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Sustainability of alternative reinforcement for concrete structures: Life cycle assessment of basalt FRP bars

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ABSTRACT

Due to the global climate emergency as a result of anthropogenic activities, an accelerated progress towards sustainable thinking is needed. The construction industry, as one of the contributors to the global emissions, must re-examine the construction materials, procedures and technologies which are traditionally used. To reach an informed design decision with regards to sustainability, the engineering community would benefit from independent and objective studies of the environmental impact of materials and systems. Crucially, decarbonising concrete structures should emerge as a priority, due to the wide availability and utilisation of the material. Although the fibre reinforced polymers have caused an interest of the construction industry due to their favourable mechanical properties, Life Cycle Assessment (LCA) studies of alternative reinforcing options are very limited to date.

This paper presents an evaluation of the environmental impact of BFRP reinforcing bars. Using an LCA approach, the conducted study aims to examine the potential of utilising BFRP for creating more sustainable reinforced concrete structures. It includes a contribution analysis of the production of BFRP bars, as well as comparison with steel, glass FRP, galvanised steel and stainless-steel bars. Additionally, a comparison of BFRP and steel reinforced beams is offered, supported by the results of experimental flexural testing. The findings of the study demonstrate that BFRP bars can contribute to large reduction of embodied emissions of reinforced concrete elements in comparison with steel, and other reinforcing materials.

1. Background

Climate change and biodiversity loss are highlighted as some of the greatest challenges of modern age, with a strong scientific consensus on the anthropogenic influence on the global warming. Significant events have marked the 1990 s with the scientific community issuing a World Scientists' Warning to Humanity (1992), the 1992 United Nations Framework Convention on Climate Change (UNFCCC), which was one of the first international treaties tackling climate change. The latter was followed by the 1997 Kyoto Protocol and subsequent Paris Agreement of 2015, negotiated at the United Nations Climate Change Conference (COP21).

While the scientific community has been calling for an urgent and drastic action, the parties to the Paris Agreement have promised to reduce their emissions to keep the global warming below 2°C, compared to pre-industrial levels. Even if the targets of the Paris Agreement were met, the climate scenarios are not optimistic (Fig. 1).

Following the initial declaration made in Darebin, Australia in 2016, other cities, counties and states have joined in acknowledging the climate change as a global issue, including the UK, some states in USA, as well as the EU. The majority of declarations were made between end of 2018 and mid-2020, to cover a population of over a billion people. As of November 2021, a climate emergency has been declared by local governing bodies in 37 countries worldwide, according to Climate Emergency Declaration and Mobilisation in Action (CEDAMIA).

In August 2021, the first contribution to the 6th assessment report (AR6) has been issued by UN's Intergovernmental Panel on Climate Change (IPCC.) The scientific report on climate change presents the first major review since 2013, published 3 months before COP26. Some of the key points of the report include [9]:

- "It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred". This statement

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underlines the anthropogenic factor as an undeniable influence on global warming, as illustrated by Fig. 2.
- Some of the damage to the hydrosphere and cryosphere is irreversible.
- Frequency of the extreme weather events (e.g., heatwaves, tropical cyclones, draughts) has increased since 1950 s, and especially in the last decades.
- We must achieve carbon neutrality as the minimum. Estimated carbon budget as of the beginning of 2020 for achieving the 2.0℃ target ranges from 900 $GtCO_2$ to 2300 $GtCO_2$, depending on the likelihood (17% and 83% respectively).

While only a few out of many conclusions presented in the full report are listed above, they are certainly sufficient to stress the urgent need for adopting low-carbon technologies. The scientific consensus strongly underlines the importance of the human activities on global warming.

COP26, held in Glasgow in November 2021, was highly anticipated as a first important 5-year post-Paris milestone global summit, in which the parties were expected to revisit their targets. The outcome of the convention was the Glasgow Climate Pact, which outlines the global strategy for mitigating the impact of climate change. The parties agreed to revisit their targets the following year, reiterating that the current pledges would not suffice to limit the global warming to an acceptable level.

1.1. Role of the construction industry

As one of the major industries, contributing 6% of UK's GDP in 2019 [13] and 24.7% of global GDP [24], the construction industry's role in the path to net-zero carbon future is proportionally large. Notable institutions and companies have accepted the responsibility of structural and civil engineers, and made commitments to encourage, facilitate and incorporate sustainable design and technologies. To this end, much guidance has been made available to engineers to enable sustainable choices and develop sustainable thinking, such as the "How to calculate embodied carbon" guidance document [6]. Likewise, the scientific community offers analyses of suitable methodologies for life cycle assessment, comparative studies of different systems etc. Numerous studies have looked into the various opportunities for reduction of the environmental impact of concrete, either via recycling [27,10]or alternative binders, such as alkali-activated concrete [18].

However, within the area of FRP reinforcement for concrete structures, a somewhat limited number of sustainability-focused studies has been published to date. Lee and Jain [12] discussed the potential of FRPs as a sustainable material, underlining main drawbacks, such as the unavailability of field-data, in particular with regards to durability, and areas for improvement, such as the improvement of the material and energy efficiency of the manufacturing process, or sustainable end-of-life pathways. The recyclability of FRPs was then examined in detail in a review by Oliveux, Dandy and Leeke [14], who also pointed out the need for the further development of innovative technologies which would enable recycling of composites within a commercially viable scale.

Furthermore, even fewer LCA studies of FRP within a structural element have been published to date. Inman, Thorhallsson and Azrague [8] conducted an assessment of BFRP and steel reinforced beams, concluding that utilising BFRP reinforcement could reduce the embodied emissions by a half. However, in their study the analysis was done for a number of beams with different dimensions and varying structural performance, therefore forming a conclusion taking into account functional equivalence is somewhat difficult. More recently, Stoiber, Hammerl and Kromoser [19] published an LCA of CFRP reinforcement, which indicated the relatively high impact of CFRP in comparison with steel reinforcement. Nonetheless, a further assessment which analysed the use of CFRP within a pedestrian bridge application, showed that CFRP reinforced elements may have a lower impact than steel reinforced ones, due to the reduced self-weight.

Expanding the literature in the field of LCA of construction materials, structural elements and systems, as well as making it accessible to engineers worldwide would provide a helpful resource for the construction industry on which to base sustainability-driven decisions. As a contribution to this base of knowledge, a study of the environmental impact of BFRP bars, as well as a comparative assessment of a select number of concrete reinforcing materials is presented in this paper.

1.2. Life cycle assessment

Life cycle assessment (LCA) is a standardised method for measuring and comparing the environmental impacts associated with the manufacture, use and disposal of a product. It is a useful technique to advance the understanding of impacts, decision making, product improvement via hot-spot identification and marketing.

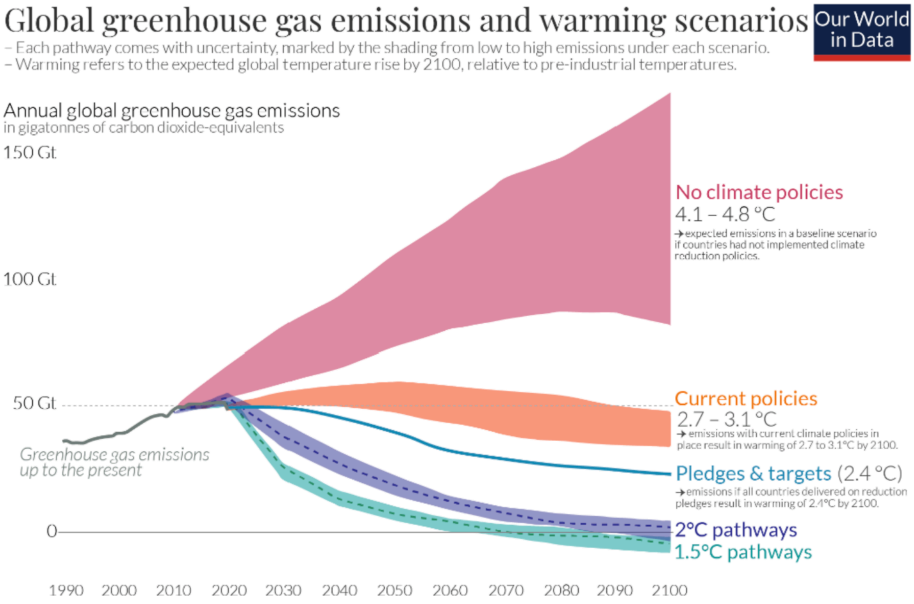

Fig. 1. Global greenhouse gas emission scenarios. Ritchie and Roser [17].

