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Comparative Cradle-to-Grave Carbon Footprint of a CFRP-Grid Reinforced Concrete Façade Panel

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Abstract: Due to climate change and current efforts to reduce emissions in the construction sector, this study evaluates and discusses the results of a comparative cradle-to-grave Life Cycle Assessment (LCA), with a main focus on Global Warming Potential for functionally equivalent carbon-reinforced concrete (CRC) and steel-reinforced concrete (SRC) façade panels for the first time. The novelty of this study is the focus on construction waste and, in particular, the worst-case application of non-recycled construction waste. The use of CRC requires a lower concrete thickness than SRC because the carbon fiber reinforcement does not corrode, in contrast to steel reinforcement. Façade panels of the same geometrical dimensions and structural performance were defined as functional units (FU). Assuming an End-of-Life (EoL) scenario of 50% landfill and 50% recycling, the Global Warming Potential (GWP, given in CO_2 equivalent (CO_2e)) of the CRC façade (411–496 kg CO_2e) is shown to perform better than or equal to the SRC façade (492 kg CO_2e). Changing the assumption of CRC to a worst-case scenario, going fully to landfill and not being recycled (single life cycle), turns the GWP results in favor of the SRC façade. Assuming a 50-year service life for the SRC façade panel and relativizing the emissions to the years, the more durable CRC façade performs much better. Finally, depending on the system boundary, the assumed EoL and lifetime, CRC can represent a lower-emission alternative to a functionally equivalent component made of SRC. The most important and "novel" result in this study, which also leads to future research opportunities, is that delicate adjustments (especially concerning EoL scenarios and expected service life) can lead to completely different recommendations for decision-makers. Only by combining the knowledge of LCA experts, structural engineers, and builders optimal decisions can be made regarding sustainable materials and building components.

Keywords: CFRP; end-of-life; life cycle assessment; reinforced concrete; steel; system boundary

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1. Introduction

The construction sector is one of the largest consumers of material resources and generators of waste and pollutant emissions [1–6]. Concrete is the second most used material in the world after water [7]. In addition to gravel, sand, and water, cement as a binder is of central importance for concrete production. The production of cement in Germany causes an average Global Warming Potential (GWP) of about 587 kg of CO_2 equivalent (CO_2e) per ton [8], and the global cement consumption was approximately 4.6 billion tons with an expected uptrend [9]. One way to reduce these concrete and cement quantities and their respective emissions is to replace steel reinforcement with non-metallic reinforcements such as carbon fiber reinforced polymer (CFRP) reinforcement. Since carbon fibers do not corrode, unlike steel reinforcement, or degrade even under sustained loading and alkaline attack [10], concrete reinforced with CFRP requires only a minimum of concrete cover to ensure the bond between matrix and reinforcement [11].

Depending on the application, CFRP-reinforced components (often shortened to carbon-reinforced concrete (CRC)) can save concrete, while maintaining the same load-bearing capacity as an equivalent steel-reinforced concrete (SRC) component when fundamentally adapted construction and detailing strategies are utilized [12–14]. Simply replacing steel does not exploit the full potential of mass reduction [15]. Additionally, non-metallic reinforcements enable completely new reinforcement layouts, and, even more important, additional protective covers typically arranged on exterior applications, such as bridges, are not required anymore [16,17]. Most important, the expected life span of constructions reinforced with CFRP increases while maintenance costs are largely reduced [18].

To be able to evaluate the environmental performance of the Carbon Reinforced Concrete innovation in addition to cost reductions and the assumption of extended lifetimes, we make use of Life Cycle Assessments. The Life Cycle Assessment (LCA) has been recognized as a relevant and nowadays well-known method to measure the environmental performance of materials and products standardized by ISO 14040/44 [19,20]. LCA enables the assessment of the environmental performance of products and materials [4,6,19–21].

The objective of this paper is to present cradle-to-grave/-cradle LCAs of CRC façade panel scenarios and a direct comparison to a functionally equivalent SRC façade panel, assuming a single life cycle (assumption of worst-case scenarios) with no or very little reuse/recycling. The novelty of this study is the focus on construction waste and, in particular, the worst-case application of non-recycled construction waste (material going into construction waste dumping/landfill) and the consideration of different lifetimes and, thus, the durability of the façades. We consider the emissions caused by material and process steps over the different life stages and lifetimes, and question which of the two façade panels is the more environmentally sustainable alternative over the entire life cycle (including different assumed lifetimes). CRC is partly named sustainable because a striking material saving might be achieved when exploiting the non-corroding nature of the reinforcement. However, in previous cradle-to-gate LCAs on other building components [22,23], the generalized statement of CRC being sustainable does not hold true compared to SRC. Depending on the assumptions made regarding lifetime End-of-Life (EoL) scenarios, system boundaries defined functional units (FU) (e.g., whether component or material), and the reference components or materials, the statements on the environmental sustainability of carbon-reinforced concrete varied greatly. On the one hand, CRC within the form of innovative building components is more sustainable (lower emissions) than comparable SRC building components. On the other hand, constructing with conservative components and neglecting lifetime is not beneficial for the environmental sustainability of CRC. In particular, with this article and also the preceding works, we want to address colleagues from outside the field of sustainability assessment and LCA, such as civil engineers, architects, or other non-LCA experts, and make them aware of the topic of environmental sustainability, LCA, and its variability. This publication includes a brief state-of-the-art on CRC and LCA, a detailed comparative LCA case study, followed by a discussion and conclusion.

2. State of the Art

2.1. Carbon Reinforced Concrete

CRC is a modern composite building material made of concrete and reinforcement of CFRP grids or bars. By using CRC, less concrete cover is required, especially in exterior applications, than with SRC because the carbon fibers do not corrode, and the polymeric resin required to bond the fibers can be chosen to be equally inert to environmental attacks [24,25]. The resulting savings of cement have great environmental relevance, as 8% of anthropogenic CO_2 emissions are caused by cement production worldwide [26]. Currently, general design principles for construction with non-metallic reinforced concrete are derived from SRC construction. To ensure the bond between reinforcement and concrete matrix, for protection against corrosion and for adequate fire resistance, Eurocode 2 (DIN EN 1992-1-1 (01/2011) [27] and German national annex DIN EN 1992-1-1/NA (04/2013)) [28] set the minimum cover for reinforced concrete to at least 10 mm for interior applications. Additionally, a mandatory allowance of 10 mm for deviations in the construction process has to be arranged. However, this minimum cover increases drastically up to 40 mm for higher exposure classes, such as exposure to chlorides from deicing agents or from seawater or simply due to frequent wet and dry cycles. This results in minimum nominal covers of 50 mm in exposed exterior applications for steel reinforcement.

The raw material for manufacturing carbon fibers is polyacrylonitrile (PAN) from petroleum. PAN, with the aid of solvents, is used to produce PAN fibers, which are wound onto spools. The subsequent conversion to carbon fibers occurs through oxidation, carbonization, possible graphitization, surface treatment, and sizing of the fiber [29]. After the production of carbon fibers, they are bundled into rovings that are further processed in textile machines into fabrics or rods and embedded within a polymeric matrix. This matrix is intended to bind and enclose all the individual carbon fibers so that load transfer between individual fibers is guaranteed. The matrix also increases mechanical resistance and improves further processability. Depending on the necessary stability and flexibility of the reinforcement element, impregnation with epoxy resin (EP) or styrene-butadiene rubber (SBR) for grids or vinyl ester resin or EP for bars is commonly used in the construction industry. CFRP in the form of grids or bars is technically and economically viable for reinforcement in concrete. This type of prefabrication is comparable to steel reinforcement bars and welded meshes [29].

