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RESEARCH ARTICLE

LCA-based evaluation of greenhouse gas reduction potentials of carbon/carbon wheel brakes for medium-haul aircraft

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Abstract

Air transport is expected to substantially grow in the next decades, presenting a significant challenge for the aviation industry to reconcile this growth with the need to mitigate climate change by reducing greenhouse gas (GHG) emissions. A viable strategy for diminishing aviation emissions involves reducing aircraft fuel consumption, which can inter alia be achieved by incorporating lightweight ceramic matrix composites (CMC) into aircraft components. However, this is offset by an energy-intensive production of CMC, and there remains limited understanding of the environmental impacts associated with this group of materials. This study aims to assess the potential of carbon/carbon (C/C) wheel brakes to reduce large passenger aircraft emissions. Employing a cradle-to-grave approach, a life cycle assessment based on ISO standards was conducted. The findings indicate that, although the production of a C/C wheel brake incurs a markedly greater carbon footprint than its metallic counterpart, the lightweight and durability aspect of C/C significantly contribute to decreased GHG emissions over the entire service life of an aircraft across all evaluated scenarios. Furthermore, the results emphasize the importance of component durability and improved manufacturing process control in enhancing emission savings, ultimately guiding stakeholders toward informed decisions regarding the use of CMC for sustainable aircraft design.

KEYWORDS
aircraft brakes, aviation, ceramic matrix composites, CMC, LCA, life cycle assessment, sustainability

1 | INTRODUCTION

Aviation accounts for 2.0%–2.5% of all global anthropogenic fossil greenhouse gas (GHG) emissions.[1–4] Within the transport sector, it is responsible for 13.9% of all GHG emissions, making it one of the most significant sources of global transport GHG emissions.[5,6] To reverse this trend and achieve net-zero emissions by 2050, transnational aviation initiatives by the member states of the International Civil Aviation Organization (ICAO) and Air Transport Association (IATA) have been established.[7–10]

However, the aviation sector today is in an early stage of its endeavors to mitigate climate change by reducing its global GHG emissions,[1,8] while air transport is expected to grow by an average of 4.3% per annum over the next two decades due to increasing demand.[11] This challenging situation necessitates the implementation of effective measures to mitigate global aviation emissions. One approach involves reducing aircraft mass by utilizing appropriate lightweight materials, such as advanced composites, to decrease fuel demand and, consequently, emissions from kerosene combustion.[12,13]

The use of composite materials have led to overall aircraft mass savings of 6%–10% (single-aisle), respectively, 2%–6% (twin-aisle).[14] Due to their advantageous material properties including higher temperature, wear, and corrosion resistance, composite materials are used for various aircraft applications.[15] This development primarily focuses on large aircraft construction,[16,17] which has steady increased the share of composite structural weight.[18] Today, composites account for 10%–50% of the structural weight of modern large passenger aircraft.[17,19,20] This has improved the weight-to-load ratio, a trend that is expected to continue and further intensify due to continuing weight reduction efforts.[21]

One class of high-temperature lightweight composites is ceramic matrix composites (CMC), produced by embedding reinforcing fibers, such as silicon carbide or carbon fibers, in a carbon or ceramic matrix. Today, CMCs are used not only in high temperature components of aircraft engines, but also in carbon fiber-reinforced carbon (carbon/carbon, C/C) heat packs, which refers to large passenger aircraft brake discs arranged in a wheel brake system (multiple disc brakes) used to provide the aircraft's wheel braking function.[15,22] As part of the landing gear, they are critical to the performance and efficiency of the wheel brakes.[22] Heat packs consist of a combination of stators and rotors arranged alternately to generate the braking force,[15,22] where the rotors rotate with the wheel assembly and the stators are stationary discs attached to the torque tube. Figure 1 shows an exemplary C/C heat pack for large commercial passenger aircraft.

FIGURE 1 Carbon fiber-reinforced carbon heat pack (reprinted with permission of SGL Carbon SE).

Based on current global market tonnage, aircraft heat packs represent the main application for carbon fibers today.[15] Aircraft brake systems can be segmented into carbon and metallic brake types.[23] While the utilization of C/C heat packs varies across different aircraft types, metallic brake discs remain a prevalent choice with a share of up to 40% in larger aircraft cargo sector. In the passenger sector, C/C brakes have prevailed almost exclusively due to their long service life and the associated potential for lightweight design.[15] Previous research indicates that a reduction of 1 kg in passenger aircraft weight results in a fuel saving of approximately 0.02–0.03 kg per 1000 km of flight distance.[24] Therefore, it can be inferred that considerable savings in kerosene, respectively, in GHG emissions could be achieved over an aircraft's lifetime through the use of lightweight C/C heat packs. However, the manufacturing of C/C heat packs involves the energy-intensive chemical vapor infiltration (CVI) process, which results in a tradeoff between the ecological impacts of lightweight C/C heat packs during production and use phase. This provides an interesting case to investigate C/C heat packs from a life cycle assessment (LCA) perspective.

Several studies have previously been conducted on the use of lightweight materials other than CMC for automotive applications, indicating a substantial potential for mitigating environmental impact. Based on the analysis of 33 LCA studies on the benefits of automotive lightweighting, Kim and Wallington emphasize that the utilization of lightweight materials instead of conventional materials leads to a reduction in GHG emissions throughout the life cycle of automotive vehicles. This effect is predominantly determined by the use phase, which dominates energy demand and GHG emissions, as fossil fuel is the dominant energy source for vehicle operation.[2,20,25] LCA results drawn from Bianchi et al., who investigated the environmental impacts associated with the production, use and disposal of CMC brakes of a sports car indicate comparable findings.[26] Regarding the aerospace sector, LCA studies on the use of lightweight and hybrid composite aviation and space structures conclude that the structural weight is the most critical parameter affecting their environmental performance over the entire life cycle; by reducing structural weight, a substantial decrease in GHG emissions over the aircraft's life cycle is investigated as most of the environmental burden is caused in the use phase by the combustion emissions of fossil jet A-1 fuel (kerosene).[27–29] Furthermore, research findings on carbon fiber-reinforced plastics indicate that, despite the ecological benefits associated with their use phase, the impact of the production phase cannot be disregarded, since in specific cases the production impacts can offset use phase savings.[29]

Against this background, this study aims to investigate the research question of whether the use of C/C heat packs instead of metallic ones can effectively contribute to the reduction of GHG emissions over the lifetime of a medium-haul aircraft. This inquiry is particularly pertinent given the considerable GHG emissions linked to the production of C/C heat packs, which were quantitatively determined in the research project CU EcoCeramic.[30] For this purpose, a LCA was conducted on both heat pack variants. The results of this study aim to provide stakeholders of CMC such as producers of CMC structures, aircraft operators, politics, and society an opportunity to explore CMC aircraft components from an ecological perspective.

2 | METHODOLOGY

The most widely recognized method for quantifying the environmental impact of a particular material, product, or process is the conduct of LCA. The LCA applied is based on the ISO 14040[31] and ISO 14044[32] standards. Figure 2 demonstrates the research approach including the steps of visualization and conclusion in a simplified manner.

The evaluation focusses on the impact category climate change, total, which is indicated as global warming potential (GWP) and quantified in kg CO_2 equivalents.[34,35]

The findings of this study are expected to assist CMC stakeholders such as manufacturers, aircraft operators, politicians, and society in investigating this material group concerning environmental considerations for aircraft applications. For this purpose, a generic metallic heat pack based on gray cast iron (EN-GJL-200) serves as a benchmark, mainly used in cargo applications.

As a relative approach, LCA is based on a defined functional unit (FU). The FU is a quantified description of the performance of a specific product or product system that serves as a reference unit in LCA.[31,32] All inputs (e.g., raw materials or electricity) and outputs (e.g., emissions to air) in the life cycle inventory, and consequently the impact assessment profile, are related to the defined FU.[31] The FU of this study is defined as fulfilling the wheel brake function for a medium-haul aircraft over an aircraft's service life of 30 years. To fulfil the wheel brake function, all stator and rotor brake discs of the main gear are considered. The focus was exclusively on distinguishing discs of both C/C and metallic aircraft wheel brakes. This is because both product variants consist of the same or comparable parts and components of the brake system, such as valves or wicks.

To evaluate the potential reduction of CO_2 equivalents associated with the utilization of C/C brakes in aircraft, the scope of the present study includes the production of brake disc material including all upstream processes (e.g., raw material extraction and preparation, production of preliminary products), the transport from the place of manufacture to the location of assembly, the use in flight operations, the transport of worn-out heat packs from the disassembly site to the place of manufacture (for refurbishment respectively disposal purpose) and an end-of-life (EoL) treatment. EoL treatment consists of refurbishing reusable C/C brake discs and recycling material for metallic brake discs. The study's scope is outlined in Figure 3.