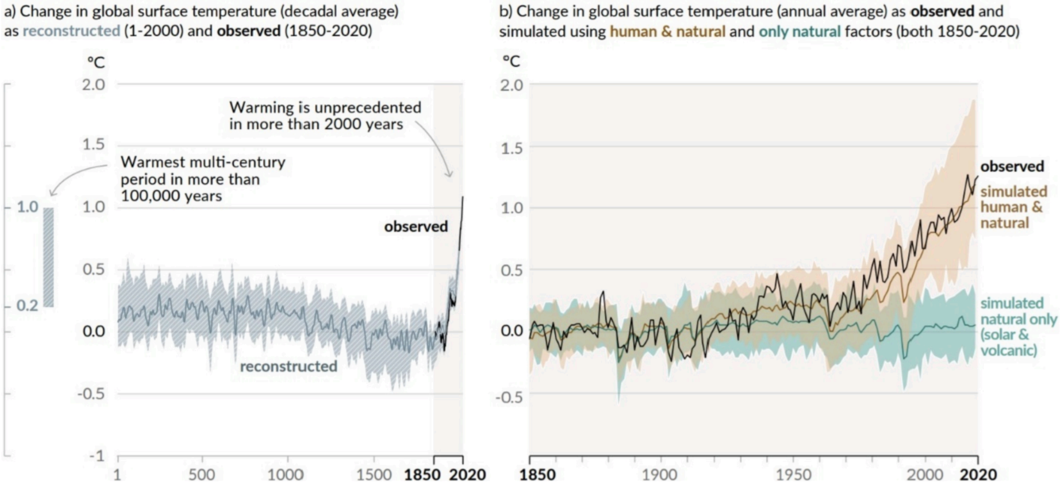

Fig. 2. Change in global surface temperature over years. From IPCC [9].

ISO14040 [23] defines LCA as the process of "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". The framework for an LCA consists of four inter-related stages: goal and scope definition, inventory analysis, impact assessment and interpretation as shown in Fig. 3. Iterative interpretation is conducted at each stage of the LCA.

The LCA considers the whole life cycle of the product to be studied, also commonly called the cradle-to-grave assessment. It encompasses all the processes in a product's life, from supply of raw materials, through production and assembly, packing and distribution, product installation and use, to final disposal or recycling at the end of its life.

At all stages of the life cycle, natural resources (e.g. natural gas, water) are consumed and emissions to air, water and soil are released into the environment. For any studied product, these consumptions (inputs) and emissions (outputs) are quantified for each life cycle stage. The compiled inputs and outputs are then related to the environmental impacts such as climate change or acidification using scientifically-derived methods. The result is a quantified potential environmental impact of the studied product.

However, it is important to keep in mind that the results of LCA should not be viewed as absolute and precise measure of environmental impact. This is due to inherent characteristics of the LCA process which includes choices regarding the definition of the functional unit and system boundaries, data uncertainty and others.

Although it is covered by relevant standards, the methodology of LCA is not fully standardised and various approaches are possible and should be selected based on the goal of each individual study. There are two main types of LCA- consequential and attributional. According to Ekvall [5] these can be defined as follows:

- Attributional LCA: LCA aiming to describe the environmentally relevant physical flows to and from a life cycle and its subsystems. It corresponds to the goal of assessing how much of the global impacts belong to the product.
- Consequential LCA: LCA aiming to describe how environmentally relevant flows will change in response to possible decisions. Its goal is to assess the influence of the product on the global environmental impact.

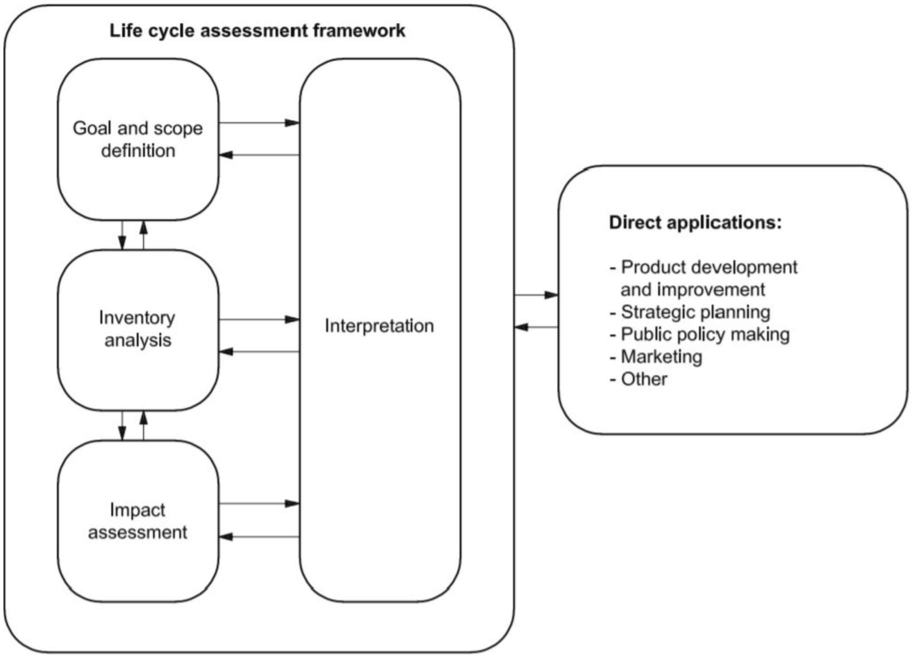

Fig. 3. Stages of a Life Cycle Assessment (ISO 14040).

2. Methodology

2.1. Tools and assumptions

The attributional approach was followed in this study. The choice of the approach was mainly based on the study aim: to quantify the emissions of the system in question without intending to consider indirect effects. The adopted system model for LCA is Allocation at the Point of Substitution (APOS), in which environmental burdens are attributed proportionally to specific processes.

The software SimaPro, version 9.1.1 developed by PRé Consultants in the Netherlands, was used to model the systems and calculate the environmental impacts of all the scenarios studied. The integrated life cycle inventory (LCI) database ecoinvent version 3.6 [26] was mainly used for sourcing of the LCI data. The database is published by non-for-profit organisation and contains a large number of datasets from various sectors, with full traceability and transparency of processes. In case a process was unavailable in the ecoinvent database, a custom process was created using SimaPro. The priority with regards to the geographical (spatial) boundary of the data was as follows:

- Country-specific data was chosen whenever the specific location of the process was known and available, e.g. Russian (RU) market for the production of BFRP.
- European (RER) average market data was used as the second-best option.
- Global (RoW/GLO) data was used only as a proxy in case that the other two options were unavailable.

Some of the fundamental principles of correct LCA practice are replicability, integrity and transparency of the data, methods and assumptions applied. Both the selected software and the LCI database follow the transparency principle, with traceability of all unit processes and corresponding links in system models. Additionally, in this study, particular effort has been made to provide sufficient detail regarding the specifics of the methodology used and, thus, enable the replicability of the study.

The system boundaries and the functional unit were defined on individual case basis, taking into account the equivalent function of the entity, as detailed in later section of the paper. Whilst drawing out the systems boundary, two important points were considered:

- The LCA study was intended to provide a comparative analysis of several options. Hence, some factors that remained the same across the different cases were kept outside the scope of study to simplify the analysis. These were explicitly declared.
- The independent, unbiased value judgement of the LCA expert is very crucial while defining the system boundary, as the results could vary significantly based on the definition.

The calculation methodology used for this study was ReCiPe 2016 Midpoint Hierarchist (H), developed by PRé Sustainability, Radboud University Nijmegen, Leiden University and the Dutch National Institute for Public Health and the Environment (RIVM). The information about the methodology can be found in the Huijbregts et al. [7] report: A harmonized life cycle impact assessment method at midpoint and endpoint level. The Hierarchist value choice perspective was selected, as it is considered the consensus scientific model. The 18 midpoint categories considered in this assessment were: Global Warming Potential (GWP), Stratospheric Ozone Depletion (SOD), Ionising Radiation (IR), Ozone Formation Human Health (OFHH), Fine Particulate Matter Formation (FPMF), Ozone Formation Terrestrial Ecosystems (OFTE), Terrestrial Acidification (TA), Freshwater Eutrophication (FEu), Marine Eutrophication (MEu), Terrestrial Ecotoxicity (TEc), Freshwater Ecotoxicity (FEc), Marine Ecotoxicity (MEc), Human Carcinogenic Toxicity (HCT), Human Non-Carcinogenic Toxicity (HNCT), Land Use (LU), Mineral Resource Scarcity (MRS), Fossil Resource Scarcity (FRS) and Water Consumption (WCon).