CRC is used in new constructions, such as façades, bridges, parking garage decks, slabs, and modular buildings (Figure 1) [16,30–32]. Nevertheless, it is also used in the reinforcement and repair of existing structural systems [22,33,34]. It can be combined with other innovative materials such as Ultra-High-Performance Concrete (UHPC) or Engineered Cementitious Composites (ECC)/Strain-Hardening Cementitious Composites (SHCC) to further extend its range of applications [35–37].

Figure 1. Examples of CFRP-reinforced large-scale ventilated façade panels. (**left**): SchieferErlebnis Dormettingen, Germany (photo: solidian GmbH); (**right**): façade of new MC Bauchemie factory [38].

CRC requires only the minimum amount of necessary concrete for bonding. The consumption of sand, gravel, cement, and water can be reduced as less concrete needs to be produced [24,25]. For each m^3 of primary concrete produced, about 200 L of additional water is needed; thus, concrete savings lead to water savings as well [39]. Moreover, CRC constructions can be designed more easily and with less primary costs as well as maintenance costs for a service life of about 100 years compared to SRC, which is more often chosen for 40–50 years for high-rise constructions and 50–80 years for bridges [10]. This expanded service life reduces material consumption and resulting emissions, which are mostly emitted during the production phase of concrete but also during maintenance works, such as the replacement of protective covers [25]. In addition to those named positive aspects, approximately 90% of the GWP occurs in the production phase due to raw material provision, transport distances, and manufacturing [40]. In most cases, carbon fibers are made of the non-renewable raw material petroleum [25]. Therefore, it is necessary to find alternative raw materials (primary and/or secondary) that are more environmentally friendly than carbon fibers, e.g., from lignin. To date, no recycling method has been industrially scaled in which the recycled carbon fiber can be re-added to the material cycle of CRC, although research in this field exists [29]. Composites made with recycled carbon fibers tend to have worse mechanical properties [41]. Thus, recycled fibers can only be applied in the field of non-structural composites, e.g., for nonwovens. The waste from the demolition of CRC components can be separated in such a way that the recycling of the carbon reinforcement and the concrete matrix is possible [29].

There are several recycling methods for carbon fibers in which mechanical recycling and pyrolysis have a high potential for industrial application [41,42]. Mechanical recycling for the separation of reinforcement from concrete is established due to its energy efficiency and high production rates and capacities, and pyrolysis is the most technologically advanced method and has convincing economic feasibility in large-scale plants [41,43–45]. None of the studies mentioned have dealt in detail with comparative LCAs of façade panels over different lifetimes with different EoL assumptions. Consequently, no previous study shows how variable and partly fragile the final results of an LCA can be, only changeable by supposedly smallest parameters. These are precisely the aspects that we want to highlight in this study. Especially for non-LCA experts, this study emphasizes that environmental sustainability should always be considered when assessing building materials and components.

2.2. Life Cycle Assessment

LCA considers and evaluates energy and material flows (as inputs) and associated waste flows and emissions (as outputs). LCA is considered a recognized and robust assessment tool with a high depth of application in diverse sectors [19,20]. Among the assessment methodologies within the Life Cycle Sustainability Assessment, which includes three pillars: economic, social, and environmental, LCA is considered the most developed methodology [46]. The origins of LCA date back to the 1970s, yet it was not until the 2000s that the basic ISO standards were developed: the ISO 14040/14044, which today include the four basic and mandatory steps of LCA [19,20].

In the first step, the definition of the objective and scope of the study, all assumptions for the LCA case study are made [19,20].

Assumptions and data definition are essential for the second and arguably most important phase of LCA: the Life Cycle Inventory (LCI). All input and output flows of energy and materials are recorded, listed in detail in mass or volume, and then linked to data sets from databases and software solutions to accelerate and simplify the modeling itself. LCI data can be obtained from the literature, internal data, or official and commercial databases [19,20].

A detailed and comprehensive LCI and a well-reasoned and appropriate selection of software and datasets enable a traceable Life Cycle Impact Assessment (LCIA), the third phase of LCA, and the outcome part of the whole LCA. Within this third phase, there are two mandatory stages: Classification and Characterization [19,20].

In the final fourth phase, the interpretation phase, Sensitivity Analyses can be applied, and a conclusion of the results is performed. Future perspectives are given here, and options for action and optimization are expressed [19,20].

Although LCA has already been standardized in many ways by ISO, this framework offers the user and analyst a high degree of freedom in defining assumptions. This already starts in the first of the four phases with the system boundaries and the choice of the FU. Furthermore, of great relevance is the data reference and, subsequently, the selection of impact categories, methods, software options, and the databases incorporated therein [47]—which can also lead to great challenges—especially in terms of interpretation and decision-making for non-LCA experts. This is the reason why the results of an LCA of two identical products, if prepared independently, are not necessarily comparable. Also, the issue of reference flows and FU is often a "comparison problem." The most important element for the validity of an LCA study is its transparency and the reproducibility of its execution, which can be successfully answered in many parts by detailed information, disclosed inventories and used data sets.

In the construction sector, in addition to the designated ISO standards 14040/44 [19,20], ISO 15686-5 (for cost analysis) [48] and DIN EN 15804 (building life cycle) [49] are known and established.

3. LCA Case Study: Façade Element

While the first applications of CRC date back decades [50], the construction method can still be characterized as new and innovative in Germany, as both reinforcing materials and design strategies are under development. For this reason, it is important that the environmental performance of CRC-based constructions is accurately assessed and communicated. Furthermore, improvement potentials should be identified early on. Therefore, in this study, we provide a case study for a CRC façade panel to evaluate and compare the environmental performance over the entire life cycle and compare it with a functionally equivalent steel reinforced façade panel.

Although some applications of CRC in façade construction have been recorded [51–54] and the first general approvals for components exist [55], this material is not very widespread in the German market. The German association Carbon Concrete Composite (C3) has presented the market trends of products in the carbon and textile construction sector [38]. The statistics show that in addition to individual components made of CFRP only, there are built-in components or complete systems made of CRC. Furthermore, the data show that façade elements are currently the most sought-after prefabricated CRC components on the market [38]. This finding was confirmed by consultation (interview) with construction experts in research and a German fiber grid producer (industry). Based on these premises, in this study, a façade element has been selected and is proposed as FU for CRC-based elements in Germany. Ventilated façade panels protect the structure from the weather, exposing it to severe environmental conditions where a non-corroding reinforcement is beneficial. In addition, the façade panel is used as an element for an individual design of buildings.

The weight reduction achieved with CRC elements, in comparison to SRC elements, leads to a better economy in production and transport and to potential reductions in the environmental impact [24,25,56,57]. CRC gives the possibility of lightweight, thin-walled, and durable façades with sophisticated surfaces. CRC façade elements are primarily used for ventilated curtain walls, although the panels can also be utilized in combination with load-bearing elements and insulation as sandwich façades. In Leipzig (Germany), a façade element with a thickness of 11 cm with house insulation standard was developed as part of the research project "vakutex—vacuum-insulated façade elements made of textile concrete" [58]. An SRC façade would have had to be four times as thick with the same physical properties [59]. CRC façade elements are a new type of material system that, in the future, can reduce raw materials for buildings when combined with insulating materials as a sandwich system [14].