As CMC recovery pathways are topic of current research,[36] a state-of-the-art refurbishment treatment of first-life C/C brake discs (cf. Section 3.5) is considered in the analysis. Regarding the EoL of the metallic product variant, the use of secondary material to manufacture metallic brake discs is considered.

The GWP associated with the supply of heat packs and weight-induced consumption of kerosene was calculated for both product variants over the entire service life of an aircraft. To quantify the associated material and energy flows over an aircraft's service life, the foreground system as shown in Figure 3 is parametrized by certain assumptions based on several data and information sources. These assumptions were then used to define various scenarios. Chapter 3 describes the assumptions and scenarios in detail. The background LCA data stems from the LCA for Experts Professional database.[37] The life cycle impact assessment (LCIA) described in detail in chapter four characterizes the resulting inventory and yields the environmental impacts.

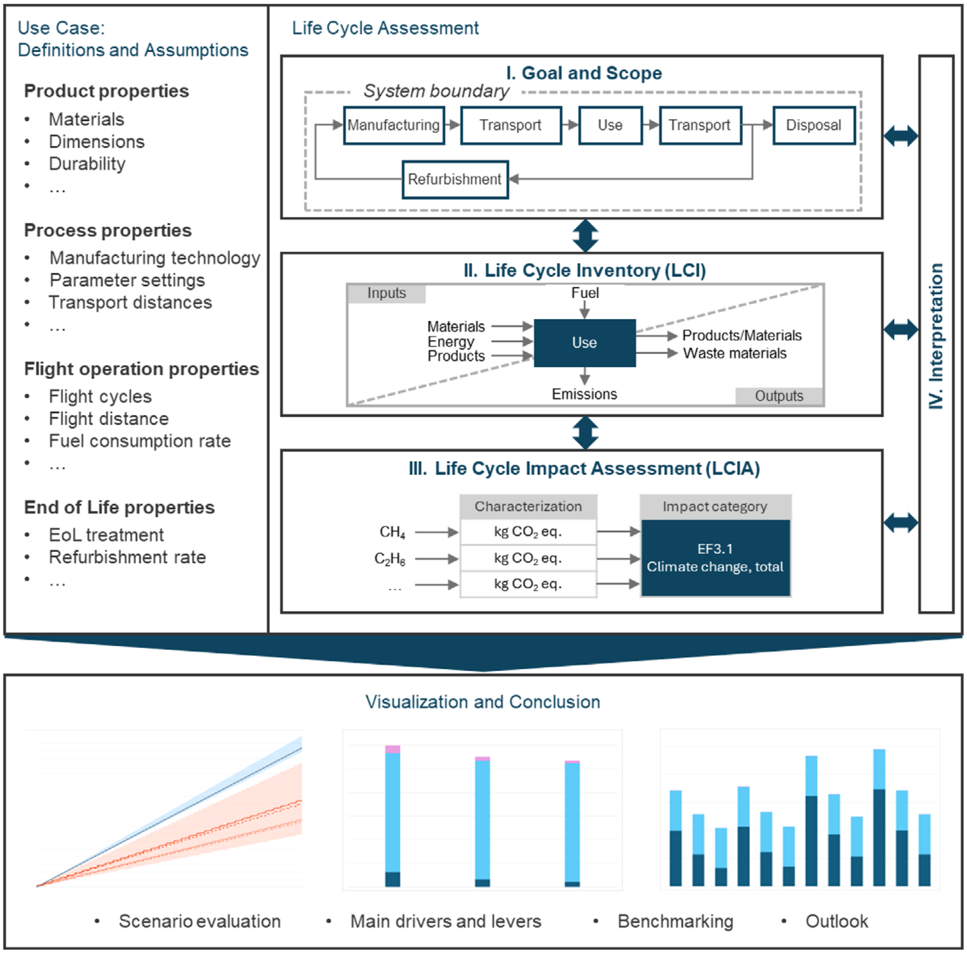

FIGURE 2 Simplified research approach of the study (inspired by Schneider et al.[33]).

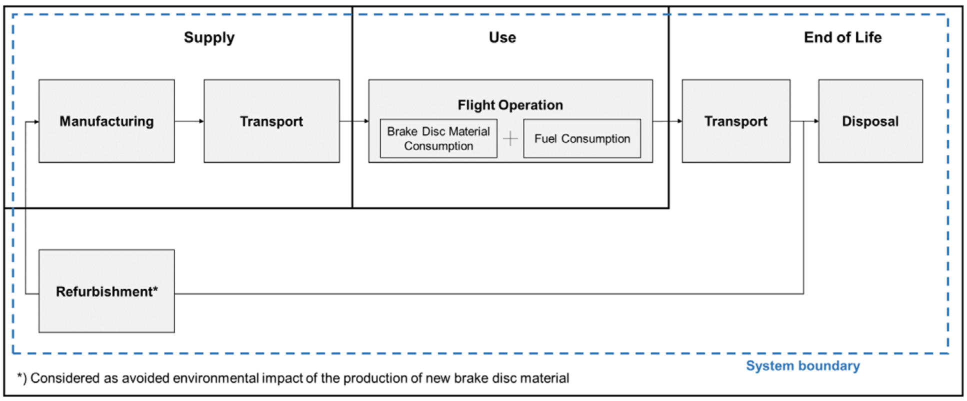

FIGURE 3 Scope and system boundary of the study.

3 | DATA BASIS AND SCENARIO DEVELOPMENT

The subsequent sections will provide a comprehensive examination of assumptions and scenarios underlying the assessment of the life cycle phases within the study's scope.

3.1 | Weight of the reference products

A key element for the present study was the estimated weight of both product variants to determine the required amount of brake disc material and the weight-induced diesel consumption (ground transport of the heat packs)

TABLE 1 Structural composition and weight of a generic carbon/carbon and metallic heat pack.

Product variant	Carbon/carbon		Metallic	
Structural composition	Stator discs 5[15]	Rotor discs 4[15]	Stator discs 4	Rotor discs 5
Weight per disc	6.5 kg		22.8 kg	
Weight per heat pack	58.5 kg		205.2 kg	

and kerosene consumption (heat packs as payload in flight). This is particularly relevant as the fuel consumption of an aircraft highly depends on its weight.[12]

Besides utilization, the dimensions of a heat pack can vary across different types of aircraft. Therefore, a generic C/C, respectively metallic heat pack, was defined in consultation with the CU EcoCeramic project advisory board, which included 24 companies that use, manufacture, and maintain aircraft brake discs, and defined generic boundary conditions, such as brake disc wear measurement, service lifetime, specific disc weight and number of discs per heat pack. This information was used to derive the weight of a generic C/C, respectively, metallic heat pack (Table 1).

A medium-haul aircraft is usually equipped with four heat packs corresponding to the four main gear wheels, each fitted with a single heat pack, while the nose gear is not equipped with heat packs.[22] The total payload of an installed set of heat packs was calculated using the respective weights per heat pack. Thus, the payload of a set of heat packs was estimated as follows:

$$m_{\mathrm{set,C/C}} = 234.0\mathrm{kg} \tag{1}$$

$$m_{\mathrm{set,metallic}} = 820.8\mathrm{kg} \tag{2}$$

3.2 | Manufacturing

Polyacrylonitrile (PAN)-based high-tensile (HT) carbon fibers are commonly used as a standard material to produce C/C composites employed in brake discs and other friction components. These fibers exhibit favorable mechanical properties and represent the most cost-effective option currently available, contributing to their widespread adoption in such applications.

In the subsequent manufacturing stage, these carbon fibers are processed into textile preforms, typically in the form of mats, felts, or nonwoven fabrics—particularly for use in aircraft brake discs. Following a shaping process that reduces the textile preforms to the desired component geometry, the carbon fiber semi-finished products undergo CVI. During this process, they are exposed to hydrocarbon gases—predominantly methane (CH_4) with a purity greater than 96%—at elevated temperatures exceeding 800°C.

Through pyrolytic decomposition of the gaseous precursor, a carbon matrix gradually forms around the individual filaments, ultimately resulting in a dense, cohesive composite material.

Within the scope of this study, the manufacturing phase of C/C heat packs includes isothermal CVI as well as upstream and downstream processes and resources.

A comprehensive description of the CVI process for C/C and C/SiC composites is described inter alia by Quenisset.[38] CVI process parameters, such as pore diffusion and deposition kinetics, are described by Diefendorf and Sohda.[39]

In the present study, the state-of-the-art process for manufacturing aircraft brake discs was investigated as a baseline scenario. This scenario is a modified, isothermal CVI process as utilized in series production. In addition to minor adjustments in the process, the waste heat from the reactors is reused directly in parallel processes via heat exchangers, which significantly reduces the process energy consumption.