2.2. LCA: Goal and scope

The goal of this LCA study is to analyse the environmental impact of BFRP in comparison with different reinforcing bars options, with a particular focus on corrosion resistant materials. The results could be useful to design engineers with regards to making an informed decision from the sustainability point of view, which is becoming an increasingly important design criterion. Additionally, the study is offered to the researchers in the area of composites for construction application to refine, improve and build upon the hereby presented analysis either by primary data collection or other appropriate means.

In this paper, the following life cycle assessment studies are presented:

- Cradle-to-Gate LCA contribution analysis of BFRP reinforcing bars aimed at identifying “hotspots” in the supply chain of BFRP manufacture. The analysis included a network diagram, as well as sensitivity studies. The parameters examined in the sensitivity studies were energy use during the continuous basalt fibre (CBF) production and fibre content. The declared unit was “1 m long BFRP bar with 10 mm diameter for concrete reinforcement application”.
- Comparative Cradle-to-Gate LCA of steel and BFRP reinforcing bars. The declared unit was “1m long reinforcing bar with 10 mm diameter for RC application”. The impact of the variation of the recycled content of steel was also analysed.
- Comparative Cradle-to-Gate LCA of corrosion resistant reinforcing bars. The comparison was made between the following materials: stainless steel, galvanised steel, GFRP and BFRP. The declared unit was “1 m long corrosion resistant reinforcing bar with 10 mm diameter for RC concrete application”.
- Comparative Cradle-to-Site LCA of reinforced concrete beams (steel or BFRP reinforced). The functional equivalence was determined based on the results of the experimental testing of beams with the same dimensions and span. The main criterion for structurally equivalent performance was the load-bearing capacity at the serviceability limit state (SLS) deflection limit of span/250 [4], as the governing criterion for BFRP reinforced elements. The functional unit was therefore defined as “Reinforced concrete beam spanning 1.7 m, with load bearing capacity of minimum of 21 kN at the SLS deflection limit of span/250”. Further details on the dimensions, reinforcement and the structural performance of the beams used in this analysis are given in a later section.

The system boundary, as shown in Fig. 4, includes all material extraction, transport and processing, and associated energy consumption to gate in case of reinforcing bars, or to the construction site in the case of RC beams. The system boundary for the LCA of reinforcing bars corresponds to product stage (Modules A1-A3), and the system boundary for the LCA of RC beams includes the product and construction stages (Modules A1-A5) as outlined by the BS EN 15978:2011 [3] standard (Fig. 5).

The use stage (Modules B1-B5) was left outside of the scope of this study as the impact during the use stage for RC beams was negligible and due to the lack of information about the maintenance schedule of BFRP reinforced elements. It is expected that their durability will be improved in comparison with steel reinforced elements, due to corrosion resistance.

There are several possible end-of-life (EoL) pathways for composite materials, as shown in (Fig. 6). Therefore, assuming a scenario for Module C and D would introduce a high level of uncertainty into the analysis. Since there is no field information available about RC structures reinforced with BFRP, the EoL stage was also left outside the scope of the study.

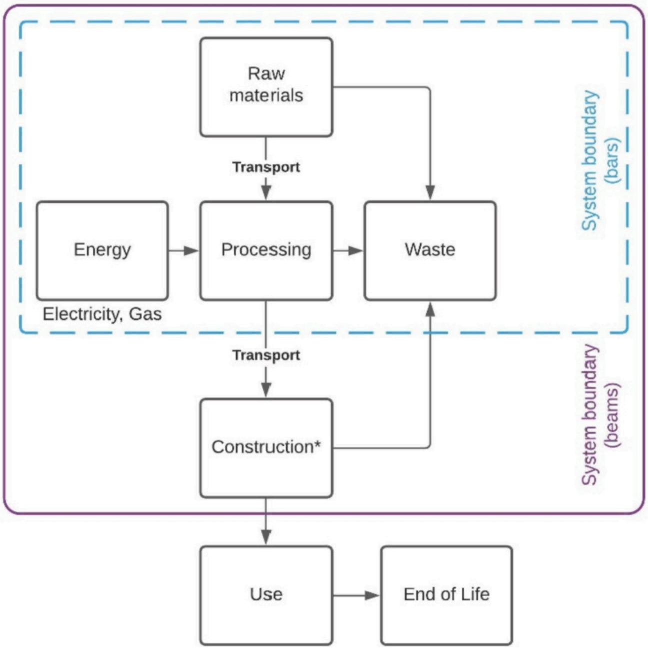

Fig. 4. System boundary. By Author.

Currently the most common of the EoL pathways presented in Fig. 6 are landfill and incineration. Thermoset resin cannot be reused; only some energy recovery (heat) is possible, although the calorific value of the resins is not very high, and thus such treatment may not be justified from the cost perspective. Fibre recovery is possible via different routes: pyrolysis (thermochemical decomposition), mechanical recycling (physical breakdown), fluidised bed combustion (thermal decomposition of the polymer in the presence of oxygen). This makes downcycling of fibres possible, as fibres can then be reused as short fibres (e.g. for FRC) or fillers ([11]). Theoretically, basalt could also be reused for manufacturing new fibres. Although, to authors' knowledge, this is not currently done, it is an important factor in the consideration of the future sustainability potential of fibrous basalt materials.

2.3. Life cycle Inventory: Data sources

The following sections provide detailed information about the sources and assumptions made while creating the Life Cycle Inventory for each reinforcing material. A summary of the processes from the ecoinvent database selected to model each material is provided in Table 1.

2.3.1. BFRP bars

2.3.1.1. Basalt fibre. The technology of the manufacturing process of continuous basalt fibre (CBF) consists of the following steps:

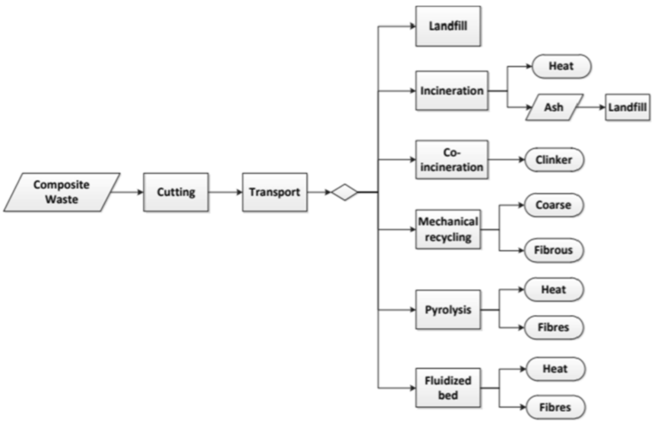

Fig. 6. End-of-life pathways for FRP materials. Vo Dong et al. [25].

Table 1
Summary of LCI data for each reinforcing material type. By Authors.

