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ABSTRACT

The circular economy and the use of lightweight composites are two promising concepts for reducing resource consumption in future products. While circular economy approaches close loops and minimize resource loss, the application-specific design of composites reduces material demand. This study combines these concepts by discussing circular economy approaches for the lightweight material class of ceramic matrix composites. Suitable approaches were identified and compared using life cycle assessments to determine the environmental impact reductions. Twenty-two circular economy approaches were identified for the primary processing routes on four different life-cycle stages (circular inputs, external and internal loops, and end-of-life (EoL)). The most significant reduction is achieved by alternative input materials and EoL options, especially by using recycled carbon fibers, followed by various EoL options, such as recycling and repair processes. Combining several circular economy approaches reduces the current global warming potential of processing routes for CMC by up to 94%.

1. Introduction

Circular Economy (CE) is a promising approach to conserving resources and reducing environmental impact by closing material and energy cycles (Geissdoerfer et al., 2017). Keeping materials in cycles extends their use and reduces the need to exploit primary resources. Another approach to maximize resource efficiency is the development of application-based materials. Ceramic Matrix Composites (CMC) are composite materials that synergistically combine the advantageous properties of their constituents, resulting in lightweight components with superior performance compared to the individual constituents (Hsissou et al., 2021). This enables the development of load-oriented lightweight design solutions, with the potential to significantly reduce overall material consumption (Watari et al., 2021). In recent years, CMC have emerged as a pivotal class of materials with increasing relevance in various applications, especially in brake systems and the aerospace industry (Sauer and Schüppel, 2023; Witten and Mathes, 2023).

While CMC consist of the common elements carbon and silicon, they could substitute critical raw materials due to their outstanding technical properties. With their high temperature and corrosion resistance, CMC are suitable for substituting scarce and expensive superalloy metals, such as nickel, molybdenum, rhenium, or ruthenium, in the aerospace sector and other high-temperature applications (Krenkel, 2008). On the downside, CMC production has long lead times and requires a significant amount of energy, necessitating efficiency gains in the process handling. In many applications, the mechanical and thermal requirements of the products are significantly exceeded by the currently used CMC type, which opens the possibility of reducing certain material properties to achieve environmental and economic savings (Sri Karthikeyan et al., 2019). This enables the implementation of circular economy approaches, which have demonstrated the potential to reduce environmental impacts by keeping materials in closed loops (Kara et al., 2022).

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This concept has been supported by several Life Cycle Assessment (LCA) studies, including those by Spreafico (2022), van Stijn et al. (2021), and Wrålsen and O'Born (2023).

Despite the potential of circular economy strategies to mitigate environmental impacts and enhance the economic sustainability of CMC, literature on environmental CE benefits for CMC is scarce (Wietschel et al., 2023). To the authors' knowledge, three publications on circular economy-related topics from an environmental perspective have been published. Bianchi et al. (2023) addressed the reduction in environmental impacts of CMC-brake discs by partially substituting virgin carbon fibers with prepreg scrap, thereby reducing overall impacts by approximately 8 %. Sri Karthikeyan et al. (2019) analyzed brake pads made from natural fibers and epoxy resin. They conclude that those fibers are suitable for use in automotive brake systems. Additionally, Halter et al. used the CMC industry to demonstrate the derivation of use-case-specific Circular economy indicator sets after a holistic literature review (Halter et al., 2025). Measuring the contribution of circular economy approaches to reducing primary material demand and mitigating the environmental impacts of material provision is a central aspect of current research. In addition to indicators and material flow analysis, LCA is suitable for analyzing the environmental benefits of CE-approaches (Sassanelli et al., 2019). LCA provides a fundamental basis for evaluating the environmental sustainability of alternative CE-approaches, enabling quantitative comparisons with the state-of-the-art and facilitating the identification of environmental hotspots. Consequently, they are widely used in the literature (André and Björklund, 2023; Hitt et al., 2023; Minunno et al., 2020). This study employs LCA based on ISO 14040 and ISO 14044 to evaluate the impact of various CE-approaches on the environmental footprint of generic CMC products, aiming to identify promising production adaptations for the CMC industry. Against this background, this paper addresses the following research question:

- RQ: To what extent can circular economy principles mitigate the environmental impact of Ceramic Matrix Composites (CMC) in the production and end-of-life (EoL) phases?

a. Which circular economy approaches can be applied to CMC produced via Liquid Silicon Infiltration and Chemical Vapor Infiltration, considering the input materials, internal and external loops, and EoL?
b. To what extent can the environmental footprint of CMC products be reduced by individual circular economy approaches and feasible combinations?

2. Background and methods

The research approach consists of three consecutive steps, outlined in Fig. 1. A detailed breakdown of two state-of-the-art (SotA) CMC production processes, including liquid silicon infiltration (LSI) and chemical vapor infiltration (CVI), forms the foundation of this work. Subsequently, CE-approaches are identified along the value chains and evaluated from an environmental perspective using LCA.

This study focuses on the most important carbon/carbon (C/C) composites, produced by CVI from carbon fibers embedded in a carbon matrix, and carbon/silicon carbide ceramics (C/SiC), produced by LSI from carbon fibers embedded in a silicon carbide matrix. Fig. 1 illustrates the state-of-the-art sequence of process steps for both routes. The first processing steps are identical for both routes, yielding a nearly net-shaped textile semi-finished product that can be produced via various textile processing methods, such as weaving, spinning, knitting, or manual fiber placement. In the CVI process route considered in this paper, a nonwoven fleece is used as a semi-finished textile product, whereas a woven textile is used in the LSI route. In the CVI route, the semi-finished product is subsequently infused with methane at high temperature in a furnace. Carbon deposits on the fiber surface within several days or a few weeks, depending on the desired structure, to create a homogeneous matrix. Generally, some larger voids remain in the matrix after the CVI process due to pore closure during the matrix formation. In the LSI route, the textile is impregnated with phenolic resin using various methods, such as warm press or resin transfer molding (RTM), to create a carbon fiber-reinforced polymer (CFRP). The first two steps can also be combined using CFRP processes, such as fiber