For the environmental assessment of the manufacturing of 1 kg of a generic C/C structure, data from related projects were used and supplemented with literature data, which were consolidated industrially. In addition, laboratory measurements were used, which were then validated by industrial partners. Measured data were critically investigated due to upscaling effects on industrial plants. Due to the constant aggregation of several data sets, a fluctuation range of life cycle inventory data were used throughout to map a range of different material and energy flows that arise due to different process management. This range was mapped by two LCI data sets for the CVI process. Two generic life-cycle inventory (LCI) manufacturing scenarios—a worst-case and a best-case—were defined, hereinafter referred to as the LOW and HIGH manufacturing scenarios. These scenarios encompass the full range of production routes currently employed by leading suppliers such as Safran Landing Systems, Meggitt PLC, Honeywell, and SGL Carbon. Based on this coverage of diverse process technologies, it is estimated by the project advisory board that a significant share of all C/C composite aircraft brake discs fall within the mass and energy flows of these two LCI scenarios (LOW and HIGH).

The efforts in CU EcoCeramic required an energy and material flow model that allows flexible calculation of life cycle inventory data and resulting impact categories for different production scenarios. In addition to the structural materials, energy, compressed air, and cooling water are also required to produce C/C components. The structural materials include the fiber and matrix production, as well as the sewing thread and binder for the finishing of the textile semi-finished products. The production technologies include all upstream and downstream process steps required to produce a C/C structure of 1 kg with the focused production process chains based on the structural materials.

A distinction can be made between the following different initial situations in data procurement:

Data sets generally available in background LCA database. A range of material data is stored in commercial LCI databases and can directly be used by LCA software.

Data sets available in the background LCA database due to various predecessors and sister projects (e.g., MAI Enviro,[40] MAI Enviro 2.0[41] or MAI ÖkoCap[42]). Several process data sets have been determined and collected in predecessor and sister projects. Some CFRP data production data sets can be used directly for CMC production, such as data for HT carbon fibers, including the production of the polymeric carbon precursor PAN and all relevant flows, or the production of semi-finished textile products.[43] However, process parameters vary, resulting in different energy consumption per kilogram of material. The C/C production data sets were adapted and industrially validated using literature and own laboratory data.

Data sets industrially collected and established. In addition to the data sets determined or researched in-house, the project was also provided with industrial data. In the CU EcoCeramic project, more than 25 companies on the Industry Advisory Board helped to ensure that correct life cycle inventory data could be used. Data were provided by four companies for the CVI process. These were aggregated to form a generic data set and then industrially validated.

Based on the findings of CU EcoCeramic, the manufacturing of C/C is distinguished by a substantial energy consumption, which significantly impacts the carbon footprint of C/C structures whereby the composition of the electricity has a decisive influence. For this reason, the LCA model considers different scenarios for the electricity grid mix used for the manufacturing of C/C structures (Table 2).

The composition of energy sources of the mentioned renewable energy grid mix corresponds to the renewable share of the German grid mix in 2023.[44]

The LCA model for the manufacturing of 1 kg C/C was evaluated separately for all four scenarios. Each result of the evaluation (carbon footprint of the manufacturing of 1 kg C/C, $CF_{production,C/C}$) was then scaled up to the mass of a set of generic C/C heat packs ($m_{set,C/C}$), taking into account the assumed refurbishment rate of C/C brake discs ($RR_{C/C}$, see Section 3.5) as a credit for the avoided CO_2 equivalents of the production of C/C brake discs.

$$CF_{production,C/C} = \left(1 - RR_{C/C}\right) \times CF_{C/C} \times m_{set,C/C} \quad (3)$$

The result was incorporated into the overall calculation for the C/C use case as soon as the currently mounted set of heat packs reached the assumed service lifetime (Section 3.4).

Regarding the manufacturing of metallic heat packs, a generic data set for the manufacturing of gray cast iron via sand casting was used. Following the same procedure for the C/C use case, the result based on the used data set was evaluated (carbon footprint of 1 kg gray cast iron, $CF_{production,metallic}$) and scaled up to the weight of a set of metallic heat packs ($m_{set,metallic}$). As the utilized data set considers the use of secondary material, the result already includes the corresponding credit for the avoided CO_2 equivalents of the production of new metallic brake discs. The result was included in the overall calculation for the metallic use case as soon as the currently mounted set of heat packs reached the assumed service lifetime (Section 3.4).

$$CF_{production,metallic} = CF_{metallic} \times m_{set,metallic} \quad (4)$$

3.3 | Transport

A truck trip distance of 3500 km was assumed for both transporting the heat packs from the manufacturing site to the assembly site and transporting the worn-out heat packs from the disassembly site to the manufacturing site (refurbishment), respectively, to the disposal site. This assumption is following the European Commission's recommendation for the LCA purpose for the standard transport scenario from factory to end customer within an intra-European supply chain.[45] It is assumed that once the new heat packs have been delivered, the truck with the disassembled worn-out heat packs would return from the assembly site to the manufacturing site for refurbishment or disposal purposes. Therefore, a total distance of 7000 km for each transport cycle was assumed for round-trip transportation for each replacement event of a set of heat packs for the aircraft considered:

$$dist_{transport} = 7000 \text{ km} \quad (5)$$

TABLE 2 Carbon/carbon manufacturing scenarios considered in this study.

Scenario	Description
LOW	An optimized process control and the use of the German grid electricity mix are assumed.
LOW-renewable	An optimized process control and the use of an electricity grid mix based exclusively on renewable energy sources are assumed.
HIGH	A non-optimized process control and the use of the German grid electricity mix are assumed.
HIGH-renewable	A non-optimized process control and the use of an electricity grid mix based exclusively on renewable energy sources are assumed.

TABLE 3 Durability scenarios for carbon/carbon and metallic heat packs, expressed in number of flight cycles.

Product variant	C/C			Metallic		
Durability scenario	Short	Medium	Long	Short	Medium	Long
Number of flight cycles	800	1.400	2.500[46]	80	160	240

In consideration of the wear-related service lifetime of a set of heat packs, the transport cycle distance was applied for each replacement event (replacement of one set of heat packs). The LCA model for transport includes the transport by diesel truck (Euro 4 emission standard, gross weight > 32t). The model is evaluated for 1 kg of transported goods (carbon footprint of the transport of 1 kg generic load mass, CF_{truck}) and scaled up to the mass of a set of C/C, respectively, metallic heat packs:

$$CF_{transport,C/C} = CF_{truck} \times m_{set,C/C} \tag{6}$$

$$CF_{transport,metallic} = CF_{truck} \times m_{set,metallic} \tag{7}$$

3.4 | Flight operation

Flight operations are subject to a variety of external factors, resulting in a highly dynamic nature of the parameters relevant to the environmental assessment of a generic medium-haul aircraft operation. The objective of the present study was to perform an analysis based on a generic flight operation scenario defined along different parameter values. The following section provides a detailed description of these parameters, including the definition of their values.

3.4.1 | Heat pack service lifetime

The wheel brake function is subject to a variety of external influences, including load, wind conditions, and the length and ground conditions of the runway. These variables directly impact the durability of a heat pack. To account for these variables, three durability scenarios were defined for each product variant (Table 3).

Except for the value of scenario C/C, Long, which is based on a publicly available manufacturer's statement, the durability values are based on expert statements conducted within the scope of the project CU EcoCeramic. For this assessment, empirical investigations were carried out at a facility specializing in the recycling of heat packs. The manufacturer's recommended service life—hereafter denoted as the long scenario—was evaluated against the replacement intervals actually recorded in operational workshop settings (medium scenario). A short scenario was defined to represent the theoretical minimum replacement interval, which is rarely encountered under typical usage conditions.