Material	Constituent	Process name
BFRP	Resin	Epoxy resin,liquid {RER}| market for epoxy resin, liquid | APOS
	Fibre	Custom process (see Section 2.3.1.1)
	Processing	Pultrusion, custom process (see Section 2.3.1.3)
GFRP	Resin	Epoxy resin,liquid {RER}| market for epoxy resin, liquid | APOS
	Fibre	Glass fibre, at plant {RER}
	Processing	Pultrusion, custom process (see Section 2.3.3)
Steel	Material Processing	Reinforcing steel {RER}| production | APOS
Stainless steel	Material Processing	Steel, chromium steel 18/8, hot rolled {RER}| production | APOS
Galvanised steel	Material Processing	Reinforcing steel {RER}| production | APOS
	Coating	Zinc coating, pieces, adjustment per µm {RER}| APOS
Concrete	Material Processing	Concrete, 25 MPa {RoW}| concrete production 25 MPa | APOS

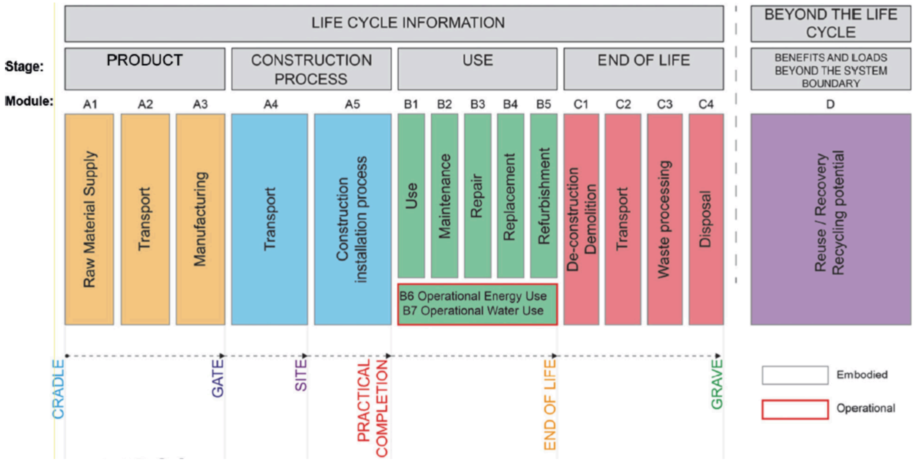

Fig. 5. Scope of LCA for buildings [6].

- Raw basalt material mining and crushing
- Melting and homogenisation
- Extrusion through the die holes of the bushing
- Winding

Energy consumption for the manufacturing of CBF is published by Osnos [15]. The process is fed by an electricity and natural gas input. The process has underwent several improvements since the launch of the first commercial plant in 1999, increasing the efficiency of the process and lowering the energy consumption through several generations of the plant. The values per kg of CBF for each of the four generations of industrial plant used for the production of CBF are given in Table 2.

Given that specific manufacturer data were not available, a sensitivity study considering all four scenarios was conducted. The energy consumption was modelled using processes representative of the Russian energy network (RU), due to the location of the manufacturer of BFRP bars used in this study.

2.3.1.2. Resin matrix. The most commonly used polymer matrices in the production of FRP materials in the construction industry are thermoset polymers, namely, epoxy resin and polypropylene. Hence, the epoxy resin was chosen as the matrix for both composite materials (BFRP and GFRP) considered in this study. The existing process for the production of epoxy resin (Epoxy resin,liquid {RER}| market for epoxy resin, liquid | APOS) available in the ecoinvent database was used to model the matrix.

The fibre fraction within the composite material mostly determines the tensile strength of the FRP rebar. According to the ASTM D 2584 "Standard Test Method for Ignition Loss of Cured Reinforced Resins" the fibre content shall not be less than 55% by volume or 70% by mass and shall be reported by volume or by mass in accordance with the method used [1]. However, a volume fraction of about 80% is common for FRP rebars and, according to Bagherpour [2], a greater fibre content beyond that does not allow the fibres to be surrounded by the resin matrix.

2.3.1.3. Fibre fraction. BFRP manufacturing process. The mass fibre fraction of 85 wt% was considered as baseline in this study, as provided by the manufacturer. However, given that this parameter was not independently tested and may vary for different manufacturers, a parametric sensitivity study from 70%wt (min) to 85%wt was also conducted.

Composite reinforcing bars are manufactured by pultrusion and the energy consumption during this process was considered as 3.1 MJ/kg, as reported by Suzuki and Takahashi [20]. The schematic process chart of BFRP bar production is shown in Fig. 7.

Additionally, a thin layer of sand is applied to the surface of the bars to improve adhesion. Bars may also be deformed by spiral winding of a filament around the perimeter to create a ribbed profile. The bars used in this study are straight with no surface deformation and a layer of sand approximately 1 mm thick. Although the inventory in this study included the sand used for surface treatment, its impact is comparatively small and may be excluded.

2.3.2. Steel

Three types of steel were considered in this study: standard reinforcing steel, stainless steel and galvanised steel. Furthermore, different recycled content of the standard reinforcing steel was also considered.

Steel is produced via two main routes: basic oxygen furnace (BOF) and electric arc furnace (EAF). BOF route uses virgin iron ore as input, with scrap used only as a cooling agent, whilst EAF can use up to 100% scrap. According to Swann [21], in Europe, steel is manufactured at a 60/40 ratio between BOF and EAF routes. However, the ratio varies for different steel products. This study considers two scenarios:

- Standard reinforcing steel, produced by a combination of BOF and EAF manufacturing. An existing process from the ecoinvent database (Reinforcing steel {RER}| production | APOS) was used;
- Reinforcing steel with 100% recycled steel content, EAF route.

Both scenarios include hot rolling as a shaping process.

Stainless steel used in this study is chromium steel grade 304. To model steel, an existing process available in the ecoinvent database was used: Steel, chromium steel 18/8, hot rolled {RER}| production | APOS. The process is based on 3,7915,860 t production and assumes a 72% recycled content. Hot rolling is included as a shaping process to manufacture stainless steel bars.

Galvanised steel bars analysed in this study were considered as hot dip galvanised reinforcing steel, shaped by hot rolling. The thickness of the zinc coating was assumed as 85 μm, as recommended in ISO 14657 [22] for galvanised steel reinforcing bars > 6 mm diameter. As this coating thickness was not available among the preset values, the process "zinc coating, pieces, adjustment per μm" available in the ecoinvent database was used to specify the 85 μm coating thickness.

2.3.3. GFRP

GFRP in this study was represented by a custom process, created using existing processes available in the ecoinvent database to represent the glass fibre production and epoxy resin production and literature data to represent the pultrusion process. Specifically:

- Glass fibre was represented by: "glass fibre, at plant/kg/RER", a process including a gate-to-gate inventory for production of glass fibre, based on a production volume of 475,000 tonnes.
- Epoxy was represented by: Epoxy resin,liquid {RER}| market for epoxy resin, liquid | APOS, same as for BFRP.
- The energy consumption required to pultrude GFRP bars was considered as reported by Suzuki and Takahashi [20]

A $70\%_{\mathrm{wt}}$ fibre fraction was assumed for the GFRP bars analysed in this study. No surface treatment (deformation, coating) was explicitly considered.

2.3.4. Concrete

Given that the LCA study of concrete beams was intended as a comparative analysis, and that the concrete grade was the same in both scenarios (steel reinforced and BFRP reinforced), modelling a custom concrete mix would not have a significant impact on the outcome of the analysis. Hence, an existing process available in the ecoinvent database was used: "Concrete, 25 MPa {RoW}| concrete production 25 MPa | APOS".

2.4. Structural performance evaluation

The equivalence of the structural performance of the RC beams was validated with experimental data obtained by quasi-static four-point bending testing of the beams until destruction. The discussion of the results of this testing is presented in a previously published study [16]. A summary of the dimensions, materials and structural performance is given in Table 3.

Serviceability limit states are considered as the governing criteria for

Table 2
Energy consumption of the manufacturing process of CBF. After Osnos [15].

	Electricity [kWh/kg]	Natural gas [m^3/kg]	Natural gas [MJ/kg]
1st generation	2.1	1.4	51.8
2nd generation	1.9	1.3	48.1
3rd generation	1.1	0.65	24.05
4th generation	0.85	0.35	12.95

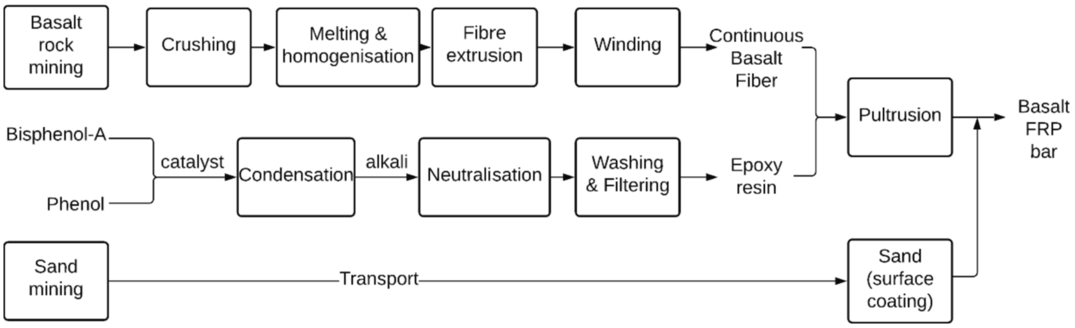

Fig. 7. BFRP bar production process. By Authors.