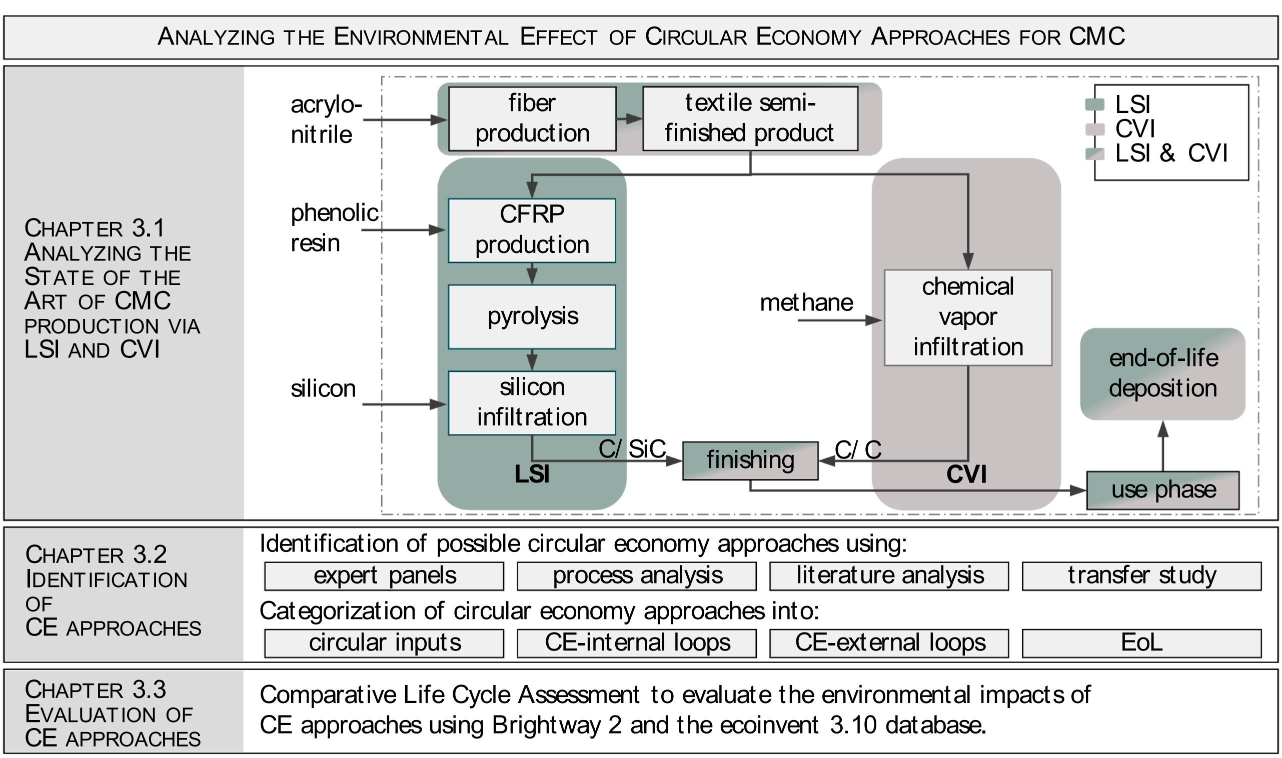

Fig. 1. Overview of standard production routes for Ceramic Matrix Composites (CMC) and the specific method employed in this study.

patch placement or prepreg winding. The polymer is pyrolyzed in the next step to create a porous carbon structure by applying a high temperature and an inert atmosphere, which prevents oxidation. The resulting C/C is infused with liquid silicon within a furnace at high temperatures. The porous carbon matrix and the silicon react exothermically to form silicon carbide. Surface treatment and finishing may be necessary for the final product shape in both routes.

The approaches considered for the LCA are based on industry practices, adaptations of related materials, and theoretical considerations. The scope of this LCA is to assess the impact of various CE-approaches and compare them with conventional processes and alternative strategies, supporting applicants and CMC producers in their decision-making. The functional unit is defined to enable optimal comparability of the CE-approaches, as described by Furberg et al. (2022). It represents the production, use, and end-of-life treatment of 1 kg CMC, which is used as a structural component with a tensile strength of at least 100 MPa for C/C and C/SiC under a constant temperature of 500 °C for one year. The LCA is performed using Brightway 2 and the Activity Browser software. Background data is sourced from the ecoinvent 3.10 database and Biosphere 3, utilizing the APOS system model, in which side products are accounted for as environmental credits. Evaluations are conducted using the Life Cycle Impact Assessment method, Environmental Footprint 3.1, as developed and recommended by the European Commission (2021). The CMC production location is modelled in Germany, while carbon fiber production follows a market-specific route from Japan to Portugal and the United States. Transport is included from resource extraction to the end-of-life (EoL) phase. The impact of machinery and production facilities is expected to be negligible and thereby excluded from this study. The data retrieved for modeling the foreground system encompass the years 2022 to 2025 to ensure time-related representativeness as a quality indicator for LCI data (European Commission, 2021).

Primary data is provided by project partners of the CU EcoCeramics project (Appendix), while several process data sets have already been determined and collected in the predecessor and sister projects, e.g., *MAI Enviro, MAI Enviro 2.0*, and *MAI ÖkoCap* (Angerer and Rechsteiner, 2024; Hohmann, 2015; Hohmann et al., 2017). Available datasets for carbon fibers and semi-finished textile production are identical for CFRP production. However, preceramic precursors and phenolic resins are produced differently due to variations in process temperatures, pressures, and holding times, resulting in differing energy consumption. The data sets used for CMC production were adapted and industrially validated, utilizing available literature data and in-house laboratory-scale measurements. Material and energy flows from industrial data are expected to be uniformly distributed between the minimal and maximal characterization.

The data for CE-approaches primarily originate from literature values and primary project data. Supplementary Materials A & B provide the data sources for each process and its corresponding process flows.

3. Results

3.1. Environmental hotspots of current CMC production

The environmental impacts per production step of state-of-the-art production are analyzed to benchmark potential impact reductions of the considered CE-approaches. The investigated SotA C/SiC structure produced via LSI results in a GWP100 of 35.73 kg CO_2eq/kg, while the C/C produced via CVI results in 244.32 kg CO_2eq/kg. The two analyzed production routes differ considerably in their matrix buildup, resulting in CMC with varying material properties, particularly mechanical properties and application cases. Especially, the higher electricity and the natural gas demand of the CVI process lead to substantially higher environmental impacts between the two production routes.