In Germany, initial implementations of CRC façades required project-specific approvals by federal authorities, but meanwhile, general construction approvals were granted so that approved façades could be used further [59]. So far, there are no generally applicable regulations (Codes, Guidelines) for CRC in the German construction industry, but the German committee for steel-reinforced concrete (DAfStb) is currently in the final steps of producing a guideline for non-metallic reinforced concrete [60].

3.1. Goal and Scope

The following assessment aims to illustrate the range of environmental impacts of cradle-to-grave—and partly cradle-to-cradle (including recycling options)—of the defined FU of a CRC façade panel. The system boundaries cradle-to-grave include the production (raw material acquisition, pre-processing, transport to manufacturing site, and manufacturing processes), the use phase [10] of a single life cycle per façade panel (which eliminates the need for replacement), which covers one transport from the manufacturer to the place of use (chapter use phase), and two EoL scenarios (chapter EoL). These system boundaries correspond to modules A1-D of EN 15804 and ISO 14040/44 [19,20,49]. Possible savings in material along the load transfer path (columns, walls, foundations) are not considered in this study as they are highly dependent on various factors, such as building height or total dead load, but the authors are well aware of their potential impact on the overall assessment.

The corresponding environmental performances with a focus on Global Warming Potential (Carbon Footprint) of cradle-to-grave and cradle-to-cradle are determined in the design phase and thus allow early identification of hotspots and optimization approaches. Furthermore, data quality and availability issues can be identified in this study. In addition, this case study will provide further examples of environmental assessment in the construction sector and focus on the relevance of appropriate End-of-Life treatment, component selection for different materials, and their diverse environmental performance. The target audience is primarily civil engineers, architects, and interested non-LCA experts. All information on the LCA is given in a transparent way; thus, modification/optimization of the models is possible for interested parties.

The following models are based on ISO 14040/44 [19,20]. The impact categories used are those of CML2001 (August 2016) [61].

The defined FU is a ventilated CFRP reinforced façade panel with the dimensions 4.0 m · 3.6 m · 40 mm without openings; additional reference flows can be represented in 1 m^3 for concrete and 1 kg for reinforcement (CFRP). The choice of reference flows is justified by simplified comparability with previous studies [22,62,63].

The balances are modeled with primary and secondary data. The dimensions of the panels and their reinforcement layouts were developed in collaboration with the industry; the concrete mixes are from university collaborations at RWTH Aachen University. Regarding the fibers, the literature and database datasets are consulted. The software GaBi ts 10.6 and various databases are used; especially useful were the databases XIV Construction Materials, XV Textile Finishing, XXII Carbon Composites, and Ecoinvent 3.6 (2020.2). The equipment and production of machines used are not considered in the study. However, the energy required for these machines—such as the concrete mixer or the scrim production machine—is included in the balance, based on the primary and literature data. The scenarios assume production in Germany. Further scenarios consider the use of renewable electricity mixes, based on current German data from 2020 [64]. The transport between the raw material (extraction) and use phase is assumed with 250 km (given by the industry); further transport distances are assumed with a general average distance of 100 km each. All transport processes are carried out with trucks powered by diesel.

3.2. Technical Description

The CFRP reinforced panel is cast with regular strength concrete according to DIN EN 206-1 [65], class C50/60 (average compressive strength of 58 N/mm^2). It is produced on a tilting table in a precast concrete plant, with the outer face downwards. The chosen one-layered, biaxial carbon grid is impregnated with EP and has an installation tolerance of +/− 2 mm (Figure 2). Concrete can be cast through the grid when proper spacers are attached to the grid. Alternatively, the first half of the concrete is cast, then the grid is placed, and the second half of the concrete is added. The fiber cross-section of each yarn is 3.62 mm^2 or 95 mm^2/m in each direction, with a yarn spacing of 38 mm per direction. The standard size of a mat is 6 m·2.30 m; thus, an overlap is required in the panel. The tensile strength is more than 2800 N/mm^2, and the modulus of elasticity is more than 230,000 N/mm^2 (both referenced to the fiber area) according to ISO 10406-1:2008 and DIN EN 1990. [66,67] Anchorages with stainless steel diagonal anchors with accompanying compression and suction anchors are planned (Figure 3). Note that such systems are also commercially available for thin ventilated façade panels (e.g., FPA-E-SL30 from Leviat (Halfen) [68]). From structural design assuming standard loads for Germany, a weight of 9.5 kg can be calculated for a representative stainless-steel fastener for a façade panel with the above-mentioned dimensions, including cast-in parts, mounting elements, additional cast-in stainless steel rods as well as suitable transport anchors. The required amount of stainless steel depends on the exact product configuration, the respective national regulations, and the assumed wind load. About 50% of the stainless-steel mass is required for the suction anchors (see Figure 3). The total CFRP reinforcement mass of the façade plate is 8.5 kg. The façade is designed to remain flexurally uncracked in serviceability limit state, as it is common for ventilated concrete façades without further cover (see Figure 4). We decided to consider in detail three different mixes of C50/60 concrete, as well as three different PAN-based fiber variants impregnated with PE. The reason for three C50/60 concretes, as well as three fiber variants, is that there is not one final solution or not one emission for C50/60 or for PAN-PE fibers. Consequently, the objective is to show a range of estimated emissions from carbon- and steel-reinforced façade panels.

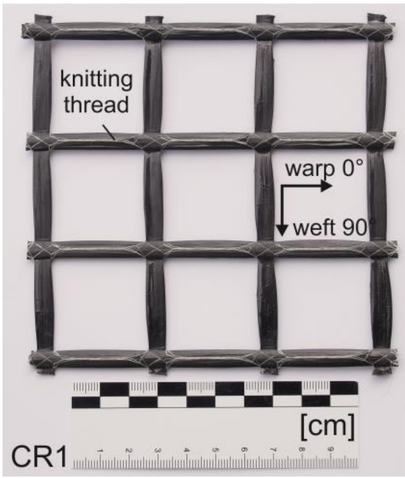


Figure 2. Section of CFRP grid utilized as reinforcement of the panel in the case study. Photo: Jan Bielak [69].

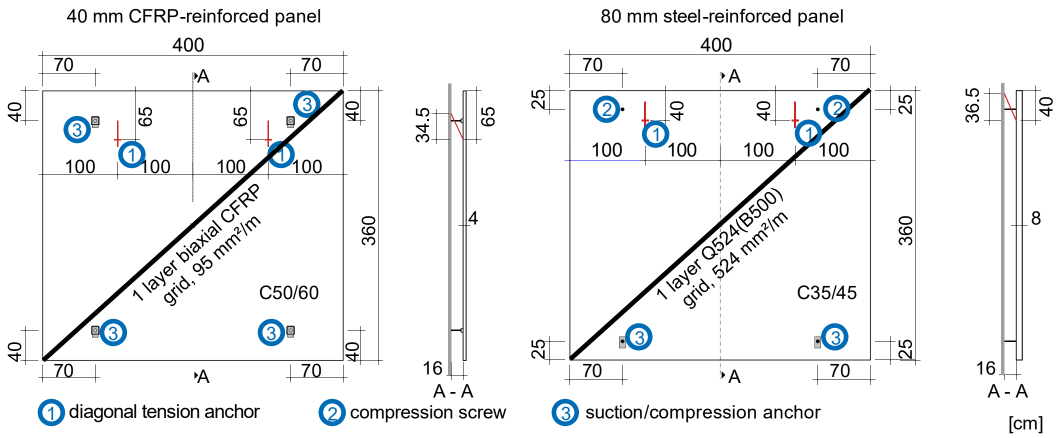


Figure 3. Dimensions of façade panels for the LCA case study and position of fasteners. (**left**): CFRP reinforced panel, (**right**): steel-reinforced reference (graphic: Jan Bielak).