Table 3
Summary of beam specifications and four point bending test results. By Authors.

ID [-]	concrete [-]	Length [mm]	Width [mm]	depth [mm]	Reinforcement [-]	F_u [kN]	F_{sls} [kN]
S0-C25-0	C20/25	1900	125	200	2Ø6 mmSteel (0% prestress)	22.5	21.0
b0-C25-0	C20/25	1900	125	200	2Ø6 mmBFRP (0% prestress)	43.9	10.9
b20-C25-0	C20/25	1900	125	200	2Ø6 mmBFRP (20% prestress)	40.1	18.8
b30-C25-0	C20/25	1900	125	200	2Ø6 mm BFRP (30% prestress)	42.2	25.4
b40-c25-0	C20/25	1900	125	200	2Ø6 mm BFRP (40% prestress)	40.1	31.4

RC elements internally reinforced with BFRP, due to the relatively low Young's modulus of the material. Therefore, the most relevant parameter for determining structural equivalence of steel reinforced beams in comparison with BFRP reinforced beams was considered to be the load at the SLS limit of span/250 as defined by Section 4.4.3.1(5) of Eurocode 2 [4]. Based on the SLS load bearing capacity and dimensions, the following functionally equivalent scenarios were selected for comparison:

1. Steel reinforced beam, corresponding to the sample S0-C25-0
2. BFRP reinforced beam, pretensioned to 30% f_{tu} or higher, corresponding to samples B30-C25-0 and B40-C25-0.

3. Results

3.1. BFRP material: Network diagram

In order to investigate the contribution of the individual processes to the chosen impact categories, a network diagram of BFRP bar production was produced in SimaPro for Global Warming Potential (GWP) -

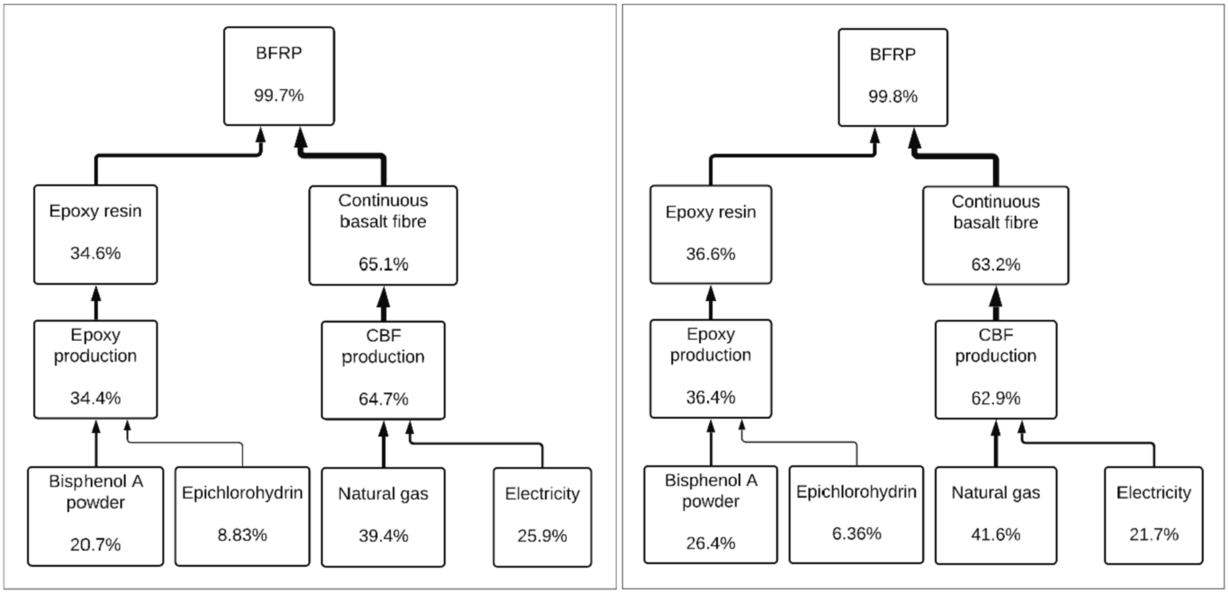

Fig. 8. Network diagram for BFRP production, Global Warming Potential (left) and Fossil Resource Scarcity (right). By Authors.

Fig. 8 (left) and Fossil Resource Scarcity (FRS) - Fig. 8 (right) categories. This type of calculation was used to graphically present the breakdown of the relative contribution of downstream processes to the overall impact. This allowed for the identification of hotspots in the process network, and thus could point at potentially significant areas for a future improvement.

With regards to both GWP and FRS, the production of CBF was identified as the main contributor to the environmental impact (measured as CO_2 equivalent and kg of oil equivalent). Further tracing the process upstream illustrates, as shown in Fig. 8, that the main contribution to GWP originates from the burning of natural gas, which is used as part of the energy input for melting of basalt rock. The electrification of the CBF manufacturing process, where the electricity is produced from renewable, non-fossil fuel sources, is likely to drastically reduce the GWP of BFRP manufacturing, by up to 65%, as well as FRS by up to 63%.

The remaining 16 midpoints are summarised in Table 4. For most of these indicators, the highest contributor was electricity, which is used in the production of CBF and the pultrusion process. Specifically, following the process upstream, the production of electricity from fossil fuel sources was identified as the largest contributor. As the electricity mix used in this analysis was that representative of the Russian electricity mix it is hence not directly applicable to other geographical boundaries. For the rest of the indicators, the highest contributor was the epoxy resin, even though this analysis was done for the 85%wt fibre fraction.

Table 4

Contribution analysis of BFRP bar production summary.

IMPACT CATEGORY	Highest contributor	Contribution [%]	Upstream highest contributor
Stratospheric ozone depletion	Electricity (pultrusion + CBF production)	74.1	Electricity production, natural gas
Ionizing radiation	Electricity (pultrusion + CBF production)	83.8	Electricity production, nuclear
Ozone formation, Human health	Electricity (pultrusion + CBF production)	45.7	Electricity production, hard coal
Fine particulate matter formation	Electricity (pultrusion + CBF production)	68.5	Electricity production, lignite
Ozone formation, Terrestrial ecosystems	Electricity (pultrusion + CBF production)	44.6	Electricity production, natural gas
Terrestrial acidification	Electricity (pultrusion + CBF production)	55.3	Electricity production, lignite
Freshwater eutrophication	Electricity (pultrusion + CBF production)	72.2	Electricity production, lignite
Marine eutrophication	Electricity (pultrusion + CBF production)	69.3	Electricity production, lignite
Terrestrial ecotoxicity	Epoxy resin	75.6	Bisphenol A (Phenol production)
Freshwater ecotoxicity	Epoxy resin	56.9	Bisphenol A (Phenol production)
Marine ecotoxicity	Epoxy resin	55.8	Bisphenol A (Phenol production)
Human carcinogenic toxicity	Electricity (pultrusion + CBF production)	58.9	Electricity production, lignite
Human non-carcinogenic toxicity	Electricity (pultrusion + CBF production)	52.9	Electricity production, lignite
Land use	Epoxy resin	54.9	Bisphenol A (Phenol production)
Mineral resource scarcity	Epoxy resin	71.6	Bisphenol A (Phenol production)
Water consumption	Electricity (pultrusion + CBF production)	61.7	Electricity production, hard coal

3.2. Sensitivity study - influence of fibre content:

Although the fibre ratio was declared as 85 wt% by the BFRP bars manufacturer there is a variation of fibre content among other manufacturers. Therefore, to expand the applicability and usefulness of the conclusions, the fibre content of the BFRP material was included in the sensitivity study stage of the LCA study conducted.