Regarding the analyzed environmental impact categories, the European Commission (2021) considers them particularly relevant if they cumulatively account for >80 % of the total impact after being combined into a single score. For the C/C CMC, this applies to the four categories: *abiotic depletion potential: fossil fuels* (38.3 %), *climate change* (20.6 %), *human toxicity: carcinogenic* (15.2 %), and *ecotoxicity: freshwater* (6.5 %). For CMC produced by LSI, seven categories are needed to reach the threshold, namely *human toxicity: carcinogenic* (18.9 %), *water use* (17.8 %), *ecotoxicity: freshwater* (16.7 %), *abiotic depletion potential: fossil fuels* (14.9 %), *climate change* (7.8 %), *photochemical oxidant formation* (3.5 %) and *acidification* (3.5 %). The composition of those categories by process steps is displayed in Supplementary A. For both production routes, environmental impacts are primarily caused by the carbon fiber production and the main processes, liquid silicon infiltration and chemical vapor infiltration, respectively. Particularly for the CVI route, other process steps contribute insignificantly to the total environmental footprint.

As most impact categories show the same process hotspots, the global warming potential (GWP), as a frequently used decision-making criterion, is examined in the following sections, while additional environmental impacts are presented in Supplementary A. Fig. 2 shows a waterfall diagram of the process contributions per route, thereby identifying hotspots.

For the CVI route, 94 % of the GWP is attributed to the chemical vapor infiltration step. This is primarily due to the significant energy requirements necessary to maintain the high furnace temperature for several days, as well as the methane needed for matrix buildup. An additional five percent results from the carbon fiber production, while other process steps insignificantly contribute. The impacts of the LSI route are more distributed between different process steps. The main contributions are carbon fiber production (46.8 %) and the liquid silicon infiltration step (36.8 %), with two-thirds resulting from the silicon input. Additional relevant process steps include CFRP production (9.7 %), pyrolysis of the CFRP (3.6 %), and the production of the textile semi-finished product (3.4 %). From an environmental perspective, hotspot processes are promising points of action for circular economy approaches.

To assess the uncertainty range, a Monte Carlo (MC) Simulation with 5000 iterations is performed for each process step, varying both background and foreground data to examine the influence of parameter uncertainty. Most of the background data in ecoinvent is log-normally distributed, while the foreground data is mainly uniformly distributed over the provided industrial data. The exact distributions are provided in the supplementary Excel file. The results of this MC-simulation are presented by violin plots in Fig. 2, which yield cumulative ranges from 27.9 to 62.2 kg CO_2eq/kg for C/SiC products and from 175.7 to 465.8 kg CO_2eq/kg for C/C products. Typical values range from 30 to 50 kg CO_2eq/kg for C/SiC and from 180 to 260 kg CO_2eq/kg for C/C. For both routes, the main process steps, CVI and LSI, have the highest uncertainty, indicated by the jump in the violin area. In the LSI, the carbon fiber and the carbon fiber reinforced plastic (CFRP) production also have considerable uncertainties.

3.2. Identified CE-approaches

In total, CE 22-approaches were identified to improve material efficiency and close loops for CMC products (Fig. 3). These are grouped into four categories: *Circular input* (In-1 to 7) utilizes renewable or second-life materials, while *CE-intern* (Int-RU1 to 6) focuses on closing loops within the production, including the internal reuse of waste streams. *CE-extern* (Ex-RC1 to 2 and Ex-RU1 to 3) approaches target waste utilization in other industrial sectors, and *EoL* (EoL-1 to 4) approaches discuss options for reusing or recycling products after their initial use phase. The following section provides an overview of all identified CE-approaches. Detailed information about the Life Cycle Inventories and modeling assumptions is provided in Supplementary A.

Circular input: Substituting input materials often comes with a ‘price’, which can be product property degradation, availability issues, or

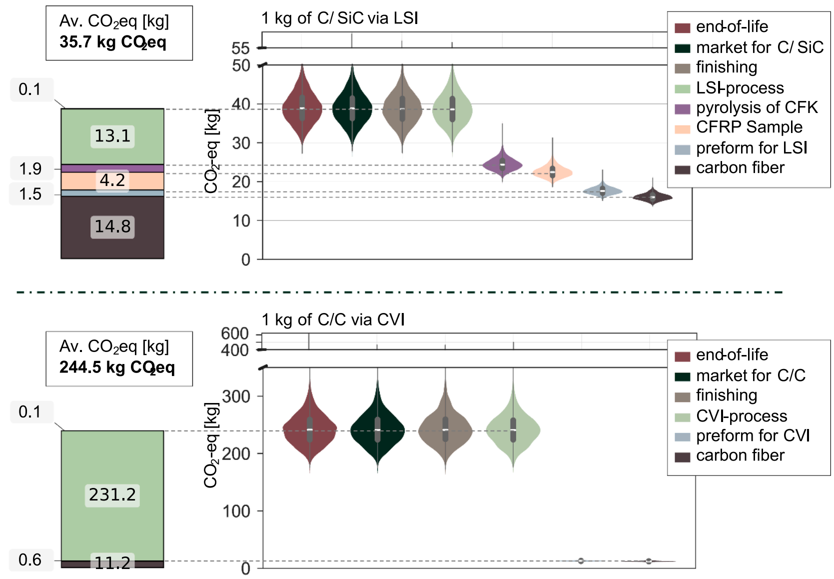

Fig. 2. Hotspot analysis of the global warming potential of state-of-the-art Ceramic Matrix Composite (CMC) production via the Liquid Silicon Infiltration (LSI) and Chemical Vapor Infiltration (CVI) routes, shown per process step. The bar chart displays the total global warming potential in kg CO_2-equivalents for each process step. At the same time, the violin plot presents the results of the Monte Carlo simulation, with the median indicated in white and the distribution's 25th and 75th quartiles represented by grey boxplots.