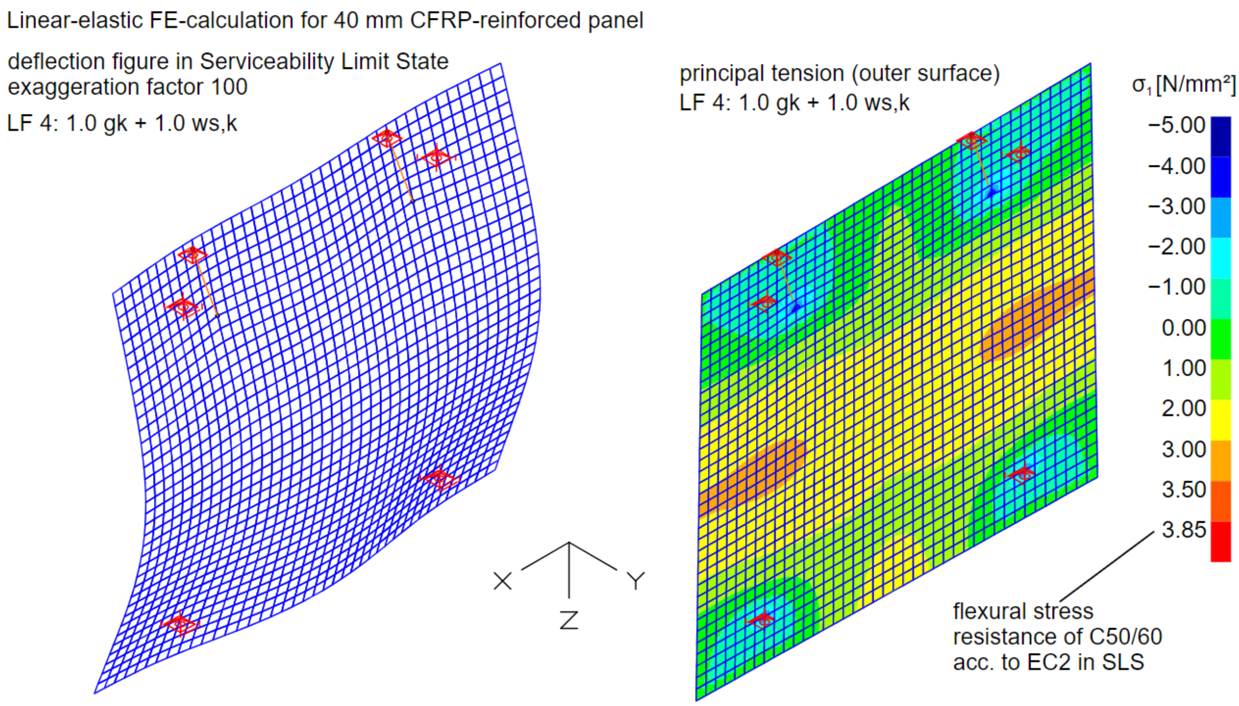


Figure 4. Results of the linear-elastic Finite-Element-calculation for the CFRP-reinforced panel under characteristic wind suction load of 1.08 kN/m^2 and self-weight. The panel remains flexurally uncracked in SLS. (own graphic).

The SRC façade panel with a size of 4.0 m·3.6 m·80 mm has a conventional (uncoated) steel reinforcement grade B500 (one layer of cross-section 5.24 mm^2/m per direction plus edge reinforcement and splices) with a mass of 150 kg. The required amount of reinforcement results from serviceability limit state verification (crack width control). The panel is cast with concrete of strength class C35/45 in the cast-through method on a tilting table in a precast plant. Due to the larger concrete mass compared to the CFRP reinforced panel, the stainless-steel fasteners are larger, resulting in a total mass of 12.7 kg, again including cast-in parts, mounting elements, additional surface-near cast-in stainless steel rods, as well as transport anchors. Note that the higher mass of the steel-reinforced panel is beneficial against wind suction loads.

3.3. Life Cycle Inventory

Conservative approaches were taken in the selection of processes and also in the adoption of data not available as the primary data or clearly defined literature data. Where possible, country-specific data sets, i.e., German data sets (assumption of German production), were used; where this was not possible, European and then global data sets were used. All data generated or analyzed as part of this study are included in this article.

3.3.1. Inventory Carbon Reinforced Concrete

Cradle-to-Gate

Concretes are first modeled and evaluated in the reference flow of 1 m^3. The masses of the three mixes in kg/m^3 vary, as can be seen in the following (Tables 1 and 2). One of the three C50/60 mixes is a GaBi process (DE: Concrete C50/60 (A1–A3)) (Option 3), which means that no inventory in detail is represented as it is a black-box process.

Table 1. Concrete mix modeled—Option 1 (primary data from RWTH research institute).

Material	Unit	Input	GaBi Process
CEM I 42.5	kg/m^3	300	DE: Cement (CEM I 42.5) Portland cement (economically allocated binders)
Gravel 8 mm		1274	DE: Gravel (Grain size 2/32)
Superplasticizer PCE		1.2	DE: Concrete admixtures—plasticizer and superplasticizer—Deutsche bauchemie e.V. (DBC)
Sand 0/2 (dried)		772	DE: Sand (grain size 0/2) dried
Water		105	DE: Tap water from surface water
Truck	km	100	GLO: Truck, euro4, 28–32 t gross weight/22 t payload capacity
Concrete Mixing	kWh/m^3	9.2	DE: Electricity grid mix (2020)

Table 2. Concrete mix modeled—Option 2 (primary data from RWTH research institute).

Material	Unit	Input	GaBi Process
CEM I 52.5	kg/m^3	300	DE: Cement (CEM I 52,5) (burden-free binders)
Gravel 8 mm		1240	DE: Gravel (Grain size 2/32)
Superplasticizer PCE		0.6	DE: Concrete admixtures—plasticizer and superplasticizer—Deutsche bauchemie e.V. (DBC)
Sand 0/2 (dried)		750	DE: Sand (grain size 0/2) dried
Water		126	DE: Tap water from surface water
Truck	km	100	GLO: Truck, euro4, 28–32 t gross weight/22 t payload capacity
Concrete Mixing	kWh/m^3	9.2	DE: Electricity grid mix (2020)

Specifically, for the raw materials cement and sand, the GaBi ts databases offer a variety of cement strength classes (e.g., CEM I 52.5 vs. 42.4 vs. 32.5), particle sizes (e.g., particle size 0/2 vs. 0/4, etc.), and emission allocations (e.g., allocated binders vs. unloaded binders). Before process selection, we evaluated each process and its respective impact. There was little difference in the balances of strength classes and allocation (<5% in kg CO_2e/m^3). For sand, grain size results in larger differences, as does dried or undried sand. In general, the most conservative option (highest GWP emission) was chosen for the selection of the processes. Concrete transports were assumed with an average Germany-wide distance of 100 km (GLO: truck, Euro 4, 28–32 t total weight/22 t payload) for each mix constituent. The energy assumption (concrete mix) of 9.2 kWh/m^3 is based on the literature [70,71]. Since the manufacturing location is Germany, mainly the database and process data refer to a manufacturing process in Germany.