3.4.2 | Aircraft service lifetime

Literature studies use a range of assumptions on aircraft service lifetime, ranging from 20 to more than 30 years, with 30 years being the most common.[47–52] Thus, this study assumes a total aircraft service lifetime of 30 years:

$$t_{aircraft} = 30 \text{ years} \tag{8}$$

3.4.3 | Flight distance per day

To determine the fuel savings associated with the C/C use case, the difference in kerosene consumption for the heat packs as payload had to be determined over the entire service lifetime of the aircraft. The initial step in this process was to ascertain the total distance flown by a medium-haul passenger per day. Based on existing analysis,[53] an average value of flight cycles per day was assumed:

$$FC_d = 4.44 \tag{9}$$

To determine this parameter value, data on currently active and recently concluded medium-haul flights were extracted through FlightAware's AeroAPI.[54] Over a period of one and a half months, global flight data, including departure and arrival airports' ICAO codes, was collected 31 times. The collected airport ICAO codes were enriched with coordinates using OurAirports[55] compiled list of airports worldwide and flight distances were calculated using the well-established Haversine formula, which is applicable for the calculation of the distance between two points on the Earth's surface at sea level, as discussed by Cox et al. for hurricane trajectories.[56] Duplicate flights, flights with no recorded arrival airport were removed from the data set before further analysis. The described API calls and data pre-processing was performed using the KNIME data analytics software.[57] Information about the investigated airplane types for filtering was pulled from the manufacturers' websites[58,59] and flugzeuginfo.net.[60] The average value was calculated based on the analyzed flight distances. This amounts to 1321 km per flight cycle:

$$\mathrm{dist}_{FC} = 1321\ \mathrm{km} \tag{10}$$

The average daily flight distance (dist_d) was determined by multiplying the average daily number of flight cycles (FC_d) and the average flight cycle distance (dist_{FC}):

$$\mathrm{dist}_d = FC_d \times \mathrm{dist}_{FC} \tag{11}$$

3.4.4 | Payload-induced fuel consumption of the mounted heat packs as payload

Scaled to the aircraft's service lifetime of 30 years, the respective fuel consumption quantities were calculated. The amount of CO_2 equivalents was evaluated using LCA background data for the supply and combustion of kerosene.

To determine the fuel savings that can be realized by using the lighter C/C heat packs, the heat packs were considered as a flight load. Following existing literature approaches, it was assumed that the thrust-to-weight ratio and the cruising speed remain constant when considering a specific aircraft type, so that fuel consumption can be assumed to be proportional to the total aircraft weight (linear fuel–mass correlation).[27] According to Steinegger, the ratio of fuel savings that can be realized by reducing the weight by 1 kg, or the amount of fuel required for 1 kg of additional weight, amounts to around 0.02–0.03 kg of fuel over a flight distance of 1000 km.[24] Following this value range, an average fuel consumption rate (FCR) of 0.025 kg fuel per 1000 km and 1 kg load was assumed for the evaluation:

$$\mathrm{FCR} = \frac{0.025\ \mathrm{kg\ kerosene} \times \mathrm{kg\ payload}}{1000\ \mathrm{km}} \tag{12}$$

The study considered the heat packs as a load to be carried during the flight, and the amount of fuel required for the mounted set of heat packs as a payload was calculated. To do so, the average FCR was multiplied by the average distance travelled per flight cycle and multiplied by the number of flight cycles per day:

$$m_{d,\mathrm{kerosene},C/C} = m_{\mathrm{set},C/C} \times \mathrm{dist}_d \times \mathrm{FCR} \tag{13}$$

$$m_{d,\mathrm{kerosene,metallic}} = m_{\mathrm{set,metallic}} \times \mathrm{dist}_d \times \mathrm{FCR} \tag{14}$$

The result was then scaled up to the aircraft's service lifetime. The difference between the resulting fuel masses for both the C/C and metallic product variant thus represents the amount of fuel saved by using lightweight C/C heat packs. To analyze the environmental impacts associated with the supply and combustion of the weight-induced fuel masses, a generic LCA data set was used in LCA for experts, which maps the supply and combustion of 1 kg of kerosene. This data set was then evaluated and the result (carbon footprint of the supply and combustion of 1 kg of kerosene, CF_{kerosene}) used to determine the CO_2 equivalents of the consumption of kerosene as part of the overall calculation for each use case.

$$CF_{d,\mathrm{kerosene},C/C} = m_{\mathrm{set},C/C} \times \mathrm{dist}_d \times \mathrm{FCR} \times CF_{\mathrm{kerosene}} \tag{15}$$

$$CF_{d,\mathrm{kerosene,metallic}} = m_{\mathrm{set,metallic}} \times \mathrm{dist}_d \times \mathrm{FCR} \times CF_{\mathrm{kerosene}} \tag{16}$$

3.5 | End-of-life scenarios

Friction applications such as aircraft brake discs are subject to high dissipation during their use phase. A significant share of the product is abraded during the braking procedure on the runway due to high rotational speed and pressure being applied on the surface, leading to particulate and a film-type of debris.[61] Depending on the design and rinsing procedure of the heat pack, the dissipated C/C undergoes combustion or is emitted as carbon particles and fibers. While most of the solid residues are cleansed during maintenance, emitted particles represent fine particulate matter that not only harm the environment but also human health.[62,63] Based on this study's calculations, 2.3 g of carbon particles are abraded on average per landing and disc with a weight of 6.5 kg. After 1400 landing cycles, a disc is worn down to about 50% of its original mass, corresponding to the maximum abrasion level during the use phase. Using modern remanufacturing methods, two worn-out C/C brake discs that are otherwise undamaged are clipped together to create a second-life disc that can perform another 1400 landing cycles before reaching EoL. According to expert statements, it can be assumed that 50% of the worn-out discs entering the maximum abrasion level are undamaged and can be refurbished, while 50% show additional signs of wear, such as cracks, making them unsuitable for a second live as a brake disc. Over several replacement cycles, these assumptions result in a calculated limit value of 20% of second-life brake disc material (refurbishment rate, $RR_{C/C}$; the detailed calculation is shared within the Supporting Information, file name *Refurbishment_CC_Calc.pdf*):

$$RR_{C/C} = 0.2 \tag{17}$$

Considering an abrasion of 50% per life cycle, on average, 30% of the primary disc enters the EoL, while 70% is dissipated. To date, only few information is available for recycling options for those EoL brake discs.[36] Therefore, it is assumed that these are not processed separately and, thus, exclude further EoL treatment from the model. Regarding the metallic heat packs, the LCA background data set considers a proportion of secondary material of 100%. This means that EoL treatment in accordance with the current state of material recycling of metallic brake disc material is considered in the present study.

4 | LIFE CYCLE IMPACT ASSESSMENT

Using LCA for Experts software version 10.7.0.183 combined with database CUP2024.1,37[37] a LCIA was carried out following the European Commission's LCIA methodology Environmental Footprint 3.1 (EF3.1) for the midpoint category climate change, total. EF3.1 addresses the effects on climate change and includes the calculation of the radiative forcing as global warming potential of 100 years (GWP100) as a science-based midpoint indicator over the life cycle of a product or service. Consequently, this study considers the baseline model of 100 years.

The calculation of the CO_2 equivalents of the respective use cases is carried out cumulatively over 30 years (equivalent to 10.950 days). The evaluation for the C/C use case included all scenario combinations resulting from the manufacturing scenarios (Table 2) and the service life scenarios for the heat packs (Table 3). An overview of all evaluated C/C scenario combinations is given in Table 4.

The results of the LCIA are presented here. Figure 4 shows the CO_2 equivalents associated with the C/C and metallic use cases over the entire aircraft's service life and thereby corresponds to the initially defined FU fulfilling the wheel brake function for a medium-haul aircraft over an aircraft's service life of 30 years. For a break-even analysis of the use of C/C instead of metallic heat packs, Figure 5 pertains to the initial 2 years of the aircraft's life cycle.

Regarding the metallic use case, all three durability scenarios (Table 3) were evaluated.

Figure 4 illustrates the cumulative tons of CO_2 equivalents associated with the manufacturing, transport, and use of heat packs over the entire aircraft service life of 30 years.

Following the analysis of all considered scenario combinations, a range of results was obtained for the C/C and metallic use cases, which are represented by the shaded areas. The blue-shaded area represents the corridor for the metallic use case, and the blue line corresponds to the CO_2 equivalents assuming an average service life. The lower corridor boundary represents the CO_2 equivalents assuming a short service life, while the upper corridor boundary corresponds to the maximum feasible service life.

The orange-shaded area describes the corridor of the C/C use case. The upper limit of the orange corridor represents the CO_2 equivalents for the manufacturing scenario HIGH and an assumed short service lifetime for the C/C heat packs, which is the least favorable scenario combination. The lower limit of the C/C corridor describes the environmental impacts of the most favorable scenario combination, which is the case for the LOW-renewable manufacturing scenario and an expected long service lifetime for the C/C heat packs. The lines shown within the orange corridor describe the carbon footprint resulting from the LOW and HIGH manufacturing scenarios, combined with an average service lifetime for the C/C heat packs. The dashed lines describe the environmental impacts of the perspective C/C manufacturing scenarios, LOW-renewable or HIGH-renewable (use of an electricity grid mix from exclusively renewable energy sources), while assuming an average service lifetime for the C/C heat packs.