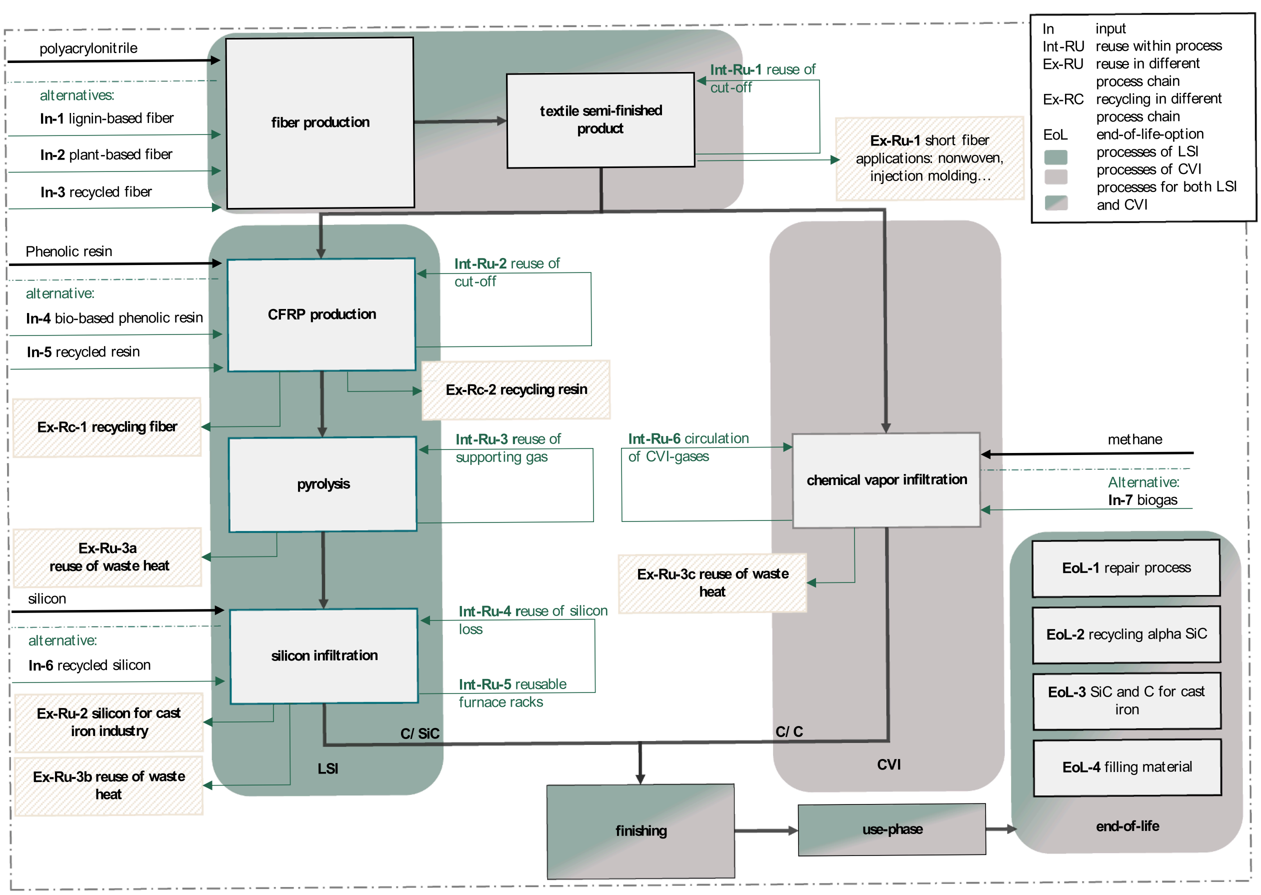

Fig. 3. Illustration of the identified circular economy (CE) approaches and indication of the corresponding process step at which each approach is applied.

higher costs (Graedel et al., 2012). This study assumes that the final product meets the functional requirements for tensile strength, heat resistance, and the intended time of use for all considered circular inputs. Circular inputs are recyclates or biobased alternatives that can replace one of the inputs: virgin carbon fibers, fossil-based phenolic resin, virgin silicon for the LSI process, and methane for the CVI process.

For carbon fibers, an increasing number of alternatives to PAN-based fibers are identified due to the high research focus on more sustainable CFRP. Lignin-based fibers (In-1) (Mainka et al., 2015), natural cellulose fibers (In-2) (Spörl et al., 2017), and recycled carbon fibers (In-3) (Borjan et al., 2021) are the most promising options and therefore considered in this work. For the recycling of carbon fibers, solvolysis with supercritical water is assumed, as this process is comparatively environmentally friendly (Schneller, 2017). For the LSI process, biological lignin-based resins (In-4) (Hirano and Asami, 2013) and recycled resins (In-5) from the solvolysis process of CFRP products can serve as substitutes for fossil-based phenolic resins (Ozaki et al., 2000). Depending on the CMC application, primary silicon can be substituted with recycled silicon (In-6). The market for recycled silicon is growing, particularly due to growing volumes of EoL solar panels (Bórawski et al., 2023; European Commission, 2011). EoL-PV-Si does not meet the purity of electronics-grade silicon, however, it is expected to have similar purity to metallurgical-grade silicon, which is already successfully utilized by several companies within the CMC industry (Project Advisory Board CU EcoCeramic, 2022). For the CVI process, methane, which is commonly obtained from natural gas, can also be derived from biogas (In-7). Due to the varying composition of by-products, some process parameters need to be adjusted to accommodate matrix build-up (Project Advisory Board CU EcoCeramic, 2022).

CE-Intern: We identified six options to close loops within the CMC production process. The first addresses the carbon fiber cut-off during the textile preform production. This cut-off can be used as short-fiber reinforcement and added to the next textile preform produced (Int-Ru-1). Additionally, there are four closed-loop options only relevant to the LSI process, including the reuse of CFRP cut-offs in subsequent CFRP preforms (Int-Ru-2). Another one is the recirculation of the supporting gas within the pyrolysis furnace (Int-Ru-3a), which ensures an inert atmosphere. The same is possible for the supporting gas within the LSI furnace (Int-Ru-3b). Furthermore, the silicon surplus within the furnace racks can be reused to substitute primary silicon despite having lower purity (Int-Ru-4) (Project Advisory Board CU EcoCeramic, 2022). Lastly, reusable furnace racks can substitute single-use racks and the boron-nitride coating (Int-Ru-5). For closing loops within the CVI route, one mutually exclusive approach was identified. The so-called 'Methanizer' purifies and reconditions exhausted reaction gas to re-enter the CVI furnace as carbon input for the matrix build-up (Int-Ru-6) (Project Advisory Board CU EcoCeramic, 2022).

CE-Extern: Those CE-approaches close loops in combination with other industrial sectors. Five of the seven approaches within this category are reuse approaches, and two are recycling processes. The first reuse approach is the reuse of carbon fiber cut-offs, which are generated during the production of semi-finished products as short fibers in the CFRP industry to produce carbon fiber fleece or fiber-reinforced granulate for injection molding (Ex-Ru-1) (de Anda et al., 2014; Kawai et al., 2017). The second reuse approach addresses the silicon surplus of the LSI processes (Ex-Ru-2). Although this silicon is slightly contaminated with carbon and boron nitride, it can be used as a silicon source in the cast iron industry (Project Advisory Board CU EcoCeramic, 2022). Additionally, the CMC production includes several high-temperature production steps. The heat surplus can be utilized in other processes or used to produce district heating within the factory or municipality (Fang et al., 2013). This is possible for the pyrolysis (Ex-Ru-3a) and siliconization (Ex-Ru-3b) steps of the LSI process, as well as for the chemical vapor infiltration step of the CVI route (Ex-Ru-3c).