The reference flow for the consideration and evaluation of the fibers was defined as 1 kg. Carbon fibers embedded in a polymeric matrix and carbon fibers for which this step has not yet been modeled are considered (Tables 3–5). The carbon fiber processes were selected based on the databases mentioned and the respective process descriptions. The selection represents carbon fibers that are distinguished by the country of manufacture (Germany), the energy requirement, and the coating (EP):

Table 3. Carbon fibers modeled—Option 1 (secondary data, based on GaBi and the literature [22]).

Material	Unit	Input	GaBi Process
Impregnated yarn (PAN bases, Epoxy Resin)	kg/m^2	0.592	DE: Carbon fiber reinforced plastic part—63—(CFRP. CF: GLO, P: DE)
Truck	km	100	GLO: Truck, euro4, 28–32 t gross weight/22 t payload capacity
Production of carbon grid	kWh	0.05	DE: Electricity grid mix (2020)

Table 4. Carbon fibers modeled—Option 2 (secondary data, based on GaBi and the literature [22]).

Material	Unit	Input	GaBi Process
Impregnated fiber (PAN bases, Epoxy Resin)	kg/m^2	0.592	DE: Carbon fiber reinforced plastic part—65—(CFRP. CF: GLO, P: DE) [optimized energy]
Truck	km	100	GLO: Truck, euro4, 28–32 t gross weight/22 t payload capacity
Production of carbon grid	kWh	0.05	DE: Electricity grid mix (2020)

Table 5. Carbon fibers modeled—Option 3 (secondary data, based on GaBi and the literature [22]).

Material	Unit	Input	GaBi Process
Raw fiber	kg/m^2	0.342	DE: Carbon fiber reinforced plastic part—8
Epoxy resin	kg/m^2	0.218	DE: Epoxy Resin (EP) Mix
Credit blend raw fiber	kg/m^2	0.02	EU-28: Textile Landfill
Truck	km	100	GLO: Truck, euro4, 28–32 t gross weight/22 t payload capacity
Production of carbon grid	kWh	1.05	DE: Electricity grid mix (2020)
Impregnation	kWh	0.44	DE: Electricity grid mix (2020)

For option 1 (Table 3), the fibers are impregnated with EP by pultrusion in a bath according to the respective process description—given by the Fraunhofer dataset (GaBi© dataset). Option 2 (Table 4) differs from the first variant in the energy defined by Fraunhofer to produce carbon fiber-reinforced plastic parts—optimized energy is assumed. The third variant (Table 5) initially represents an uncoated fiber (raw fiber from PAN) (Gabi© database, Fraunhofer data set), which is individually warp-knitted and impregnated. A 5% admixture is assumed (according to [72]), which leads to landfilling and is fed back into the grid as energy. The weight for a 1 m^2 impregnated carbon grid is assumed to be 592 g. For a 1 m^2 carbon grid, the weight is 324 g when uncoated. The impregnation for a 1 m^2 carbon grid is 218 g (primary data given by industry). Raw fibers are impregnated with polymeric matrices, for which the corresponding energy was assumed by Hohmann (2019) [72]: 3.8 MJ/kg (=1.05 kWh/kg). For the self-modeled third option (Table 5), complete production and impregnation was assumed in Germany.

Due to the lack of detailed German primary data on fibers, only GaBi© datasets were considered. The dataset and the selected process for the coated fibers were chosen from the GaBi© database XXII Carbon composites, developed by Fraunhofer IGVC, Germany (Fraunhofer IGVC, 2021). The same assumptions are made for the transport as for the concrete mixtures.

To evaluate the sustainability performance of CRC and to determine a worst-case and a best-case scenario, as well as to define hotspots and optimization approaches, a combination of the presented individual concrete compositions and fiber compositions was used in the scenarios. For this purpose, the reinforcement and the necessary concrete mix have to be transported to the production site and combined. For this purpose, the transport of the grids and concrete to another plant was assumed to average 100 km each (GLO: truck, Euro 4, 28–32 t total weight/22 t payload).

To compare a conventional product of an SRC façade slab, we assumed a functionally equivalent façade. For the modeling, we assumed a C35/45 concrete mix from the GaBi data pool (EU-28: Concrete C35/45 (Ready-mix concrete) (EN15804 A1–A3)). The exemplary steel for the blast furnace (BF) route already has a GWP of 2.2 kg CO_2e/kg steel and is represented by the GaBi process EU-28: Steel forged component (EN15804 A1–A3); one assumed alternative steel (as an example for recycled steel (secondary production) or from the EAF/hydrogen production) we assumed steel with a GWP of 0.9 kg CO_2e/kg product (GaBi process: EU-28: Steel sections (EN15804 A1–A3)); a last assumption is a steel process with a GWP of 0.5 kg CO_2e/kg steel (GaBi process: EU-28: Reinforced steel (wire) (EN15804 A1–A3) [73,74]. These assumptions allowed us to map and compare a theoretical range of emissions from the façades.

The required combination of energy could not be found in the literature, so we used primary data by individual and industrial measurements. Concrete must certainly be compacted, so it was assumed that a formwork vibrator, driven by electricity, is used in this case. This is a common practice for precast concrete. We assumed for both CRC and SRC façade panels a duration of compaction of 5 min. A suitable machine for this purpose is, for example, an external vibrator from Wacker Neuson. Each external vibrator has a power demand of 1.2 kW, and we assumed four vibrators to be needed for our façade panels, equally distributed on the horizontal formwork. Resulting in the equation of $1.2\ \text{kW}\cdot45/60 = 0.4\ \text{kWh}$.

Use-Stage

In the use phase, we only consider the transportation of both façade panels from the manufacturer to the place of use at a distance of about 250 km [8]. Repairing, cleaning, and even the energy required for attachment with the stainless-steel brackets are not considered. Although the thinner CRC panel requires less crane lifting capacity, the difference in energy consumption for the lifting operation was neglected because the energy consumption for the erection and arrival of a mobile crane is similar regardless of its lifting capacity. These assumptions are based on industry data. Note that the thickness of the concrete cover is selected so that the steel reinforcement is adequately protected from corrosion during the assumed service life. One difference in the use phase of the SRC and CRC panels is that we assumed a longer service life for the CRC façade panel than for the SRC façade panel: the CRC panel is expected to fill the wall for 100 years, and the SRC panel for 50 years (or 80 years) [10]. For both façades, only a single life cycle is assumed, which consequently excludes replacements.

