Michal Budzik DK
Prof. Gerald Pinter AT	Prof. Lucas Da Silva PT
Prof. Silvestre Pinho UK	Dr. Andreas Endruweit UK
Prof. Yentl Swolfs BE	Prof. Mariaenrica Frigione IT
Dr. Julie Teuwen NL	Dr. Larissa Gorbatikh BE
Dr. Panayota Tsotra CH	Dr. Martin Hirsekorn FR
Prof. Wim van Paepegem BE	Prof. Vassilis Kostopoulos GR
Prof. Dimitrios Zarouchas NL	Prof. Jacques Lamont FR
Dr. Andrey Anishevich LV	Prof. Staffan Lundstrom SE
Prof. Christian Berggreen DK	Prof. Peter Mitschang DE
Dr. Nicolas Boyard FR	Dr. Soraia Pimenta UK
Prof. Valter Carvelli IT	Prof. Paul Robinson UK
Prof. Klaus Drechsler DE	Dr. Olesja Starkova LT
Prof. Bodo Fiedler DE	Prof. Sofia Teixeira de Freitas NL
Dr. Nathalie Godin FR	Dr. Stavros Tsantzalis GR
Prof. Roland Hinterholz AT	Prof. Danny van Hemelrijck BE
Prof. Ian Kinloch UK	Prof. Michele Zappalorto IT
Dr. Thomas Kruse DE	Dr. Miroslav Cerny CZ

Local Organizing Committee

Prof. Anastasios P. Vassilopoulos, EPFL
Prof. Véronique Michaud, EPFL

Angélique Crettenand and Mirjam Kiener, Lausanne Tourisme

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

A comparative study on the effect of different accelerated ageing environments on the degradation of filament wound composites	1
Assessment of the properties of two high-temperature thermosetting POLYIMIDES	8
Methodology for transverse cracking simulation in 90 plies of composite laminate under fatigue loading	16
Transverse cracking characterization and prediction in heat treated polymer composites under quasi-static tensile loading at elevated temperature	23
Laser stripping of thermally aged epoxy coatings for aeronautical applications	31
Hygro-thermal effects on the translaminar fracture toughness of composite laminates	39
Recovery and reuse of carbon fibre and acrylic resin from thermoplastic composites used in marine application	47
New ways to recycle composites and biocomposites from windblades and airplanes (EROS and ELIOT project)	55
The used surgical masks: from waste to resource	63
Dynamic mechanical analysis of polyamide 11 (PA11), polyamide 12 (PA12) and their recycled long carbon fiber composites	69
Performance of recycled glass fibers from composite parts by different treatments	77
Eco-clip: development of novel recycled material from CF/ LMPAEK factory waste	85
From sail to structure: end-of-life sails as a feedstock for circular manufacturing	93
Composite pyrolysis oil: a source of industrially relevant chemical feedstock molecules?	101
Development of recycled thermoplastic composites technology for aerospace in a real-world environment	109
Effect of shredding parameters on the formation of airborne fiber dust during mechanical recycling of fiber reinforced thermoplastics	119
A composite approach to mechanically upcycle post-consumer mixed engineering plastics	126
Novel method for uncured prepreg recycling using supercritical carbon dioxide extraction	133
New trends in plastics and thermoplastic composites upcycling: THERMOPRIME® & THERMOSAIC® technologies	141
High performance multi-functional composite structures with inkjet printed embedded circuits	147
Validating simulated residual strains due to thermoforming using FBGS	155
Advanced multifield models for waves propagation analysis in smart composite panels	162
Ultra-thin, high porous paper sensors	171
Nanostructured self-sensing piezoelectric composite laminate	179
Rate dependent electromechanical characterization and modeling of graphene based fiber reinforced polymer laminates	187