Additionally, the carbon fibers of the CFRP cut-off resulting from the preform production can be recycled (Ex-Rc-1). We considered recycling via solvolysis due to its environmental benefits compared to other options (Butenegro et al., 2021). The same applies to the resin surplus, which can also be recycled via solvolysis (Ex-Rc-2) (Ozaki et al., 2000).

EoL: We identified four options for end-of-life CMC products. As no EoL treatment for CMC is currently implemented, landfilling remains the primary option. Although the environmental harm during this stage is minor due to CMCs' corrosive and chemical resistance, methods with lower downcycling should be preferred because of the high embodied energy and environmental impacts associated with CMC production (Helbig et al., 2022). Using CMC scrap as a filling material (EoL-4) in infrastructure corresponds to severe downcycling, however, it is preferable to landfilling. Another option is comminution, followed by material recycling through repurposing crushed CMC as a source of carbon and silicon in the metallurgical industry (EoL-3) (Project Advisory Board CU EcoCeramic, 2022). Alternatively, the recycling process of bulk silicon carbide can be adapted to recycle C/SiC to alpha-silicon carbide (EoL-2) for high-temperature applications (Adler et al., 2023). Lastly, repairing CMC products (EoL-1) with minor material damage, such as cracks and chips, is a viable option in some instances to extend the product's use phase. This study assumes a 50 percent lifetime extension of the original use phase (Project Advisory Board CU EcoCeramic, 2022).

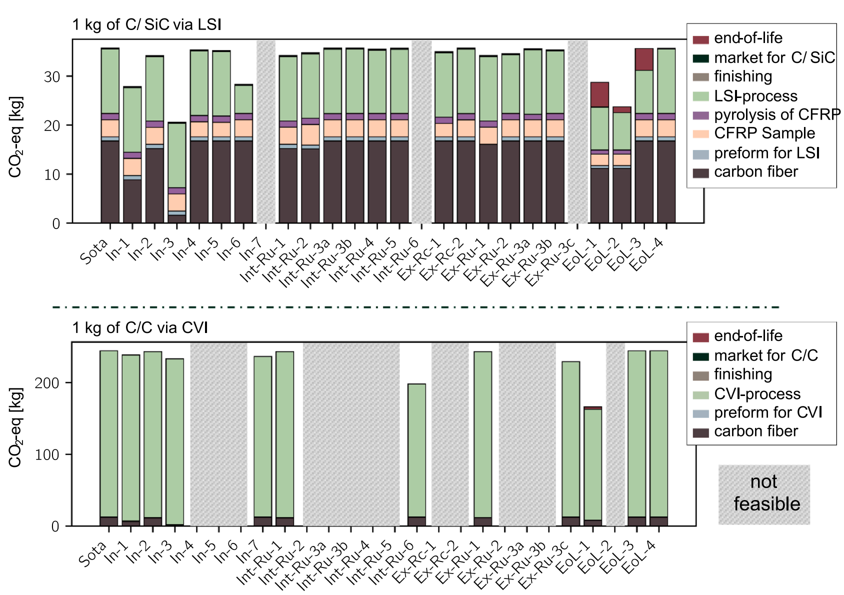

Fig. 4. Illustration of the absolute change in global warming potential resulting from the modeled circular economy (CE) approach. The first bar represents the emissions of the state-of-the-art process, serving as a reference.

Table 1
Displays the reduction in global warming potential for each circular economy approach and all possible combinations, including the respective approach. In the last columns, the optimal combination in terms of saved global warming potential is presented.

abb	CE-approach	reduction			combinations				max. combined reduction			
		LSI	CVI	In	Int-Ru	Ex-Ru	Ex-Rc	EoL	LSI		CVI	
	base-case	35.73 kg CO2eq	244.45 kg CO2eq									
In-1	lignin fiber	22.09 %	2.36 %	4,5,6,7	1,2,3,4,5,6	1,2,3	1,2	1,2,3,4	In1,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	77 %	In1,7; IntRU1,6; ExRu3c; EoL1	51 %
In-2	plant fiber	4.30 %	0.46 %	4,5,6,7	1,2,3,4,5,6	1,2,3	1,2	1,2,3,4	In2,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	62 %	In2,7; IntRU1,6; ExRu3c; EoL1	49 %
In-3	recycled fiber	42.36 %	4.52 %	4,5,6,7	1,2,3,4,5,6	1,2,3	2	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %	In3,7; IntRU1,6; ExRu3c; EoL1	52 %
In-4	bio-based phenolic resin	1.15 %		1,2,3,6	1,2,3,4,5	1,2,3ab	1	1,2,3,4	In3,4,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	93 %		
In-5	recycled Resin	1.47 %		1,2,3,6	1,2,3,4,5	1,2,3ab	1	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
In-6	recycled Silicon	20.73 %		1,2,3,4,5	1,2,3,4,5	1,2,3ab	1,2	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
In-7	biogas for CVI		3.27 %	1,2,3	1,6	1,3c	-	1,2,3,4			In3,7; IntRU1,6; ExRu3c; EoL1	52 %
Int-Ru-1	reuse of CF cut-off	4.26 %	0.46 %	1,2,3,4,5,6,7	1,2,3,4,5,6	2,3	1,2	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %	In3,7; IntRU1,6; ExRu3c; EoL1	52 %
Int-Ru-2	reuse of CFRP loss	2.73 %		1,2,3,4,5,6	1,2,3,4,5	1,2,3ab	-	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
Int-Ru-3a	reuse of supporting gas pyrolysis	0.11 %		1,2,3,4,5,6	1,2,3b,4,5	1,2,3ab	1,2	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
Int-Ru-3b	reuse of supporting gas LSI	0.03 %		1,2,3,4,5,6	1,2,3a,4,5	1,2,3ab	1,2	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
Int-Ru-4	reuse of silicon loss	0.62 %		1,2,3,4,5,6	1,2,3,5	1,3ab	1,2	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
Int-Ru-5	reuseable furnace racks	0.16 %		1,2,3,4,5,6	1,2,3,4	1,2,3ab	1,2	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
Int-Ru-6	reuse of CVI gas		18.96 %	1,2,3,7	1	1,3c	-	1,2,3,4			In3,7; IntRU1,6; ExRu3c; EoL1	52 %
Ex-Ru-1	CF for short fiber industry	4.25 %	0.45 %	1,2,4,5,6,7	2,3,4,5,6	1,2,3	1,2	1,2,3,4	In3,5,6; Int-RU2,3ab,4,5; ExRu1,3ab; EoL2	94 %	In3,7; IntRU6; ExRu1,3c; EoL1	52 %
Ex-Ru-2	Si for cast iron	3.16 %		1,2,3,4,5,6	1,2,3,5	1,3ab	1,2	1,2,3,4	In1,5,6; Int-RU1,2,3ab,5; ExRu2,3ab; EoL2	94 %		
Ex-Ru-3a	reuse of waste heat: pyrolysis	0.47 %		1,2,3,4,5,6	1,2,3,4,5	1,2,3ab	1,2	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
Ex-Ru-3b	reuse of waste heat: Si infiltration	1.15 %		1,2,3,4,5,6	1,2,3,4,5	1,2,3ab	1,2	1,2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
Ex-Ru-3c	reuse of waste heat: CVI		6.23 %	1,2,3,7	1,6	1,2,3c		1,2,3,4			In3,7; IntRU1,6; ExRu3c; EoL1	52 %
Ex-Rc-1	CFRP recycling: fiber	2.10 %		1,2,4,5,6	1,2,3,4,5	1,2,3ab	1	1,2,3,4	In3,5,6; Int-RU1,3ab,4,5; ExRu3ab;ExRc1; EoL2	91 %		