End-of-Life

According to two previous publications about the EoL of CRC and SRC [45,75], we provided the following scenarios for the CRC façade panel: The façade is completely unhooked and transported for another average of 100 km to be subsequently crushed in mechanical recycling [45]. The crushed CRC façade panel results in two theoretical scenarios: (1) the panel is not reused in any parts and ends up fully in a construction waste landfill (LF)—which is the important novelty of this study (EU-28: Construction waste dumping (EN15804 C4) Sphera)) [45]—and (2) 50% of concrete is used in road construction (all fiber ends up in landfill; assumed credit for gravel (crushed concrete may function as a substitute for new gravel in an unbonded base layer)). The SRC façade is likewise suspended and transported 100 km. At this point, we are again guided by previous publications (where the process steps can be found in detail) [75] and assume a separation of the two components, steel and concrete. The steel (GLO: a market for reinforcing steel Ecoinvent 3.5) and the stainless-steel hangers of the slab are re-melted and thus returned to the steel cycle. With regards to the concrete, we assume that we can use 50% of the sorted concrete in downcycling for road construction, while the other half, identical to the CRC façade panel, ends up in the landfill in order to present a realistic scenario for the actual construction sector and the End-of-Life treatment. Details and justifications, as well as assumptions made and the background literature on the different EoL options, can be found in two previous publications [45,75]. It should be noted that we use the landfill process from GaBi, valid from 2021 to 2024. All relevant background data, such as energy and auxiliary material, are taken from the GaBi Databases, keeping consistency. The data set represents the country-specific situation in Europe, focusing on the main technologies, the region-specific characteristics, and/or import statistics.

3.4. Life Cycle Impact Assessment and Interpretation

GaBi ts 10.0 was used as a software tool. Especially in the discussion, we focus on the indicator Climate Change/Global Warming Potential (GWP) (in kg CO_2e, GWP100), assessed with the CML methodology. Further, all additional midpoint indicators are provided and shortly discussed. GWP and all other midpoint indicators are calculated with the help of the software according to the CML methodology. The exact calculation of the GWP, for example, would go too far at this point and can be read in detail in the description of the methodologies (LCA Impact Assessment and CML) [19,20,61,76]. In the following, abbreviations are used for simplified graphics and tables. For better understanding, these are shortly explained in Table 6.

Table 6. Fiber and concrete abbreviations and explanations used for the following LCIA.

Abbreviation	Explanation—Related to Life Cycle Inventory
F1C1	fiber impregnated, conventional energy, and CEM I 42.5
F1C2	fiber impregnated, conventional energy, and CEM I 52.5
F1C3	fiber impregnated, conventional energy, and C50/60
F2C1	fiber-impregnated, optimized energy, and CEM I 42.5
F2C2	fiber-impregnated, optimized energy, and CEM I 52.5
F2C3	fiber-impregnated, optimized energy, and C50/60
F3C1	fiber own model and CEM I 42.5
F3C2	fiber own model and CEM I 52.5
F3C3	fiber own model and C50/60
SRC1	steel, blast furnace (2.2 kg CO_2e/kg), and C35/45
SRC2	steel, electric arc furnace (0.9 kg CO_2e/kg), and C35/45
SRC3	Steel, recycling steel/electric arc furnace (0.5 kg CO_2e/kg), and C35/45

The impact categories used (for cradle-to-gate and use phase and EoL = cradle-to-grave) are those of CML2001 (August 2016) (CML—Department of Industrial Ecology, 2016): Abiotic depletion potential (ADP elements [kg Sb eq.], ADP fossil [MJ]), acidification potential (AP [kg SO_2 eq.]), eutrophication potential (EP [kg phosphate eq.]), freshwater aquatic ecotoxicity (FAETP inf. [kg DCB eq.]), global warming potential (GWP [kg CO_2 eq.]), human toxicity potential (HTP inf. [kg DCB eq.]), marine aquatic toxicity (MAETP inf. [kg DCB eq.]), ozone depletion potential (ODP, steady state [kg R11 eq.]), photochemical ozone creation potential (POCP [kg Ethene eq.]), and terrestrial ecotoxicity potential (TETP inf. [kg DCB eq.]).

As announced, we first focus on the CO_2 footprint, considering the scenario of 50% landfill and 50% concrete recycling for CRC; the façade panel, when made of CRC, has a CO_2e range of 411 to 496 kg CO_2e (Table 7 and Figure 5). The EoL accounts for only a fraction of GWP over the entire service life of the façade panel, which can easily be explained by the credit gained from downcycling of concrete balancing the CO_2e required for transport and construction waste dumping. In the case of primary steel (SRC 2.2), which is considered very conservative and has high emissions, the production emissions (cradle-to-gate) are substantially higher, but the large credit gained from steel reuse/recycling at EoL balances the emissions from production. Thus, the SRC 2.2 variant is roughly equal to the worst CRC-panel variant, but about 16% worse than the best CRC variant F2C1. It can therefore be deduced from Figure 5 that the entire life cycle must always be considered and that, in the future, construction waste and, in particular, its processing will be of the greatest relevance for the sector's emissions. The difference in CO_2e credit gained by different types of processing (upcycling, downcycling, reuse) or disposal (landfill, construction waste dumping) at the EoL highly influences the outcome of the LCA.

Table 7. GWP (Climate Change in kg CO_2e) for relevant CRC and SRC combinations in the FU of a façade panel—cradle-to-gate/grave (assessed via LCA in GaBi) (* assuming that 50% of the concrete at EoL is dumped as construction waste and 50% is reused in road construction as filler, replacing gravel; † assuming that 100% of the concrete at EoL is dumped as construction waste).

In kg CO_2e	F1C3 * (Worst)	F2C1 * (Best)	F1C3 † (Worst)	F2C1 † (Best)	SRC 2.2 *
Cradle-to-gate	**467**	**382**	**467**	**382**	**733**
in % of total	94%	93%	88%	86%	149%
Use phase (transport)	**29**	**29**	**29**	**29**	**59**
in % of total	6%	7%	6%	7%	12%
EoL	**0.2**	**0.2**	**31.5**	**31.5**	**−299,9**
in % of total	0%	0%	6%	7%	−61%
Total	**496**	**411**	**527**	**442**	**492**

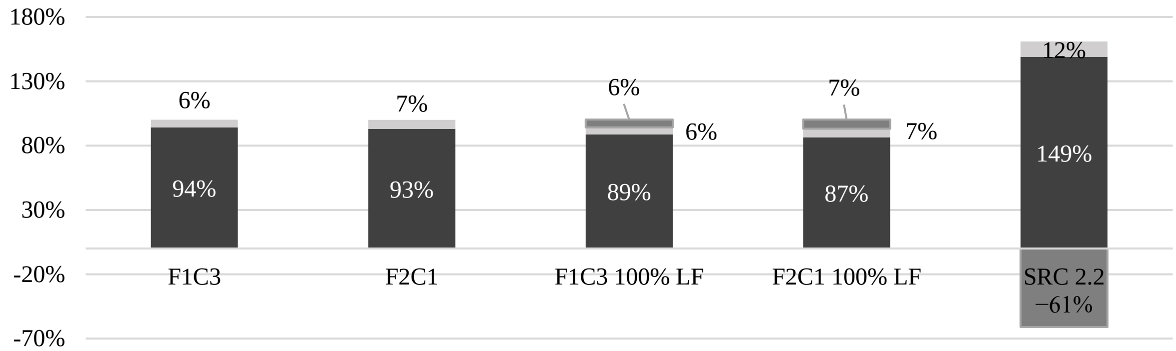


Figure 5. Composition of Life Phases: GWP (Climate Change in kg CO_2e) for best and worst case of FU's CRC panel and one FU SRC panel.