As the manufacturing- and transport-induced impacts occur with each replacement event, the lines and corridors for both use cases take the form of a staircase (due to the given scale, the effects of the metallic use case appear linear, but are also step-shaped). The gradient between two steps represents the increase of CO_2 equivalents generated by the supply and emission of kerosene consumed for the heat packs as a payload in flight over time until the currently installed set of heat packs is replaced by the end of its service lifetime (=next step-shaped increase). The FU is achieved at the end of the aircraft's life. The corresponding values when the FU is achieved are listed in Table 5.

TABLE 4 Evaluated scenario combinations for the carbon/carbon use case.

Manufacturing scenario	**Low-renewable**			**Low**			**High-renewable**			**High**		
Durability scenario	Short	Avg.	Long	Short	Avg.	Long	Short	Avg.	Long	Short	Avg.	Long

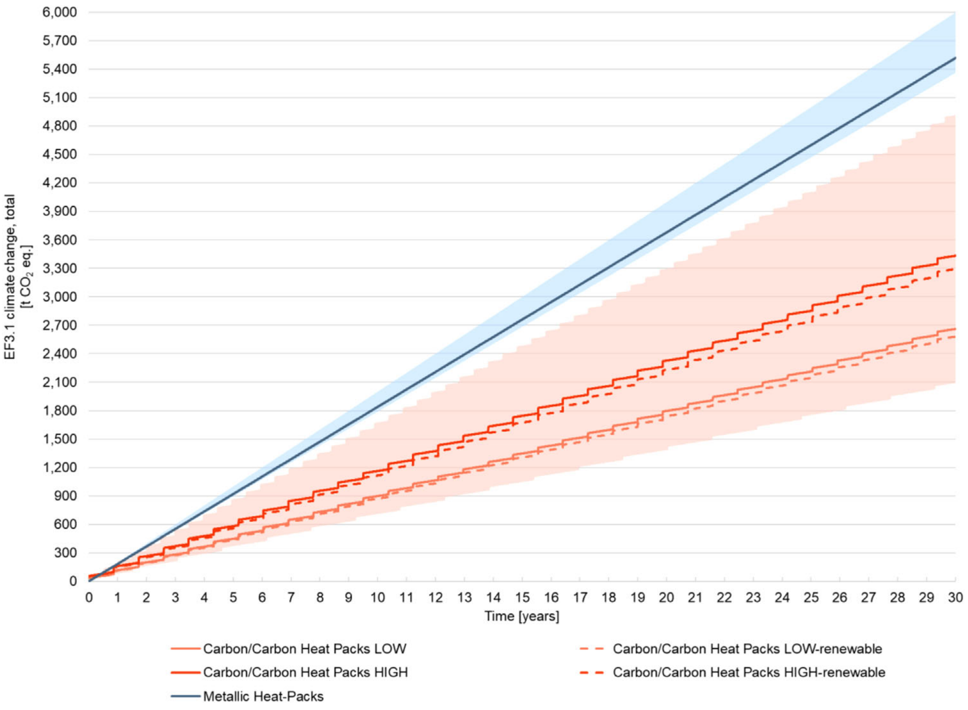

FIGURE 4 Environmental impact for the EF3.1 impact category climate change, total to fulfill the functional unit (FU) by using generic carbon/carbon and metallic heat packs (development over time).

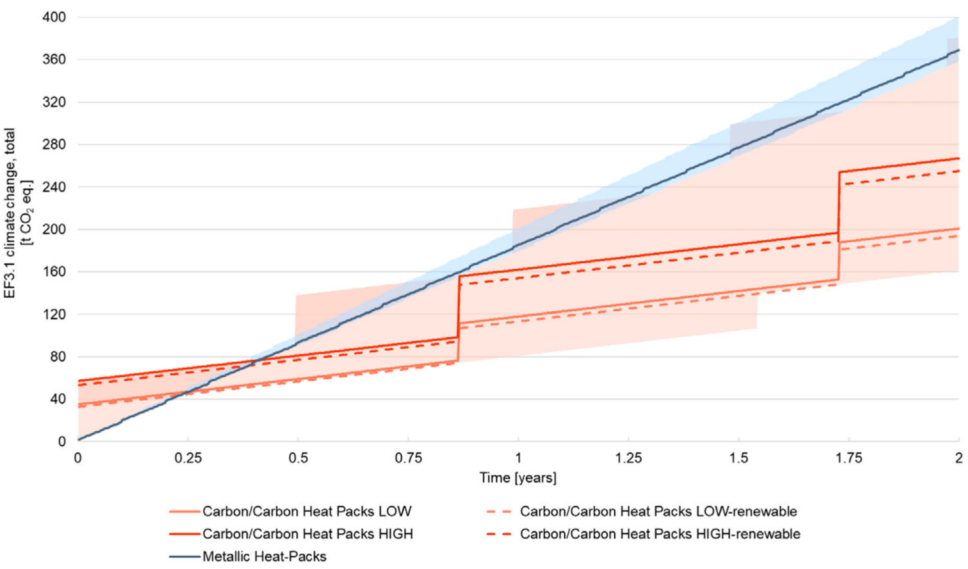

FIGURE 5 Break-even period of the environmental impact for the EF3.1 impact category climate change, total of using carbon/carbon, and metallic heat packs.

TABLE 5 Results for the EF3.1 impact category climate change, total at the moment of fulfilling the functional unit through the use of carbon/carbon, respectively, metallic heat packs.

Manufacturing scenario assuming an average service lifetime of the heat packs	Global warming potential (CO_2-eq./FU)
C/C—LOW-renewable	2.580 t
C/C—LOW	2.661 t
C/C—HIGH-renewable	3.293 t
C/C—HIGH	3.432 t
Metallic	5.518 t

Abbreviations: CO_2-eq., CO_2 equivalents; FU, functional unit.

The use of C/C heat packs proves to be favorable across all evaluated scenarios, which is already evident in an early phase of the aircraft's service life. This is despite the production of C/C heat packs is associated with significantly higher CO_2 equivalents than the production of metallic heat packs. The reason for the advantageous performance of the C/C use case primarily is given by the lightweight construction induced reduction in kerosene consumption, and an overall longer service life of the C/C heat packs. Even the least favorable C/C use case scenario combination relates to fewer CO_2 equivalents than the most favorable metallic use case scenario. This underlines the dominant role of those two aspects in the overall results.

The range of results of the C/C use case (orange area) implies that both the service lifetime of the heat packs and the manufacturing process control are important levers to reduce the amount of CO_2 equivalents associated with the C/C use case. This finding corroborates existing research results, which imply that an increase in service life of lightweight composite components leads to significantly enhanced environmental benefits due to the reduction of aircraft GHG emissions.[25]

Improved process control in the manufacture of C/C heat packs can additionally reduce GWP significantly by 22%/FU (HIGH vs. LOW). Moreover, utilizing a renewable electricity grid mix reduces CO_2 equivalents by 25%/FU (HIGH vs. LOW-renewable).

HIGH and HIGH-renewable are mediocre as the manufacturing of the C/C brake discs is more energy intensive due to suboptimal process parameters. However, the lighter C/C heat packs have a lower GWP in flight operation than the metallic use case when the FU is fulfilled due to dominant lightweight-induced fuel savings and the longer service life of C/C heat packs. Metallic heat packs represent the scenario with the highest overall GWP. The production of metallic brake discs has a significantly lower GWP than C/C, indicating that the high GWP is primarily attributable to the higher payload-induced fuel consumption that occurs during flight operation for the heavier metallic heat packs. Additionally, the evaluation diagram demonstrates that the durability of the heat packs exerts a substantial influence on the GHG emissions over time. This is particularly evident in the C/C use case, given its significantly higher manufacturing-induced impacts compared to the metallic use case.

Figure 5 shows the evaluation diagram for the first 2 years of flight operation for the intersection analysis of the C/C and metallic applications.

The intersection of the C/C MIN and metallic lines occurs at approximately 0.25 years, or, when considering the manufacturing scenario HIGH, at around 0.5 years. For the perspective manufacturing scenarios (C/C LOW-renewable and C/C HIGH-renewable), the intersection points are slightly shifted forward in time.

Figure 6 shows the results of the individual scenario combinations, including the respective shares of contribution to the environmental impact by the production of the heat packs, the associated kerosene consumption, and the associated diesel consumption (truck transportation of the heat packs).

The longer service life of the heat packs not only improves the overall result but also increases the relevance of kerosene consumption. In addition, the positive effect of a longer service life of the heat packs is more significant for HIGH and HIGH-renewable than for LOW and LOW-renewable due to the higher production-induced impact. The transportation of the heat packs by truck to the assembly site and back to the manufacturer represents a clearly subordinate contribution to the overall results for all scenario combinations.