(*continued on next page*)

Table 1 (*continued*)

abb	CE-approach	reduction			combinations				max. combined reduction			
		LSI	CVI	In	Int-Ru	Ex-Ru	Ex-Rc	EoL	LSI		CVI	
Ex-Rc-2	CFRP recycling: resin	0.08 %		1,2,6	1,2,3,4,5	1,2,3ab	2	1,2,3,4	In3,5,6; Int-RU1,3ab,4,5; ExRu3ab;ExRc2; EoL2	94 %		
EoL-1	repair process	19.62 %	32.01 %	1,2,4,5,6,7	1,2,3,4,5,6	1,2,3	1,2	2,3,4	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL1	64 %	In3,7; IntRU1,6; ExRu3c; EoL1	52 %
EoL-2	recycling alpha SiC	36.94 %		1,2,4,5,6	1,2,3,4,5,6	1,2,3	1,2	1	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL2	94 %		
EoL-3	SiC and C for cast iron	12.78 %	0.05 %	1,2,4,5,6,7	1,2,3,4,5,6	1,2,3	1,2	1	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL3	79 %	In3,7; IntRU1,6; ExRu3c; EoL3	30 %
EoL-4	filling material	0.19 %	0.00 %	1,2,4,5,6,7	1,2,3,4,5,6	1,2,3	1,2	1	In3,5,6; Int-RU1,2,3ab,4,5; ExRu3ab; EoL4	66 %	In3,7; IntRU1,6; ExRu3c; EoL4	30 %

3.3. Evaluation of circular economy approaches

This section first examines the effect of CE-approaches on the GWP for the LSI process. Among the different types of CE-approaches, circular input materials and end-of-life approaches have the highest potential to reduce the environmental impact, as shown in Fig. 4. The highest single reduction of 42 % can be achieved by using recycled carbon fibers as an alternative input. Lignin fibers can reduce the GWP by 22 % and recycled silicon by 20 %. The use of cellulose fibers and bio-based phenolic resin results in minor reductions, which can be explained by relatively high impacts of their primary production compared to lignin fibers, which are made from paper production waste streams. Additionally, the impacts of the recycled silicon and recycled carbon fibers are minor, as they are primarily allocated to their first life cycle in the applied APOS approach.

EoL approaches can lead to significant reductions in environmental impacts, with recycling to alpha-SiC showing the highest reduction potential. Our results show that the production of primary alpha SiC requires a significantly higher energy input compared to the recycling of crushed CMC into alpha SiC. The same applies to repairing damaged CMC components, which adds additional environmental impacts due to energy and material demands, but extends the use phase by 50 % and thereby substitutes for primary CMC. Due to the changed function, the impacts are subsequently distributed over the extended use phase and partly allocated to the functional unit. Crediting the substitution of primary silicon carbide with crushed EoL-CMC in the cast iron industry results in a 12 % reduction of the GWP. Matching the hierarchy of EoL treatment (European Union, 2008), the use of EoL-CMC as filling material corresponds to a severe downcycling with little environmental benefits. The reduction resulting from closing internal and external loops is minor compared to those previously discussed, ranging from 0.03 % for the recirculation of supporting gas to 4.25 % for the recycling of carbon fiber cut-offs.

For the CVI route, different CE-approaches show the highest impact-reduction potential. The most promising single approach is the repair process, which extends the lifetime by 50 %. The second-highest reduction can be achieved by internal natural gas reuse via the Methanizer. Alternative input materials are less effective at reducing environmental impact, even though the absolute reductions are comparable to those of the LSI process, because the energy demand of chemical vapor deposition dominates the total environmental impact.

While single CE-approaches can reduce the GWP by up to 42 %, certain approaches can be combined to further reduce the impact. Table 1 displays the individual reductions in GWP of each CE-approach. Additionally, the technically feasible combinations with other approaches are presented, along with the combination that yields the highest possible GWP reduction.

Some reductions can be added directly as the approaches do not interfere, while others are not cumulative. Primarily, the reductions caused by the reuse or recycling of waste streams depend on the input materials used. For instance, the reduction potential of Int-RU-1 decreases from 4.26 % to 2.89 % if lignin fibers are used, as their environmental impact per kg is lower. Furthermore, some approaches cannot be combined as they address different production routes or the same material flow, for instance, different types of carbon fiber substitutes.

The combination with the highest reduction for the LSI process consists of three circular inputs, six internal reuse options, one external reuse option, and the recycling of EoL products to alpha SiC, resulting in a 94 % reduction in GWP, leading to 2.3 kg CO_2eq/kg CMC compared to state-of-the-art production, which has >35 kg CO_2eq/kg. It includes the circular inputs: recycled carbon fibers, recycled silicon, and bio-based phenolic resin. Additionally, internal CE-approaches that are viable for the LSI process are applied, including the circulation of supporting gas for pyrolysis and liquid silicon infiltration, the reuse of carbon fiber and CFRP cut-offs, reusable furnace racks, and the reuse of silicon surplus. The only external CE option possible is the reuse of heat for the pyrolysis and siliconization steps. Recycling EoL products into alpha-SiC further reduces the environmental footprint.