The lowest emissions in terms of GWP are formed by the combination (Table 7: F2C1) of fibers with optimized energy and the CEM I 42.5 concrete (C1). Regarding the fibers, this is not a surprising result, since the production of the PAN fiber is energy intensive and results in high emissions even per kg of fibers produced [22]. Likewise, the results [22] confirm that CEM I 42.5 is more emission friendly compared to a CEM I 52.5, consequently resulting in a lower GWP.

Table 7 shows that the SRC façade significantly exceeds the GWP of the CRC façade. If we assume recycled steel or, for example, primary production in the EAF or in the future with hydrogen, the GWP is significantly lower.

To stay with the comparison between SRC and CRC for now, in all other midpoint categories, the SRC performs more sustainably (with lower emissions) than the functionally equivalent CRC façade. This is independent of the EoL assumption made—consequently, this is the case for 100% landfill and 50/50 landfill and recycling of the CRC façade panel. Only a change in the lifetime assumptions (an assumption that SRC has 50 years of service life) changes the statement in favor of CRC concerning the indicators AP, EP, and HTP.

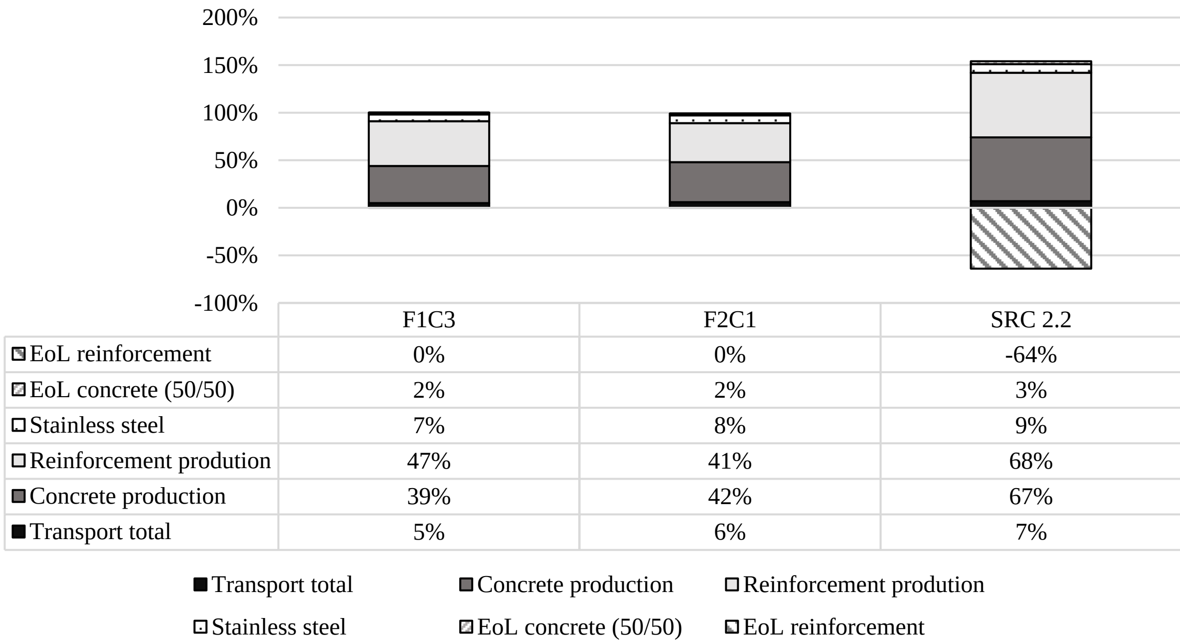
Focusing again solely on the variants of CRC: About the GWP, the F1C3 combination has the highest emissions. This cannot be fully supported in the other midpoint categories. F1C3 represents the highest emissions in ADPe, AP, EP, ODP, POCP, FAETP, and TETP, which represents a large part of the total midpoint indicators. Nevertheless, the F1C2 (CEM I 52.5) combination is also striking concerning the two indicators not yet named: ADPf and MAETP. The situation is equally variable for the lowest emissions for the CRC façades. In GWP, the combination F2C1 is the one with the lowest CO_2 footprint. A clear favorite of a CRC façade combination and thus with the lowest emissions is hard to define, even though F2C2 and F2C3 show equally 'good' emissions.

At this point, it can already be said that CRC in the form of the defined façade panel shows fewer CO_2 emissions than a functionally equivalent SRC façade panel in the best case. Resource savings could have also been shown in other components, whereas emissions could not be reduced as clearly as in the façade example in the source [22].

Focusing in detail on the composition of the production steps—where we now only consider the worst case, the best case of the CRC façades (Table 7: best is F2C1, worst is F1C3), and the SRC façades, for the sake of simplicity—it gets clear that in the case of the CRC façades, the reinforcement production and the concrete itself contribute roughly equal percentages to the GWP (Figure 6). In the case of conventionally produced steel, the concrete has a higher share than the reinforcement in the total GWP; whereas in the case of a theoretical secondary steel/EAF production, the reinforcement only has a share of 6–10% in the total GWP and the concrete is responsible for almost 30% of the GWP. If emissions are to be further optimized, the reinforcement and its recycling must be worked on in CRC façades; in the SRC façade, on the other hand, if secondary steel or newer production methods (EAF; hydrogen) are used, the concrete mix can be optimized significantly more, which would then also benefit the CRC façade. In all cases, the production of the façade itself (compaction) is not relevant for the emissions, nor does the stainless steel or the transport have a significant impact (<10% of the total GWP). Optimizations at these points are, therefore, limited. Again, it is important to note that the concrete should ideally be 100% recycled/reused, otherwise, the emissions from landfill and non-use of construction waste alone will be dramatically high.

For the SRC façade, the EoL provides a credit of 61% of the total GWP. If we were to make different EoL assumptions for the CRC façade at this point, for example, by considering that mechanical separation of reinforcement and concrete is easily feasible, as shown earlier [45,75,77], emissions could be further reduced. However, the chosen scenarios here are the current state of the art, which is why only this form is presented. Furthermore, these scenarios show that research must continue to work on the EoL and the resulting EoL-options for CRC (no credit possible, as fibers are not assumed to be reused (only landfill)). Clearly, the technological advances in the next 100 years to come will provide better means for recycling CRC and CFRP in general.

Focusing on the lifetimes of the two façades (assuming the five principal scenarios), the SRC façade has a regular lifetime of about 50 years, which can be extended to 80 years, while the CRC façade is typically designed to have a lifetime of about 100 years. If this difference in the lifetime is included in the emission evaluation and the emissions are relativized to 50 (or 80) (SRC) and 100 (CRC) years, the same picture of the final statements about the "environmental performance" of the analyzed façade panels continues to emerge (Table 8): CRC represents the lower-emission alternative in the form of a façade panel with the system limits cradle-to-grave, for both assumptions on concrete recycling (Table 8: green/yellow vs. red cells).



	F1C3	F2C1	SRC 2.2
EoL reinforcement	0%	0%	-64%
EoL concrete (50/50)	2%	2%	3%
Stainless steel	7%	8%	9%
Reinforcement prodution	47%	41%	68%
Concrete production	39%	42%	67%
Transport total	5%	6%	7%

Figure 6. CML2001: GWP in % of total kg CO_2e per façade panel (concrete and reinforcement) (assessed via LCA in GaBi).