One way to express the sensitivity of a result to a certain parameter is to use the sensitivity ratio (SR), which can be calculated as:

$$SR = \frac{\frac{\Delta result}{initialresult}}{\frac{\Delta parameter}{initialparameter}} \tag{1}$$

The results of the sensitivity analysis on the influence of the fibre content, along with the sensitivity ratio are given in Table 5. It is evident that increasing the fibre content, decreases the total impact, across all 18 midpoint categories. The highest sensitivity can be observed in the case of terrestrial ecotoxicity, where an increase by 15% of the fibre content, reduces the TE score by 2.37 kg SO_2 eq (42.5%). The sensitivity of the result for Mineral resource scarcity is also high, for which an increase by 15% of the fibre content results in a decrease by 0.0024 kg Cu eq (40.8%). On the other hand, the sensitivity of stratospheric ozone depletion and ionizing radiation to the fibre content appears to be much lower ($SR=|0.34|$ and $SR=|0.38|$ respectively). As a category of high interest, it is also important to note that for GWP, a 15% of increase of fibre content results in a decrease of 0.48 kg CO_2 eq (15.1%).

The relative impact of epoxy resin vs CBF production was also analysed using breakover analysis for the GWP midpoint category. The results are plotted on the graph shown in Fig. 9. This demonstrates that at fibre fraction lower than 75 wt% the contribution of the resin is greater than that of CBF. This indicates that the impact of the epoxy resin is

Table 5

Results of the fibre ratio sensitivity analysis.

Impact category	Unit	70%	85%	SR
Global warming	kg CO2 eq	3.20E + 00	2.71E + 00	−0.70
Stratospheric ozone depletion	kg CFC11 eq	1.85E-06	1.71E-06	−0.34
Ionizing radiation	kBq Co-60 eq	3.35E-01	3.08E-01	−0.38
Ozone formation, Human health	kg NOx eq	5.32E-03	4.02E-03	−1.14
Fine particulate matter formation	kg PM2.5 eq	5.06E-03	4.28E-03	−0.72
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.62E-03	4.22E-03	−1.16
Terrestrial acidification	kg SO2 eq	8.48E-03	6.75E-03	−0.95
Freshwater eutrophication	kg P eq	1.06E-03	8.80E-04	−0.80
Marine eutrophication	kg N eq	7.77E-05	6.31E-05	−0.88
Terrestrial ecotoxicity	kg 1,4-DCB	5.57E + 00	3.20E + 00	−1.99
Freshwater ecotoxicity	kg 1,4-DCB	1.07E-01	6.99E-02	−1.62
Marine ecotoxicity	kg 1,4-DCB	1.37E-01	9.01E-02	−1.60
Human carcinogenic toxicity	kg 1,4-DCB	8.84E-02	6.73E-02	−1.11
Human non-carcinogenic toxicity	kg 1,4-DCB	2.16E + 00	1.53E + 00	−1.36
Land use	m2a crop eq	2.43E-01	1.62E-01	−1.56
Mineral resource scarcity	kg Cu eq	5.81E-03	3.44E-03	−1.91
Fossil resource scarcity	kg oil eq	1.16E + 00	9.67E-01	−0.79
Water consumption	m3	3.85E-02	3.10E-02	−0.91

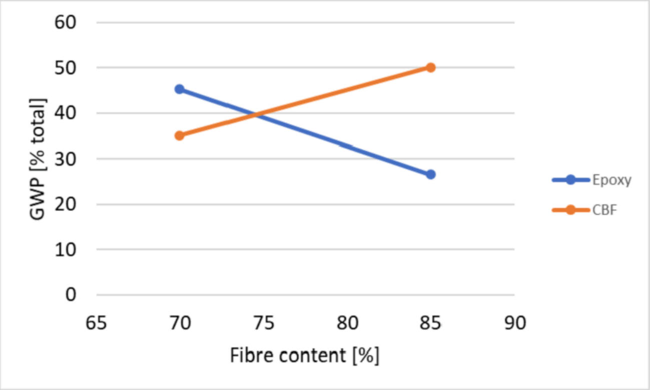

Fig. 9. Breakover analysis of the fibre fraction sensitivity of BFRP for GWP midpoint category. By Authors.

disproportionate to its mass share in the material. In turn, this suggests that a further potential area for improvement of the sustainability of BFRP material is manufacturing of the resin; if a more sustainable material substitute for epoxy resin can be found, this would significantly improve the environmental performance of BFRP overall.

3.3. *Sensitivity study – Energy consumption for CBF production*

The results of the sensitivity analysis based on the input data for the energy consumption from the continuous basalt fibre production are shown in Table 6. Given that each scenario considered in this analysis (1st generation to 4th generation) corresponds to a pair of input parameters (electricity consumption, natural gas consumption), the sensitivity ratio could not be applied. However, analysing the results shows that with each generation of the CBF production equipment, the impact of the entire process of BFRP production improves across all 18 analysed midpoint categories, which was expected given that each scenario (generation) represents a decrease in electricity and natural gas consumption. For example, with regards to GWP, the upgrade of the process from 1st to the 4th generation results in a decrease of 2.63e-5 kg CO_2 eq (65.4%). With a refinement of the CBF manufacturing process efficiency, a further improvement of the environmental impact can be reasonably expected. Once the efficiency of the process has been achieved, further improvement of the environmental impact can be realised, as previously mentioned, by electrification of the process in combination with sourcing of the energy from renewable ("clean") energy sources, instead of fossil fuels.

Table 6
Results of the energy consumption for CBF production sensitivity analysis. By Author.

Impact category	UNIT	1st gen	2nd gen	3rd gen	4th gen
Global warming	kg CO2 eq	4.02E-05	3.75E-05	2.22E-05	1.57E-05
Stratospheric ozone depletion	kg CFC11 eq	2.41E-06	2.22E-06	1.35E-06	1.04E-06
Ionizing radiation	kBq Co-60 eq	4.38E-05	4.03E-05	2.58E-05	2.11E-05
Ozone formation, Human health	kg NOx eq	1.74E-05	1.64E-05	1.11E-05	8.97E-06
Fine particulate matter formation	kg PM2.5 eq	1.29E-05	1.20E-05	7.85E-06	6.38E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.13E-05	2.00E-05	1.36E-05	1.10E-05
Terrestrial acidification	kg SO2 eq	1.42E-05	1.33E-05	8.75E-06	7.00E-06
Freshwater eutrophication	kg P eq	9.22E-05	8.56E-05	5.86E-05	4.99E-05
Marine eutrophication	kg N eq	9.41E-07	8.76E-07	6.06E-07	5.17E-07
Terrestrial ecotoxicity	kg 1,4-DCB	2.04E-04	1.98E-04	1.75E-04	1.66E-04
Freshwater ecotoxicity	kg 1,4-DCB	3.79E-03	3.63E-03	2.91E-03	2.68E-03
Marine ecotoxicity	kg 1,4-DCB	5.83E-03	5.56E-03	4.45E-03	4.08E-03
Human carcinogenic toxicity	kg 1,4-DCB	1.76E-03	1.65E-03	1.17E-03	1.00E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	6.93E-04	6.55E-04	4.97E-04	4.45E-04
Land use	m2a crop eq	1.74E-06	1.68E-06	1.44E-06	1.36E-06
Mineral resource scarcity	kg Cu eq	2.12E-09	2.05E-09	1.68E-09	1.54E-09
Fossil resource scarcity	kg oil eq	1.22E-04	1.14E-04	6.74E-05	4.75E-05
Water consumption	m3	9.23E-06	8.61E-06	5.79E-06	4.76E-06

3.4. *Comparison with steel*

The results of the comparison of BFRP with steel reinforcing bars (40/60 steel and 100% recycled content) are shown in Fig. 10. The comparative Cradle-to-Gate Life Cycle Impact Assessment (LCIA) shows that the impact of BFRP bars is lower than that of (theoretical) 100% recycled content steel, and much lower than that of standard steel across all 18 midpoint categories. For example, GWP of BFRP bars was found to be around 25% of that of 60/40 reinforcing steel bars. Furthermore, it is worth mentioning that while it may seem counterintuitive that 100% recycled steel has a higher relative impact than standard steel for certain midpoints, the results should be viewed keeping in mind that the 100% recycled steel scenario assumes manufacturing via the electric arc furnace route. The impact of this process will depend greatly on the electricity grid mix used, and in this study it was assumed to be the average European electricity grid (RER geographical system boundary). The total impact of any process, including steel manufacture via EAF route, can be lower if the electricity is sourced mostly or entirely from renewable energy sources.