The best combination for the CVI process reduces the GWP by 53 %, from 244 kg CO_2eq/kg to 114 kg CO_2eq/kg CMC, by using recycled carbon fiber and biogas as circular input materials. Two additional internal CE-approaches are applied, including the reuse of carbon fiber cut-offs and the reuse of biogas within the CVI reactor. External CE options show lower benefits, with only waste heat reuse during the CVI step being beneficial. The repair process is chosen for the EoL treatment.

The environmental impacts of both routes depend heavily on the energy mix, which differs significantly across countries. Fig. 5 shows the current GWP for different countries, and the change through the implementation of selected CE-approaches. Since energy and natural gas streams have the highest impact on GWP, Norway is chosen for its high renewable energy share, France for its high nuclear energy share, and Poland for its fossil-based energy grid. Fig. 5 illustrates a consistent trend of GWP reduction across all countries and CE measures, except for the electric energy-intensive Methanizer. The LSI process is mainly electricity-driven, wherefore countries with low electricity GWP already have a considerably lower impact per kg CMC produced in SotA processes. While the absolute reduction potential from CE measures is similar across countries, the relative contribution per CE measure is

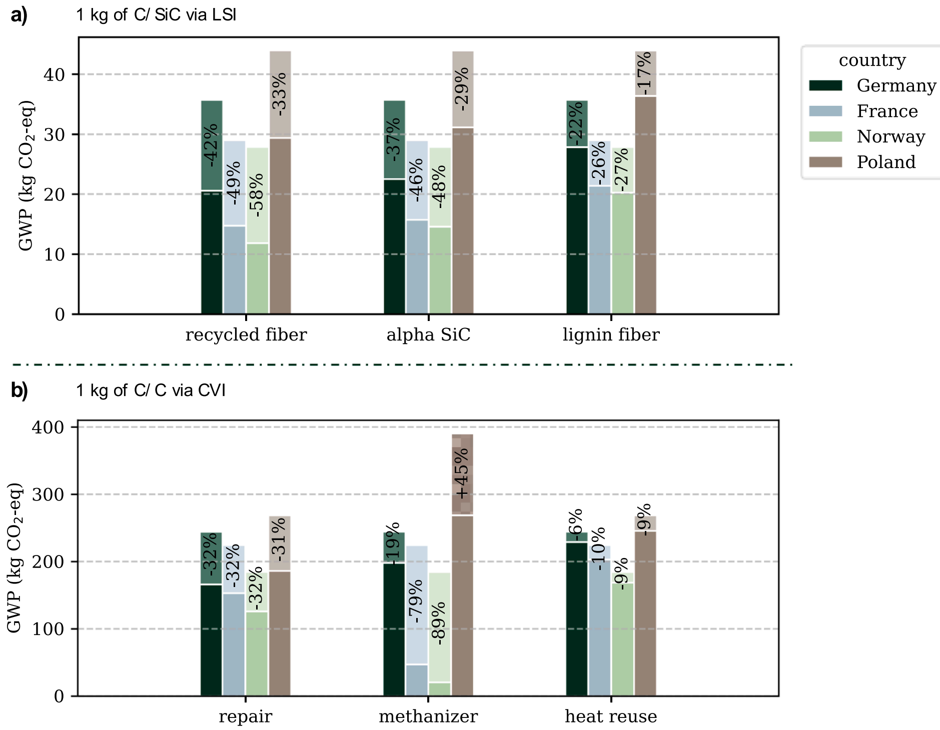

Fig. 5. Barchart with current global warming potential (GWP) of the production of a) one kg C/SiC via Liquid Silicon Infiltration and b) one kg C/C via Chemical Vapor Infiltration for different countries and the GWP change through the implementation of selected CE-approaches.

therefore even higher in countries with a high renewable electricity share. In the case of C/C via CVI, especially the case of heat reuse, demonstrates the strong influence of the considered substituted product, as the GWP of district heat varies across countries. Whereas, using a Methanizer shifts natural gas demands towards increasing electricity demands, wherefore this CE-measure shows great potential in countries with high renewable electricity shares, where the reduction can be as high as 89 % (Norway), while the total impact through applying a CE-measure can even increase if the GWP per kWh of electricity is higher than that of natural gas.

Considering that the hotspots of CMC production are similar to those of other environmental impacts, the reduction contributions of the CE-approaches are mostly consistent with those presented here. Detailed modeling, environmental impacts, and altered process contributions are provided in Supplementary A.

4. Discussion

The following discusses the results in light of the corresponding literature. For the C/SiC produced via LSI, Bianchi et al. (2023) report an environmental impact of approximately 32 kg CO_2eq/kg, Narres et al. (2025) report values ranging from 22 to 45 kg CO_2eq/kg, depending on the specific route. The similar route has just below 40 kg CO_2eq/kg. The slightly lower value of Bianchi et al. may result from deviations in semi-finished textile and CFRP production, and the considered industrial-scale CMC break disc production, compared to the cross-section of various industrial sectors, ranging from pilot-scale to industrial-scale operations, analyzed in this work. The work of Narres et al. yields slightly higher impacts, despite similar assumptions, modeling choices, and the same dataset. This can be explained by the different background database (this work uses ecoinvent 3.10 (ecoinvent association, 2023), Narres et al. use LCA for experts with the background database CUP 2024.1 (Sphera, 2024). Additionally, Narres et al. (2025) assumed electronics-grade silicon with higher environmental impacts, compared to solar-grade silicon assumed in this study. To the authors' knowledge, only Dorling et al. (2025) have investigated the environmental impact of C/C produced via CVI for aviation brake discs. Since Dorling applies a performance-based functional unit, the results are not comparable.