Toward sustainable active cellulose nanocrystals-based ink for structural health monitoring	195
Fiber reinforced polymer composites with self-powered sensing capabilities – an experimental and simulation study	201
Embedded carbon nanotubes for localized cure monitoring	208
Fully integrated carbon nanotube epoxy film sensors for strain sensing in GFRP	216
FBG sensors for process and structural health monitoring of a small type III composite overwrapped pressure vessel for unmanned aerial vehicle	224
3D printed polymer nanocomposites engineered with graphene and metallic nanoparticles for optical detection of water pollutants	231
Self-healing vitrimer composites for soft robotics	239
Soft carbon-based multi-sensory resistive receptors	247
Characterization of a soft magnetic composite for use in road-embedded wireless-charging systems	255
Thermoelectric 0D/2D cement composites for future large-scale thermal energy harvesting	263
Evaluating viscoelastic shear properties in clear wood via off-axis compression texting and digital image correlation	270
Self-sensing properties of different carbon nanomaterial based composites for sustainable infrastructures	276
Development of methodology for experimental parameter identification for inelastic 3D material model	282
Life cycle assessment and life cycle costing on recycled post-industrial composite waste	290
Additive manufacturing of multilayered polymer composites: durability assessment	298
Material design-for-excellence (m-DFX) – new methodological approach applicable to composite materials	306
Green carbon / carbon with CVI – possible or not?	314
Energy efficiency oriented decision-making for additive manufacturing of carbon fiber reinforced polyamide 12	323
Life cycle assessment of CFRP panels used in aerospace applications	331
Environmental impact assessment of thermo-stamping carbon fibres reinforced polyphenylene sulfide composite parts	339
Effects of the hygrothermal aging history on epoxy resins and GFRP composites	347
Evaluating the sustainability of lightweight drones for last mile delivery: towards a suitable methodology for assessment	355
Static and fatigue behavior of flax/epoxy composite: impact of the process of manufacturing	363
How can CFRP prepreg scraps be reused? the “CIRCE” life project	371
Economic assessment of carbon fiber prepreg scraps reuse in automotive components	379
Transient thermal analysis and thermal aging behaviour of carbon fibre reinforced plastics for “green” moulding of aerospace grade composites	391

Sensitivity factor analysis and optimization of recycled glass fibre composite waste reinforced FE-rich inorganic polymer using Taguchi and ANOVA methods	399
Sustainable scrapping method of thermoplastic composite materials	407
Approaches on self-healing of an interpenetrating metal ceramic composite	419
Using near-infrared-spectroscopy for quality inspection of prepregs before processing	427
Development of a recipe for the production of chitosan/ glycolipids biocomposites for plant protection	435
New solutions for the recycling of CFRP composites	440
Conductive smart nanocomposite materials for structural health monitoring and motion detection .	449
Sustainable POLYBUTYLENE succinate biopolymer for 3D printing applications	457

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

a: Augsburg University, Institute of Material Resource Management, Chair Materials Engineering; denny.schueppel@mrm.uni-augsburg.de

b: Augsburg University, Institute for Business Administration, Chair Production & Supply Chain Management

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, CO₂-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

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, whether 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.

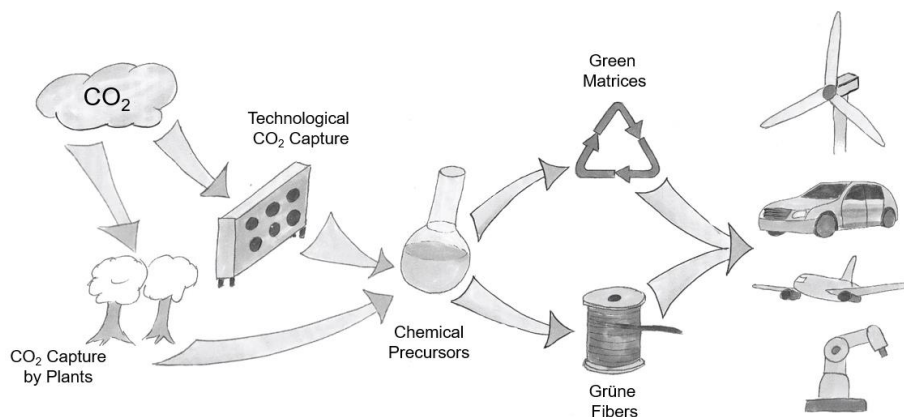


Figure 1: Generic sustainable production route for sustainable ceramic matrix composites, source: Ceramic Composites, Composite United e. V.

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 CO₂ footprint can be made as a function of the degree of complexity.

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

Furthermore, central boundary and framework conditions were defined for the subsequent CO₂ 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.