Figure 7 shows the results for the metallic use case for the different heat pack durability scenarios, including the shares of manufacturing, kerosene consumption of the aircraft, and diesel consumption of the truck transports.

The range between the overall results is significantly smaller than in the C/C use case, which is due to the lower variance of the assumed heat pack durability. In contrast to the C/C use case, it is noticeable here that the proportion of kerosene consumption accounts for a significantly higher proportion of the overall result, as the higher weight-induced kerosene consumption and the lower amount of manufacturing-induced CO_2 equivalents result in a different ratio of these proportions. Nevertheless, the result can be significantly influenced by a higher durability of the heat packs. In contrast to the C/C use case, the share of truck transportation in the overall result is more significant.

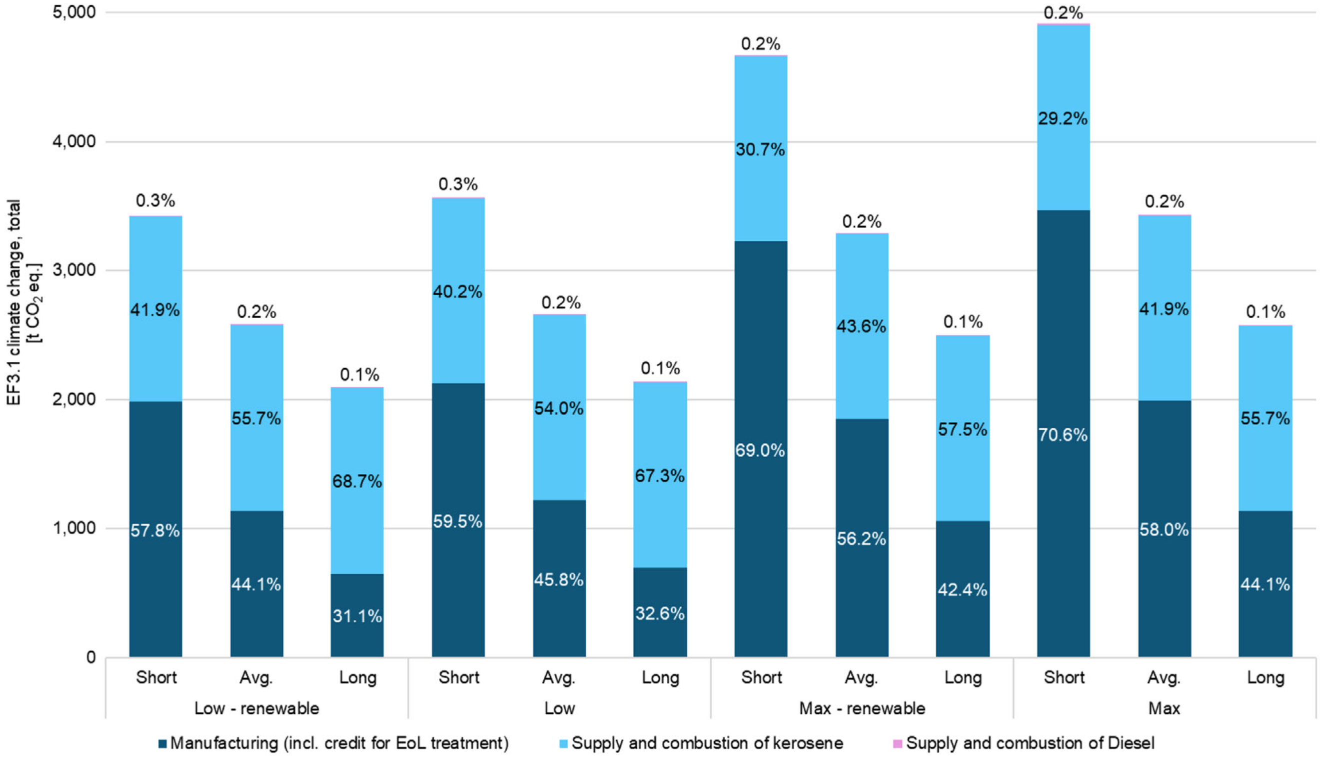

FIGURE 6 Results of the carbon/carbon scenario combinations at the moment of fulfilling the functional unit by the respective share of contribution.

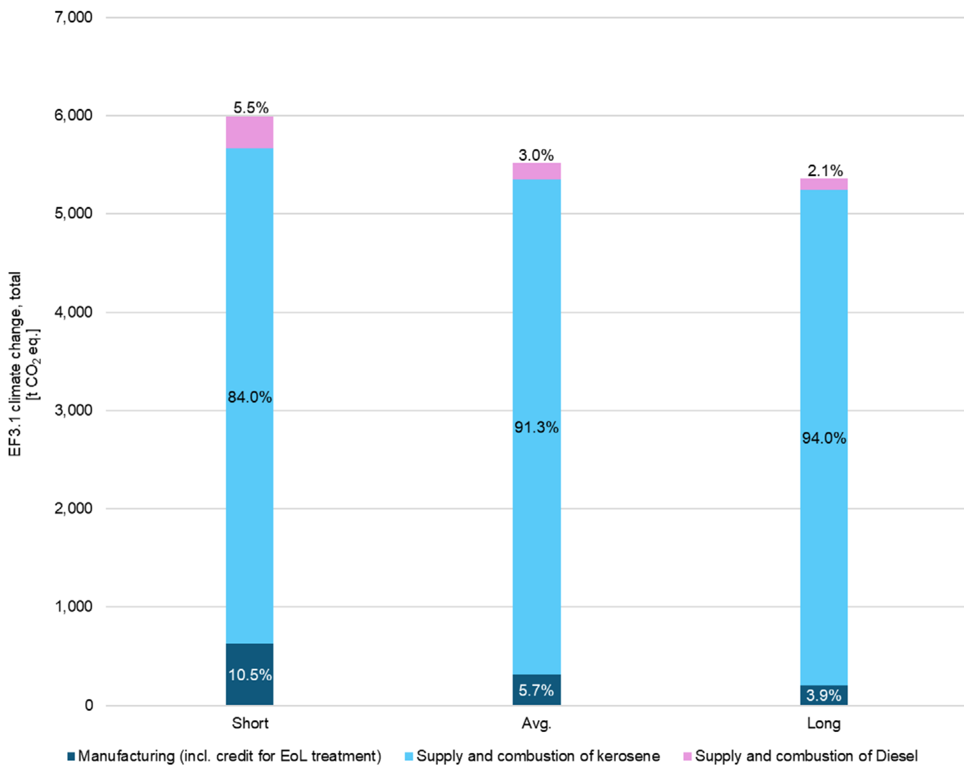

FIGURE 7 Results of the metallic scenarios at the moment of fulfilling the functional unit by the respective share of contribution.

5 | DISCUSSION AND OUTLOOK

The analysis of the GHG emissions associated with the use of C/C-based heat packs over the lifetime of a medium-haul aircraft reveals major benefits regarding the GWP, although the manufacturing of C/C heat packs is associated with a significantly higher carbon footprint compared to the manufacturing of the metallic product variant. Assuming an average heat pack service lifetime, the benefits of the C/C use case are already realized within the first year of flight operation. Specifically, the long service lifetime of the heat packs and the improved process control in C/C production can be identified as pivotal factors in reducing the carbon footprint of the C/C use case. These benefits are evident in the wide range of results observed in the fulfillment of the FU.

All scenario combinations examined for the C/C use case prove to be advantageous, primarily due to the reduced kerosene consumption induced by the lightweight aspect of C/C, while additional kerosene consumption due to higher weight is the main contributor to the carbon footprint of the metallic use case. This finding can also be attributed to the concurrent effect of the longer service life of the C/C heat packs. This corroborates existing research results, which imply that an increase in service lifetime of vehicle components, respectively, travel distance over time, leads to enhanced GHG emissions benefits from using lightweight materials.[25]

ICAO's basket of measures for achieving its net zero emissions goal considers the utilization of sustainable aviation fuel (SAF). This measurement holds significant potential for reducing aviation GHG emissions.[64,65] Considering the anticipated future application of SAF and aircraft propulsion technologies with reduced climate-impacting emissions, a decreasing significance of fuel-related GHG emissions on the overall emissions related to the use of C/C heat packs can be expected. Consequently, the significance of optimized process control in C/C manufacturing and the use of electricity from renewable energy sources as a lever for reducing emissions will increase.