This evaluation confirms that CE-approaches can substantially reduce impacts of CMC products. Within the modelled scope of Germany and the reference years 2022–2025, the GWP reductions of single approaches can reach 42 %. Combining several CE-approaches yields considerable reductions of over 50 % for CVI and 94 % for LSI. Circular input materials are the most promising options for reducing the environmental impact of CMC. The best combination of all feasible CE-approaches for the LSI process reduces the GWP to 2.3 kg CO_2eq/kg C/SiC, making CMCs competitive with alternative lightweight materials (Eckelman et al., 2014). The circular inputs recycled fiber from EoL CFRP, combined with recycled silicon from PV systems, yield the highest potential. However, to date, the market for high-quality recycled fibers is small due to limited solvolysis recycling capacity and companies' reluctance to use secondary fibers (Ateeq, 2023). With increasing volumes of end-of-life PV modules, the market for secondary silicon is assumed to increase in the near future (Mirletz et al., 2023). For the successful use of secondary silicon from EoL-PV modules, the CMC industry should conduct research into its usability and develop partnerships to draw on the available supply. By funding research into recycling technologies and their scale-up, politics can set the course for increased use of secondary materials. The environmental impacts will also be further reduced by higher shares of renewable electricity, as the case of Norway in the country-based analysis indicates. This analysis shows that CE-approaches remain relevant with higher renewable electricity shares. However, in coal-based systems (Poland), energy-intensive methods (e.g., Methanizers) may not reduce impacts, requiring case-specific analysis. Using bio-based inputs (like biomethane or lignin-based fibers) reduces the GWP and shifts emissions from fossil-based to bio-based. According to Lura et al. (2025), silicon carbide is a promising material for permanently storing biogenic carbon and removing it from the atmosphere. This would apply to C/C and C/SiC CMC and could considerably reduce the GWP. However, circular and bio-based inputs might reduce the mechanical properties. Different characteristics of input materials can not only influence the properties of the final product, but also the handling and production parameters, like input quantities, temperatures, or holding times.

Internal CE-approaches yield lower reductions in GWP, except for the methane recirculation, which addresses the environmental hotspot of the CVI. While other internal approaches address low-impact waste streams, they offer benefits like monetary savings from waste handling. Unlike circular inputs, internal reuse largely preserves product properties. The exception is silicon surplus reuse, where lower purity may reduce mechanical performance, potentially making it unsuitable for high-requirement applications. External CE-approaches can also provide minor impact reductions, but are generally outperformed by internal methods due to transport and downcycling.

Alongside circular inputs, EoL approaches are particularly promising and should be the focus of future research. The repair process and recycling to high-value alpha silicon carbide exhibit higher reduction potentials than downcycling into cast iron additives or filling materials, aligning with the theoretical foundations (Helbig et al., 2022). As large-scale solutions for repair and recycling do not yet exist, recycling in the cast iron industry should be considered as a favorable interim solution.

These results are subject to certain limitations, particularly regarding the assumptions used to model the CE-approaches. Except for a few, such as the reuse of methane within the CVI process, most approaches have not yet been applied on an industrial scale, and experiments on a laboratory scale are rare, resulting in incomplete primary data and necessitating assumptions. These assumptions, although based on the most current literature, industry expert estimations, and panels, may lead to deviating results in future studies. The results provide a clear direction for potential environmental benefits; more in-depth information will be obtained once the measures are successfully implemented on a pilot or larger scale. Additionally, not all approaches are suitable for every product or company due to technical implementation difficulties or high product quality and regulatory requirements.

5. Conclusion

Our work shows that circular economy approaches are promising in reducing the environmental impacts of CMC. Especially when combined, CE-approaches have the potential to drastically reduce the impact and thus open new application areas for CMC-products. Those impacts can be further reduced, for example, by using renewable energy to accelerate this reduction. However, CE-approaches have to be evaluated carefully, since they do not always reduce impacts.

This work investigated the impact reduction potential of the CMC life cycle by evaluating 22 different CE-approaches through life cycle assessment. Hotspots in the production processes were identified, and promising approaches, along with their optimal combinations, were outlined. Especially, alternative input materials and EoL options address these hotspots and, therefore, show promising environmental impact reductions. While most analyzed measures are technically feasible, only a few are already implemented by the industry for various reasons. This work shows the industry a way to reduce its emissions through CE-approaches. As CO_2 prices rise, the economic relevance of emission reductions will increase further in the coming years (European Commission, 2015).

Future work should implement these approaches and evaluate their impact on product properties and environmental impact using primary data. Additionally, the trade-off between the mechanical properties of the final product and the reduction of environmental impact should be further evaluated to identify potential use cases for CMC materials, as started by Schneider et al. (2022). This study lays the foundation for a new generation of materials science research: sustainability should no longer be assessed retrospectively, but rather be an integral part of materials development.

CRediT authorship contribution statement

Florian Halter: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Lars Wietschel:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Denny Schüppel:** Writing – review & editing, Validation, Project administration, Funding acquisition, Data curation, Conceptualization. **Nicoletta Narres:** Writing – review & editing, Validation, Methodology, Data curation. **Anna Schneller:** Writing – review & editing, Validation. **Kevin Christopher Dorling:** Writing – review & editing, Validation. **Andrea Thorenz:** Writing – review & editing, Supervision, Conceptualization. **Dietmar Koch:** Writing – review & editing, Validation, Supervision. **Axel Tuma:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Florian Halter reports financial support was provided by Industrial Research Association (IGF) from the Federal Ministry of Economic Affairs and Energy (BMWK). This paper is emerged from a research project undertaken by the CU (The Research Association Composites United) and performed by Florian Halter at the University of Augsburg. The research project was carried out in the framework of the industrial collective research programme (IGF no 22,037 N). It was supported by the Federal Ministry for Economic Affairs and Energy (BMWK) through the AiF (German Federation of Industrial Research Associations eV) based on a decision taken by the German Bundestag. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108776.

Appendix: Project Internal Data CU EcoCeramic

The primary data used for modeling life cycle inventories, as well as the central findings in possible Circular Economy approaches, were derived from project partners. The methods used are expert interviews, surveys, site inspections, discussion panels, and validation of assumptions. To comply with the antitrust law, no direct matching of data to a specific company or person is made. The participating companies are listed on the project advisory board.

Project advisory board CU EcoCeramic:

- Airbus
- Ariane Group GmbH
- Automation Steeg und Hoffmeyer GmbH
- BJS Ceramics GmbH
- Brembo SGL Carbon Ceramic Brakes GmbH
- CVT GmbH & Co. KG
- diondo GmbH
- DLR Institute of Structures and Design
- Gühring KG
- Hufschmied Zerspanungssysteme GmbH
- MTU Aero Engines AG
- Röder Präzision GmbH
- Schunk Kohlenstofftechnik GmbH
- Tenowo Hof GmbH

Project committee meeting:

- 22.04.2022
- 04.08.2022
- 29.11.2022
- 06.03.2023
- 09.05.2023
- 29.09.2023
- 14.11.2023
- 29.02.2024
- 14.03.2024

Survey:

- Kreislaufwirtschaftsindikatoren für CMC (18.10.2023)

Data availability

Data will be made available on request.

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