3.4.1. *Uncertainty analysis (Monte Carlo simulation)*

In addition to the uncertainty introduced to the analysis by the choice of system boundaries and assumptions, there is also inherent uncertainty of the input data processes, which can follow any of the common statistical distribution patterns. Thus, to gain confidence in the outcome of the LCA study comparing BFRP with the traditional reinforcement choice - steel, uncertainty analysis was performed. The analysis was performed using the in-built function of SimaPro, which allows to conduct a Monte Carlo simulation, comparing a randomised set of chosen values within the statistical distribution for each uncertain dataset. The results of the calculations are stored and the analysis is repeated for a chosen number of iterations ($n = 2000$ was used in this analysis). Fig. 11 shows the "tornado" graph of the results, comparing the BFRP bar with the steel reinforcing bar. The confidence of the results is very high, >90% for most midpoint categories. The only exception is water consumption, for which the confidence in the outcome (BFRP < steel) was calculated to be 53%. Given that the difference between BFRP and steel for this category is 75%, which is higher than the uncertainty, the confidence in the outcome of all results can be considered satisfactory.

3.5. *Comparison with corrosion resistant bars*

The results of the comparative cradle-to-gate LCIA of corrosion resistant bars are shown in Fig. 12, expressed as normalised, relative values (%). Based on this analysis, the BFRP bars had the lowest score across all 18 midpoints from all four materials considered. The most significant reduction of impact of BFRP in comparison with the material with the highest impact was calculated for Water Consumption, Mineral

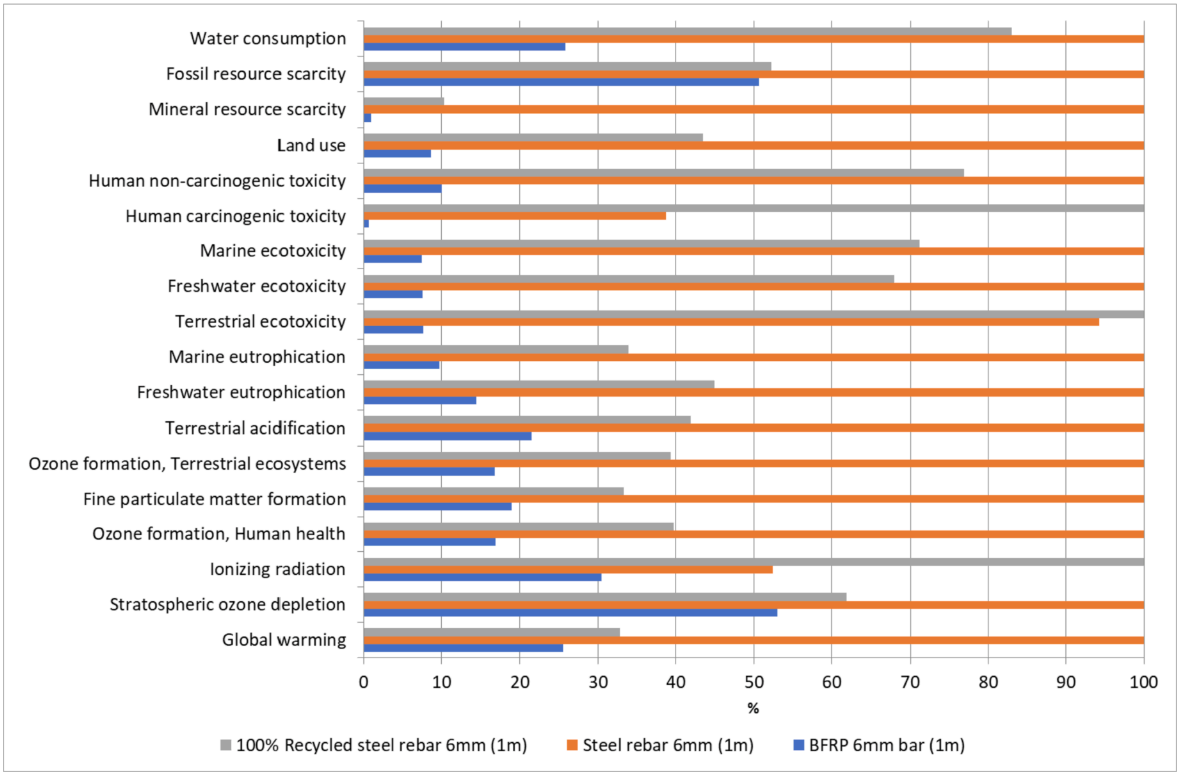

Fig. 10. Comparison of BFRP and steel reinforcing bars. By Author.

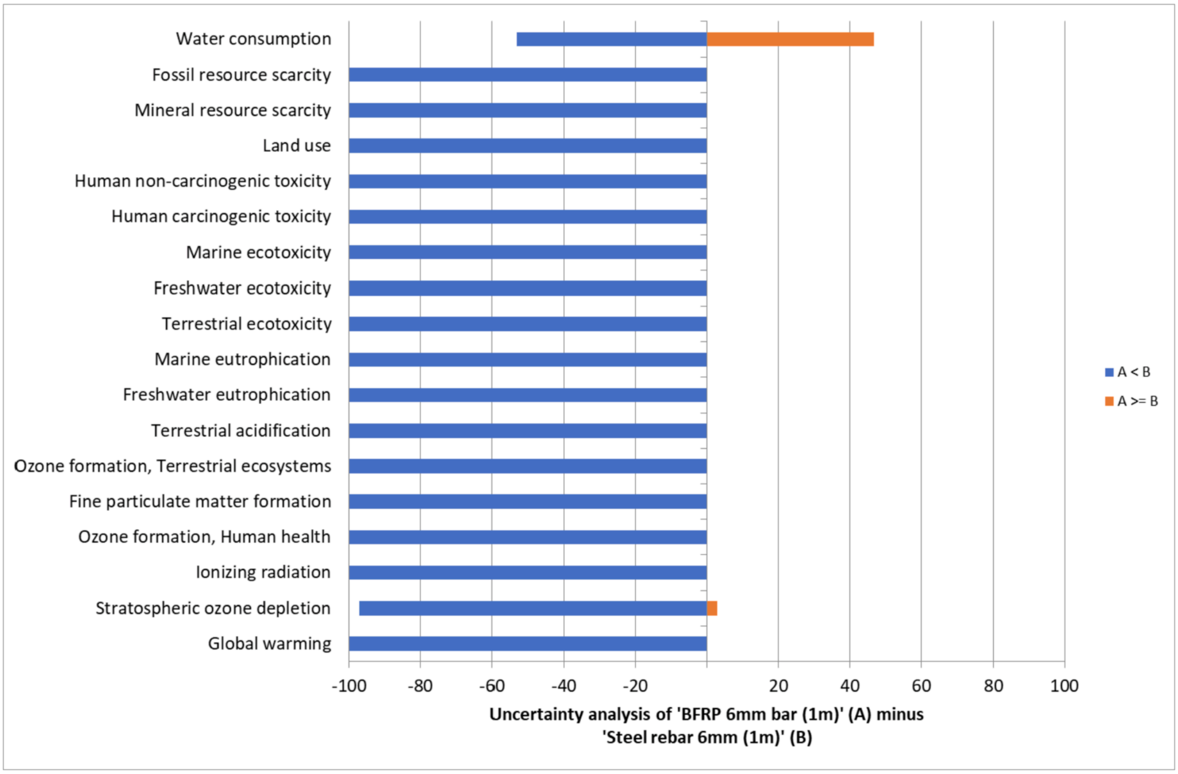

Fig. 11. Uncertainty analysis results, comparing a BFRP bar with a steel bar of equal dimensions. By Author.

Resource Scarcity and Terrestrial Ecotoxicity. Global warming potential of a 1 m BFRP bar was determined to be 88% lower than stainless steel, 49% lower than galvanised steel and 44% lower than GFRP bar of equal dimensions.