Given the increasing service lifetimes of passenger aircraft, it can be assumed that a longer aircraft service life further increases the importance of the use phase regarding the ecological benefits of C/C lightweight components for aircraft applications, which follows the findings of existing research.[25]

The estimation of the use phase of composite structures depends on which application is considered. Since the intended use of a large aircraft can strongly influence its flight frequency, average flight distance, and other parameters, commercial passenger transport was chosen as the intended use of an exemplary medium-haul aircraft. For other applications (e.g., air cargo missions), the parameters for flight operations on which this study is based must be re-evaluated. The study represents generic results based on the assumptions made and data collected. Therefore, these results should not be regarded as universally valid and are not suitable for product comparison statements. Considering that production process control and product durability are significant factors identified in this study, separate LCA studies should investigate the GHG emissions reduction potential of other CMC aircraft components, as this can vary greatly by component and use case.

In the course of this study, it was recognized that there is a limit to solutions for the EoL treatment of CMC. Therefore, investigating the ecological effect of additional EoL scenarios for CMC serves as a starting point for future research efforts. These efforts will follow the expressed necessity outlined in existing research.[27]

6 | CONCLUSIONS

This study investigates the potential of a lightweight aircraft component made of CMC to reduce aircraft GHG emissions over the service life of a large passenger aircraft. The investigation of GHG reduction potential (expressed in CO_2 equivalents) for C/C heat packs in commercial aviation is expected to assist both manufacturers of aircraft wheel brakes and aircraft operators in evaluating this type of brake with respect to environmental considerations.

To investigate this issue, the method of LCA was applied, analyzing a generic C/C heat pack and a generic metallic heat pack for a medium-haul aircraft. The analysis considered the supply (manufacturing and transportation) of the heat packs, their use during flight operations, and their EoL. A generic use case was described for both product variants based on specific parameter values, including evaluated real flight data. Both use cases were analyzed using the LCIA method Environmental Footprint 3.1 for the impact category climate change, total. The evaluation included different manufacturing and product durability scenarios to account for variations in manufacturing and use.

The results show that the C/C use case is associated with lower CO_2 equivalents than the metallic use case across all scenarios considered. The primary factors influencing this are the reduced kerosene consumption realized by the lightweight C/C heat packs as flight loads, and their longer service life. This finding aligns with the corresponding results of existing LCA studies on lightweight components in the automotive and aerospace sectors. In addition, the study's results indicate that optimized manufacturing process control and, to a lesser extent, the use of renewable energy in production were identified as levers for reducing the GHG emissions of the C/C use case. In view of the potential use of SAF, it is expected that these levers will increasingly gain importance in the future compared to the fuel saving aspect of lightweight aircraft components. Assuming an increasing use of SAF in the future, LCA studies including specific LCA data sets for the supply and combustion of SAF is recommended. Furthermore, as only limited information and solutions exist for the EoL treatment of C/C components to date, this study highlights the need for future research in this area.

AUTHOR CONTRIBUTIONS

Conceptualization: Kevin Christopher Dorling, Denny Schüppel, Tobias Manuel Prenzel, and Nicoletta Narres. *Methodology*: Kevin Christopher Dorling, Tobias Manuel Prenzel, and Nicoletta Narres. *Modeling*: Nicoletta Narres and Kevin Christopher Dorling. *Validation*: Tobias Manuel Prenzel, Denny Schüppel, and Nicoletta Narres. *Formal analysis*: Kevin Christopher Dorling and Denny Schüppel. *Data curation*: Kevin Christopher Dorling, Denny Schüppel, and Malte Tusche. *Writing—original draft preparation*: Kevin Christopher Dorling, Denny Schüppel, Lars Wietschel, and Florian Halter. *Writing—review and editing*: Florian Halter, Lars Wietschel, Nicoletta Narres, Tobias Manuel Prenzel, Denny Schüppel, and Dietmar Koch. *Visualization*: Kevin Christopher Dorling, Denny Schüppel, and Malte Tusche. *Project administration*: Denny Schüppel, Nicoletta Narres, and Tobias Manuel Prenzel. *Funding acquisition*: Denny Schüppel. All the authors have read and agreed to the published version of the manuscript.

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REFERENCES

1. IPCC. Climate Change 2023: Synthesis Report, H Lee, J Romero, editors. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 35–115, https://doi.org/10.59327/IPCC/AR6-9789291691647
2. IEA. Aviation. Available from: https://www.iea.org/energy-system/transport/aviation#tracking. Accessed 15 Jan 2025.
3. European Commission. The European Green Deal. 2019.
4. Ritchie H. What share of global CO_2 emissions come from aviation? Our world in data. 2024.
5. IEA. Transport—energy system. Available from: https://www.iea.org/energy-system/transport. Accessed 15 Jan 2025.
6. European Commission. Reducing emissions from aviation. Available from: https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-aviation_en. Accessed 15 Jan 2025.
7. ICAO. ICAO Environmental Report 2019. Chapter 6: Climate change mitigation. CORSIA. 2019.
8. EASA. European aviation environmental report 2022: executive summary and recommendations. 2022.
9. ICAO. States adopt net-zero 2050 global aspirational goal for international flight operations. Available from: https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx. Accessed 15 Jan 2025.
10. IATA. IATA Annual Review. 2021.
11. International Civil Aviation Organization. Future of aviation. Available from: https://www.icao.int/Meetings/FutureOfAviation/Pages/default.aspx. Accessed 4 Jun 2025.
12. Klimaschutz-Portal. CO_2 Eingespart mit Leichtigkeit. Available from: https://www.klimaschutz-portal.aero/verbrauch-senken/am-flugzeug/gewicht-einsparen/. Accessed 15 Jan 2025.
13. European Commission. Flightpath 2050—Europe's vision for aviation: report of the high-level group on aviation research. Luxembourg: Publication Office of the European Union; 2011.
14. Cumpsty N, Mavris D, Kirby M. Chapter one—aviation and the environment: outlook. ICAO 2019 Environmental Report. 2019.
15. Schüppel D, Klemm H, Klopsch L, Koch D, Kühnel M, Reichert F, et al. Ceramic composites market report—the global market for ceramic matrix composites: manufacturers, OEM, clusters, applications and production volumes—extended version for members. Augsburg. 2023.
16. Xu Y, Zhu J, Wu Z, Cao Y, Zhao Y, Zhang W. A review on the design of laminated composite structures: constant and variable stiffness design and topology optimization. Adv Compos Hybrid Mater. 2018;1(3):460–77. https://doi.org/10.1007/s42114-018-0032-7