Table 8. EoL Scenario: GWP for CRC and SRC combinations in the FU of a façade panel—cradle-to-grave per expected lifetime (CRC: 100 years, SRC: 50/80 years); red = highest emissions, yellow = medium emissions, green = lowest emissions (assessed via LCA in GaBi).

	EoL-Scenario for Both Façade Panels			
	GWP in kg CO_2e/ Façade Panel/Lifetime	Assumed Lifetime in Years	GWP in kg CO_2e/ Façade Panel/Lifetime	Assumed Lifetime in Years
F1C3	4.96	100	4.96	100
F1C3 100% LF	5.27		5.27	
F2C1	4.11	100	4.11	100
F2C1 100% LF	4.42		4.42	
SRC1 (2.2)	9.84	50	6.15	80

Consequently, the lifetime, in addition to the assumed system boundaries (e.g., cradle-to-gate vs. cradle-to-grave) and the assumed EoL-scenario, also plays a crucial role in the environmental performance of functionally equivalent façade panels made of CRC and SRC. This insight into the variability of assumptions and the resulting variability of results is an important statement that this publication aims to highlight. Therefore, engineers, decision-makers, LCA experts, and implementers alike must be extremely cautious when making sweeping and hasty statements concerning sustainability.

4. Discussion and Limitations

A detailed LCA study (cradle-to-grave) on a façade panel made of carbon or steel-reinforced concrete with different concrete mixes, fibers, impregnations, and steel variants was carried out, related to the FU of a façade panel of size 4000·3600 mm with a thickness of 40 mm or 80 mm for CRC and SRC, respectively. A reproducible inventory is available, allowing global optimization and post-modeling. The disadvantage of this method, the LCA, is that it can be implemented primarily with the help of purchasable software and database solutions in a reasonable time frame. If financial resources are lacking or if value is placed on an independent and proprietary data basis, the methodology can only be implemented with the greatest effort.

The current study is limited by the combination of primary and secondary data use (e.g., concrete (primary data) vs. fibers (secondary data)). We focused only on assumptions for the EoL of both façades, considering the actual available and best techniques, further assuming different lifetimes for CRC and SRC. If complete primary data were available, as well as an open-source software solution and complete database, some of the limitations could be removed. In the future, the actual service life and the actual handling at the EoL of CRC will also have to be considered, which may look different in reality than is currently assumed by small research projects.

Especially fiber production has a high impact on emissions, and partly also concrete might get optimized according to GWP/Climate Change. Fibers and their coatings need to become of particular future relevance, and innovations such as increased incorporation of calcinated clay (Urban and deutschlandfunk.de, 2020) as a binder into concrete may be of additional interest. In this study, only the PAN (polyacrylonitrile) fiber base was investigated; materials such as a PE (polyethylene) base or even glass fibers or lignin as reinforcement were not considered. Other machinery, such as a crane for hanging or attaching the façades, was also not included. Future studies should be conducted using data from different companies to have a better picture of the inputs and technologies used and provide even more variation.

As extremely relevant, especially for the audience of non-LCA experts (e.g., civil engineers), we consider in the context of our study the evaluation regarding differently defined system boundaries (cradle-to-gate vs. cradle-to-grave), as well as the assumptions regarding different lifetimes for the CRC and SRC façades and the assumed EoL scenarios (important difference in key message depending on landfill or recycling). It is clear that the choice of design lifespan (by the client, the designer, or, as is usual, by building regulations) of a component might also affect the choice of concrete cover (and thus thickness), as well as the type of concrete and reinforcement used. Although not considered in this study, variations in the definition of the boundary of the FU will further affect and complicate the analysis. As an example, the comparative assessment of wide-spanning lightweight structural members made of high-performance materials (e.g., [78,79]) to conventional heavy building elements made of normal-strength materials [80] might yield a better LCA result of the conventional members regarding a FU of one square meter surface area. However, by choosing the whole building as FU, it might turn out that the use of lightweight members made of high-performance materials is the more favorable solution, as their reduced total weight allows for minimizing the dimensions and embodied materials of supporting structural elements (columns, walls, foundations) [81]. These possible savings in material along the load transfer path are not considered in this study, but are likely to lead to important additional savings.

Elements with low mass, such as the stainless-steel fasteners or the CFRP reinforcement, have a relevant influence on the result of an LCA. Such adjustments can result in completely different recommendations for the decision maker, which, if no LCA expert is present at these decisions, should be considered critical. Similarly, the LCA expert seldom knows alone about the design lives and the resulting regulations for design, for example, when it comes to partial safety factors, concrete covers to prevent carbonation and thus reinforcement corrosion, or the depth of weathering for concrete. Only by combining the knowledge of LCA experts, structural engineers, and builders can an optimal decision be made.

5. Summary and Conclusions

The aim of this study was to evaluate and discuss the results of a comparative cradle-to-grave LCA for functionally equivalent CRC and SRC façade panels. In the context of cradle-to-gate, the CRC façade is shown to perform significantly better than the equivalent SRC façade. To further reduce CRC façade emissions in production, PAN fibers would need to be considered in detail and optimized. The fibers account for over 40% of GWP (cradle-to-gate). Yet, optimization of the concrete should not be ignored—insights that could also be used for the SRC façade. Extending the system boundaries to the full life cycle is highly dependent on the EoL assumption. Changing the assumption of CRC going fully to landfill and not being recycled influences the GWP results only marginally. Assuming for both façades a recycling option, in the best case, the CRC façade results in less CO2e than the functionally equivalent SRC façade, yet the worst case results roughly in equal CO2e. Similarly, consider the lifetimes of the façades: if we assume 50 or 80 years as the lifetime for the SRC façade panel and relativize the emissions to the years, the CRC façade performs better in emissions per year with an assumed 100 years lifetime.

Regarding carbon storage and delayed emissions, an optimization can be achieved in future studies, since credits associated with temporary (carbon) storage or delayed emissions are not considered in the calculation of the Global Warming Potential impacts for the default impact categories. It can therefore be assumed that CO2 can be absorbed in the EoL and the use phase, but this was not taken into account in this study due to a lack of data.

With the help of this study, we would like to draw attention to "small" adjusting screws and their large leverage effect concerning decisions. The results lead to new findings and, thus, to completely different recommendations. Depending on the system boundary, the EoL assumptions and lifetime, CRC can represent a lower-emission alternative to a functionally equivalent component made of SRC. Nevertheless, the results and especially the implementations of an LCA have to be considered in detail, especially for non-LCA experts. In the future, interdisciplinary collaborations will be essential to make the building sector truly sustainable and free of vague assumptions. We will also need to look at the service life, EoL, and LCA software and database challenges.

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Abbreviations

C	Concrete
CFRP	Carbon Fiber Reinforced Polymer
CO_2e	Carbon Dioxide Equivalent
CRC	Carbon Reinforced Concrete
EoL	End-of-Life
EP	Epoxy Resin
FU	Functional Unit
F	Fiber
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
PAN	Polyacrylonitrile
PE	Polyethylene
SBR	Styrene-Butadiene Rubber
SRC	Steel Reinforced Concrete
UHPC	Ultra-High-Performance Concrete

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