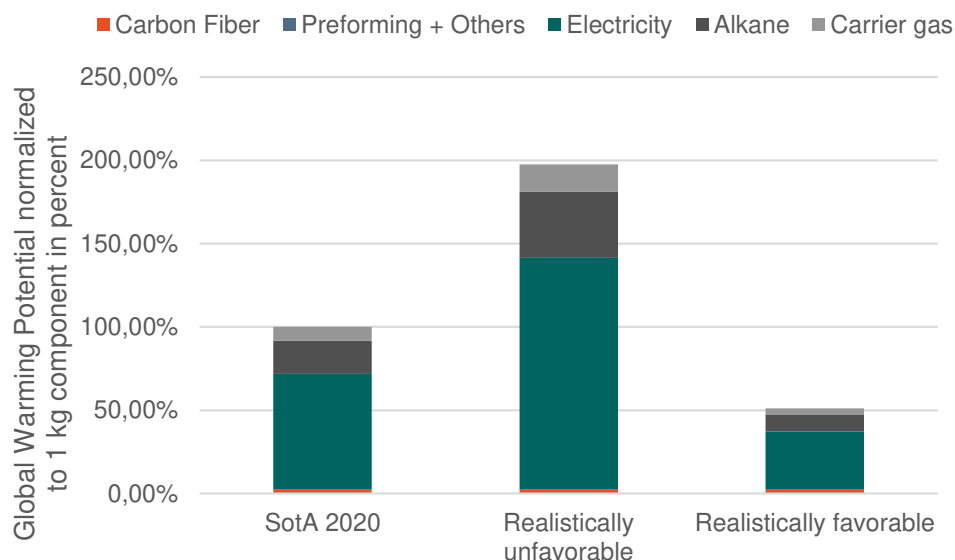


Figure 5: Normalized GWP - State of the Art Process and Realistically Unfavorable / Favorable

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 CO₂ 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 emitted 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 %.

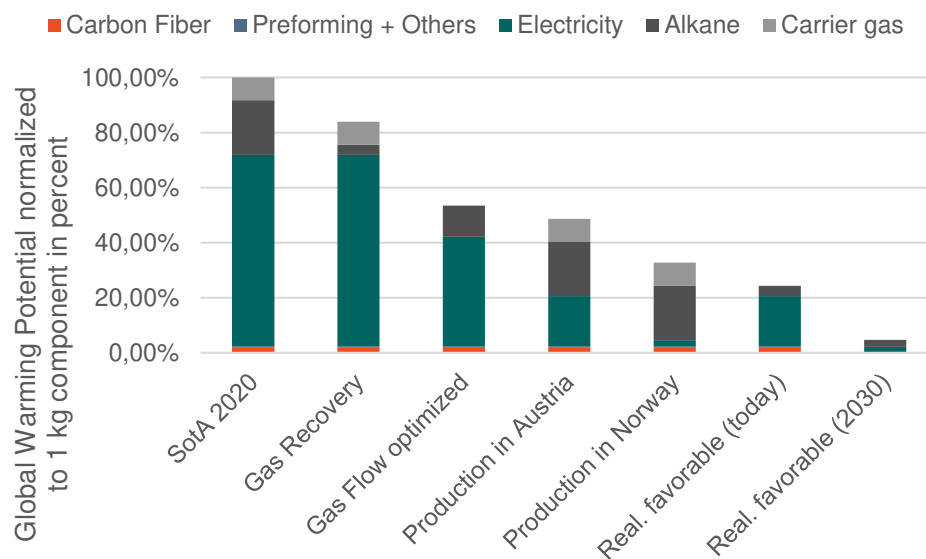


Figure 6: Ecological optimization potentials in comparison to the State of the Art 2020

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

electricity required), less alkane (-42 %) is needed and carrier gases can be completely omitted. This reduces the CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions in production. Green precursors, especially biogas compared to natural gas, have just under 20% influence on the CO₂ footprint of C/C products via the CVI route.

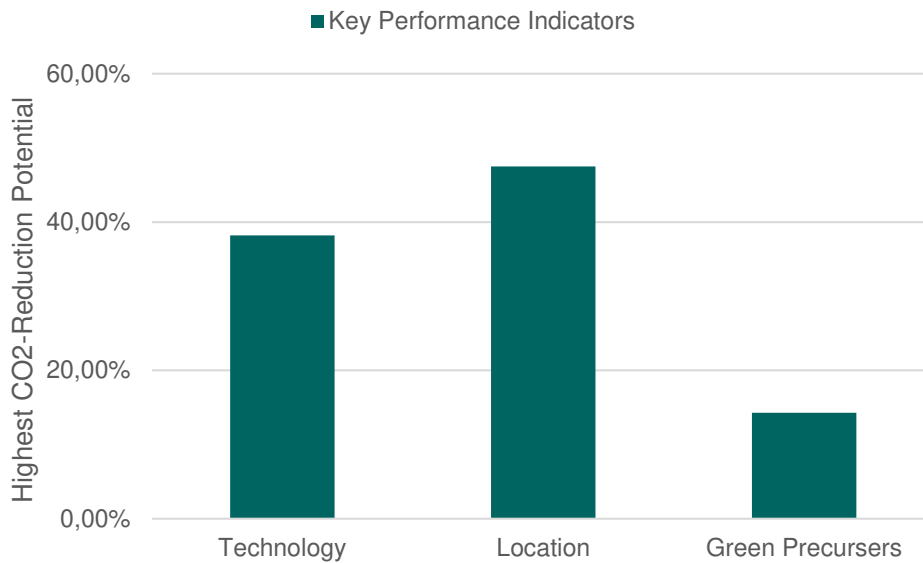


Figure 7 : Key Performance Indicators

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 CO₂ from the environment. Powered by renewable electricity, the question arises: will we even achieve a CO₂ 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. Composites 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