17. Giurgiutiu V. Introduction. In: Giurgiutiu V, editor. Stress, vibration, and wave analysis in aero-space composites for SHM and NDE applications. Chapter 1. Elsevier; 2022. p. 1–27.
18. Cauquil O, Sánchez Gómez J, Gayoso I, Blanco T. 3rd generation of composite materials for airframe: world materials forum—workshop on composites. 2015.
19. Ilg R, Mehra S-R, Sedlbauer K. Ein methodischer Ansatz zur ökologischen Betrachtung von Luftfahrtsystemen. Dissertation. Fraunhofer-Institut für Bauphysik.
20. Song YS, Youn JR, Gutowski TG. Life cycle energy analysis of fiber-reinforced composites. Composites Part A: Appl Sci Manuf. 2009;40(8):1257–65. https://doi.org/10.1016/j.compositesa.2009.05.020
21. Gobbie S, Dudebout R, Steinmetz G, Upton E, Parry B, Knappen L, et al. Advancing aviation technology towards industry decarbonisation. ICAO 2022 Environmental Report. 2022.
22. S.A.S. Airbus. A320 aircraft characteristics airport and maintenance planning: AC. Issue: Sep 30/85. 44th ed. Blagnac Cedex; 2024.
23. The Business Research Company. Aircraft Brake System Global Market Report 2025—By component (braking system components, brakes, wheels), by actuation (power brake, boosted brake, independent brake), by brake type (carbon breaks, steel breaks, others), by aircraft type (fixed wing, rotary wing, unmanned aerial vehicles), by end-user (commercial aircraft, defense aircraft)—market size, trends, and global forecast 2025–2034. Available from: https://www.thebusinessresearchcompany.com/report/aircraft-brake-system-global-market-report. Accessed 15 Jan 2025.
24. Steinegger R. Fuel economy for aircraft operation as a function of weight and distance. ZHAW Zürcher Hochschule für Angewandte Wissenschaften; 2017.
25. Kim HC, Wallington TJ. Life-cycle energy and greenhouse gas emission benefits of lightweighting in automobiles: review and harmonization. Environ Sci Technol. 2013;47(12):6089–97. https://doi.org/10.1021/es3042115
26. Bianchi I, Forcellese A, Simoncini M, Vita A, Delledonne L, Castorani V. Life cycle assessment of carbon ceramic matrix composite brake discs containing reclaimed prepreg scraps. J Clean Prod. 2023;413:137537. https://doi.org/10.1016/j.jclepro.2023.137537
27. Scelsi L, Bonner M, Hodzic A, Soutis C, Wilson C, Scaife R, et al. Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment. Express Polym Lett. 2011;5(3):209–17. https://doi.org/10.3144/expresspolymlett.2011.20
28. Timmis AJ, Hodzic A, Koh L, Bonner M, Soutis C, Schäfer AW, et al. Environmental impact assessment of aviation emission reduction through the implementation of composite materials. Int J Life Cycle Assess. 2015;20(2):233–43. https://doi.org/10.1007/s11367-014-0824-0
29. Stergiou V, Konstantopoulos G, Charitidis CA. Carbon fiber reinforced plastics in space: life cycle assessment towards improved sustainability of space vehicles. J Compos Sci. 2022;6(5):144. https://doi.org/10.3390/jcs6050144
30. Composites United e.V. Project CU EcoCeramic: Studie zur Lebenszyklusanalyse relevanter Fertigungsprozessketten für CMC-Strukturen mit ökobilanzieller Analyse und ökonomischer Bewertung inkl. Betrachtung der Kreislaufwirtschaft. Available from: https://composites-united.com/en/projects/cmc-enviro/. Accessed 7 July 2025.
31. International Organization for Standardization. ISO 14040:2006: Environmental management—life cycle assessment—principles and framework. 2nd ed. 2006. Available from: https://www.iso.org/standard/37456.html
32. International Organization for Standardization. ISO 14044:2006: Environmental management—life cycle assessment—requirements and guidelines. 1st ed. 2006. Available from: https://www.iso.org/standard/38498.html
33. Schneider T, Wietschel L, Schüppel D, Riesner J, Konrad K, Thorenz A, et al. Multicriteria optimization as enabler for sustainable ceramic matrix composites. Int J Appl Ceram Tech. 2022;19(6):3247–54. https://doi.org/10.1111/ijac.14174
34. de Haes HU, Heijungs R, Jolliet O, Climate Change. Ch. 4.2 of the life cycle impact assessment definiton study: background document III: analysis of midpoint categories. Life cycle impact assessment programme of The UNEP/SETAC Life Cycle Initiative. 2003. Accessed 31.10.2025.
35. European Commission. International reference life cycle data system (ILCD) handbook: general guide for life cycle assessment—provisions and action steps. Luxembourg: Publications Office; 2011.
36. Wietschel L, Halter F, Thorenz A, Schüppel D, Koch D. Literature review on the state of the art of the circular economy of ceramic matrix composites. Open Ceram. 2023;14:100357. https://doi.org/10.1016/j.oceram.2023.100357
37. LCA for Experts: Software System and Database for Life Cycle Engineering. Sphera Solutions GmbH; 2024.
38. Quenisset JM. Carbon combinations. Carbon–carbon composites. By G. Savage Chapman & Hall, London 1993, 389 pp., hardcover, £ 40, ISBN 0-412-36150-7. Adv Mater. 1994;6(2):176–77. https://doi.org/10.1002/adma.19940060222
39. Sohda Y, Diefendorf RJ. The Chemical Vapor Deposition of Carbon in OpenEnded Capillary Tubes. Proceedings of the 17th Biennial Conference on Carbon. University of Kentucky, Lexington, KY. June, 1985.
40. Composites United e.V. Project MAI Enviro: Daten zum Energieverbrauch für exemplarische Prozessketten und Nachhaltig-keitsbewertung. Available from: https://composites-united.com/en/projects/mai-enviro/. Accessed 7 July 2025.
41. Composites United e.V. Project MAI Enviro 2.0: Ökobilanzielle Bewertung zum nachhaltigen Umgang mit CFK-Strukturen. Available from: https://composites-united.com/en/projects/mai-enviro-2-0/. Accessed 7 July 2025.
42. Composites United e.V. Projekt MAI ÖkoCaP: Technische und ökobilanzielle Bewertung von recycelten Carbonfasern in industriellen Prozessen. Available from: https://composites-united.com/projects/mai-oekocap/. Accessed 7 July 2025.
43. Fraunhofer Institute for Building Physics IBP. Advanced Materials and Processes Database. Sphera Solutions GmbH; 2024.
44. Umweltbundesamt. Renewable energies in figures. Available from: https://www.umweltbundesamt.de/en/topics/climate-energy/renewable-energies/renewable-energies-in-figures. Accessed 12 Mar 2025.

45. European Commission. Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. Off J Eur Union. 2021;64(471).
46. Safran SA. Airbus A320ceo/neo long life carbon brake. Available from: https://www.safran-group.com/products-services/airbus-a320ceoneo-long-life-carbon-brake. Accessed 3 Feb 2025.
47. Johanning A. Methodik zur Ökobilanzierung im Flugzeugvorentwurf. Dissertation. Verlag Dr. Hut; 2017.
48. Kingsley-Jones M. Airbus begins tests to extend service life of A320 family. Flight Global 2008. January 2008. Available from: https://www.flightglobal.com/airbus-begins-tests-to-extend-service-life-of-a320-family/78350.article. Accessed 15 Jan 2025.
49. Airbus. Operating life—from delivery to service retirement. Available from: https://www.airbus.com/en/products-services/commercial-aircraft/the-life-cycle-of-an-aircraft/operating-life. Accessed 15 Jan 2025.
50. Howe S, Kolios AJ, Brennan FP. Environmental life cycle assessment of commercial passenger jet airliners. Transp Res D Trans Environ. 2013;19:34–41. https://doi.org/10.1016/j.trd.2012.12.004
51. Forsberg D. Aircraft retirement and storage trends: economic life analysis reprised and expanded. 2015.
52. Gomez-Campos A, Vialle C, Rouilly A, Hamelin L, Rogeon A, Hardy D, et al. Natural fibre polymer composites—a game changer for the aviation sector? J Cleaner Prod. 2021;286:124986. https://doi.org/10.1016/j.jclepro.2020.124986
53. Aircraft Commerce. A320 base check maintenance inputs. Aircraft Commerce. Vol. 111. p. 69–80. 2017. Available from: https://www.aircraft-commerce.com/wp-content/uploads/aircraft-commerce-docs1/Maintenance/2017/111_MTCE_A.pdf. Accessed 31.10.2025.
54. FlightAware. AeroAPI® Flight Tracking and Flight Status API—FlightAware. Available from: https://www.flightaware.com/commercial/aeroapi/. Accessed 24 Feb 2025.
55. Megginson D. OurAirports. Available from: https://ourairports.com/. Accessed 24 Feb 2025.
56. Cox TS, Hoi CSH, Leung CK, Marofke CR. An accurate model for hurricane trajectory prediction. IEEE 42nd Annual Computer Software and Applications Conference (COMPSAC), Tokyo, Japan. 2018. p. 534–39. https://doi.org/10.1109/COMPSAC.2018.10290
57. Berthold MR, Cebron N, Dill F, Gabriel TR, Kötter T, Meinl T, et al. KNIME: The Konstanz Information Miner. Studies in classification, data analysis, and knowledge organization (GfKL 2007). Springer; 2007.
58. Airbus. Pioneering sustainable aerospace for a safe and united world. Available from: https://www.airbus.com/en. Accessed 26 Feb 2025.
59. Boeing. The Boeing Company Official Website. Available from: https://www.boeing.com/. Accessed 26 Feb 2025.
60. Palt K. flugzeuginfo.net. Available from: https://www.flugzeuginfo.net/. Accessed 26 Feb 2025.
61. Blanco C, Bermejo J, Marsh H, Menendez R. Chemical and physical properties of carbon as related to brake performance. Wear. 1997;1997(213):1–12.
62. Kennedy IM. The health effects of combustion-generated aerosols. Proc Combust Inst. 2007;31(2):2757–70. https://doi.org/10.1016/j.proci.2006.08.116
63. Oberdörster G, Sharp Z, Atudorei V, Elder A, Gelein R, Kreyling W, et al. Translocation of inhaled ultrafine particles to the brain. Inhal Toxicol. 2004;16(6–7):437–45. https://doi.org/10.1080/08958370490439597
64. ICAO. Emerging and cross-cutting aviation issues—sustainable aviation fuels. Available from: https://www.icao.int/annual-report-2021/Pages/emerging-and-cross-cutting-aviation-issues-sustainable-aviation-fuels.aspx
65. Zhang W, Li Y, Li H, Liu S, Zhang J, Kong Y. Systematic review of life cycle assessments on carbon emissions in the transportation system. Environ Impact Assess Rev. 2024;109:107618. https://doi.org/10.1016/j.eiar.2024.107618

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