The impact of BFRP was closer to that of GFRP, while galvanised and stainless steel had a much higher calculated impact for most categories. Out of the two corrosion resistant steel bars considered, galvanised steel was more favourable, scoring higher than stainless steel only in 4

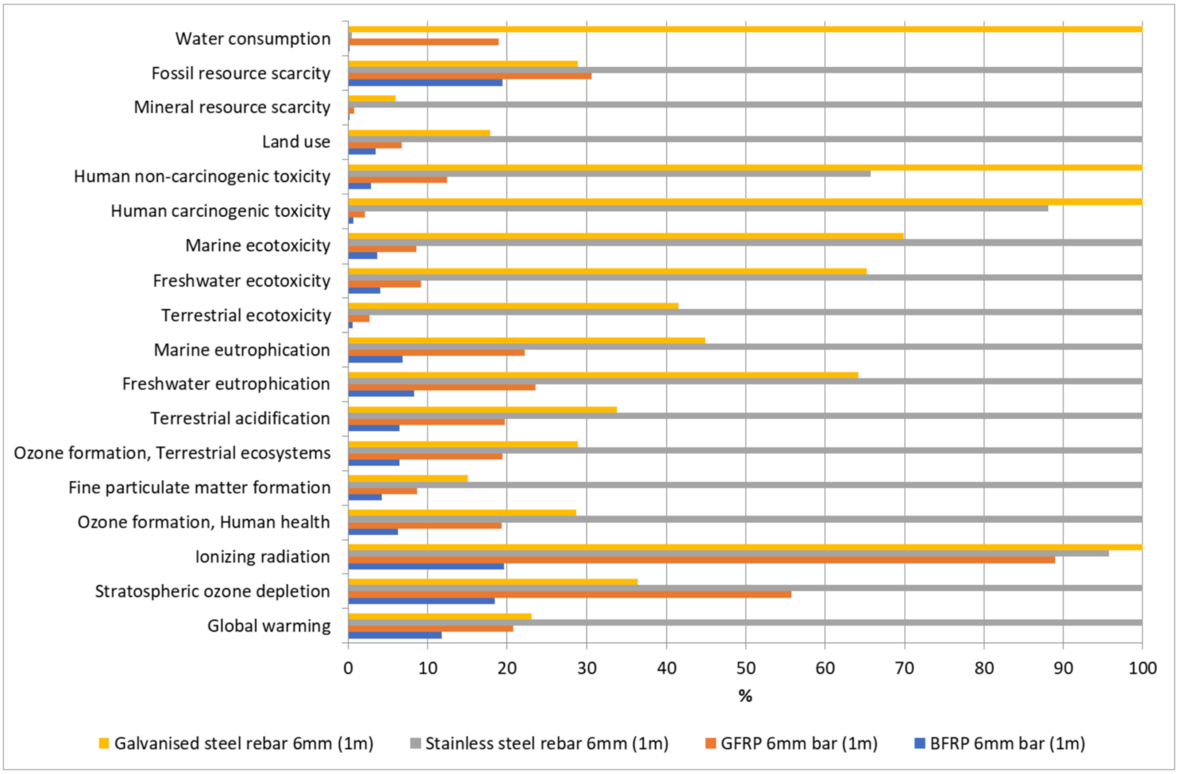

Fig. 12. Results of the comparison of corrosion resistant reinforcing bars. By Author.

categories.

3.6. Beams comparison

Given the large uncertainty with regards to transport distances (from reinforcement manufacturing facility to site), the comparative LCIA of reinforced concrete beams was initially conducted neglecting the transport. The normalised results showing the relative impact of BFRP RC beams in comparison with steel RC beams of equivalent function as defined by the functional unit is given in Fig. 13. The results for the BFRP reinforced beam scenario indicate an improvement of 4% (Ionizing radiation) to 21% (human carcinogenic toxicity) compared to the steel reinforced beam, for all 18 midpoints. The GWP of BFRP reinforced beam was calculated to be 7% lower than that of steel. The results of this analysis, however, should be viewed keeping in mind that the BFRP reinforced scenario reflects the replacement of only the main tensile (bottom) reinforcement with BFRP bars, as this corresponds to the experimentally tested samples used to validate the functional equivalence of the scenarios. The potential environmental savings for a full substitution of steel reinforcement with BFRP reinforcement are therefore much greater.

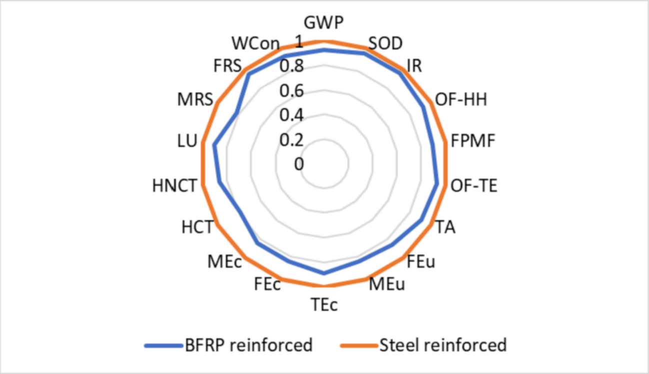

Fig. 13. Relative impact of BFRP vs Steel reinforced beams, excluding transport.

Given that the BFRP bars utilised in this study were imported from Russia to the UK, transportation of bars was considered important to be included. The analysis was thus conducted assuming transportation via lorry from the BFRP factory in Russia to the UK for the BFRP bars (2971 km), while the average European (RER) scenario was considered for the transportation of steel. Despite the large difference between the distances in the two scenarios, the influence on the outcome of the analysis was not significant, as the impact of the BFRP reinforced scenario was calculated to be lower than that of steel reinforced beams across all 18 midpoints.

Given that the mode of transportation as well as exact location of the construction site and BFRP factory may vary significantly, the quantification of the difference between scenarios with and without transport is not of primary interest. The results are included here for completeness on Fig. 14, which shows the normalised impact of scenarios with and without transport. The most significant difference when including transport was observed for Ionizing radiation (56%) and terrestrial ecotoxicity (25%). The increase in the result for Fossil resource scarcity when including transport was also more noticeable than others, due to the fuel consumption of the transportation vehicle. These results should be viewed only as illustrative of the unchanged outcome of the comparison of BFRP and steel, even when transporting bars over large distances using a non-environmentally friendly mode of transportation.

4. Conclusions

The hereby presented LCA study was conducted under the assumptions congruent with the current state-of-art, using currently available data. The aim of the study was to provide an independent sustainability assessment of alternative options for reinforcement of concrete structures, complemented by a comparison of structurally equivalent RC beams.

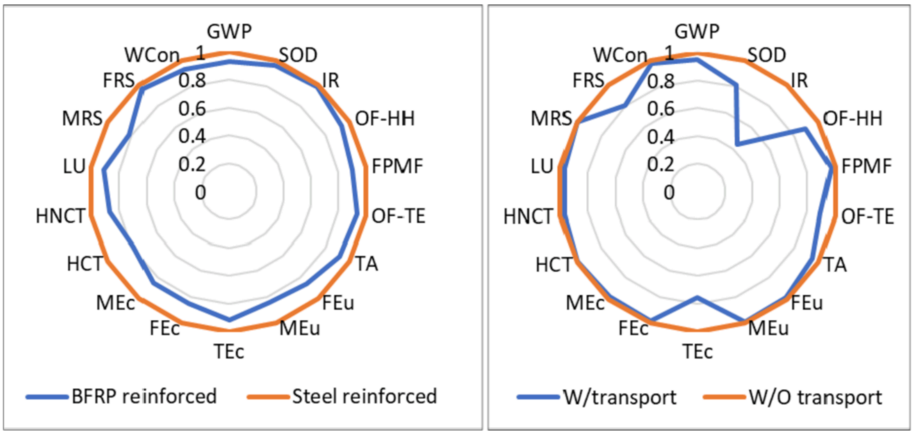

Fig. 14. Influence of the transport of bars on the outcome of the analysis.

Initially, a contribution analysis for the BFRP bar manufacturing was conducted in order to highlight the hotspot areas with regards to global warming potential and fossil resource scarcity, as areas of high interest. It was concluded that the highest contributor to the environmental impact as measured by these two categories was due to burning of the natural gas, used as energy source for production of continuous basalt fibre. This indicates that significant further improvement of the sustainability of BFRP bar manufacturing can be achieved by utilising renewable energy sources in production and hence avoiding the use of natural gas.

The sensitivity study of the influence of fibre content demonstrated that the change of fibre fraction by 15% can influence the impact of BFRP by up to 42.5%. By further breakover analysis it was shown that the contribution of epoxy resin to the overall environmental impact is disproportionate to its mass share in the material. Namely, for fibre fractions under 75 wt% the relative impact of the matrix is greater than that of continuous basalt fibre production.

LCA studies comparing BFRP reinforcing bars with steel, as well as non-corrosive reinforcing bars on a volumetric basis were conducted, with the following conclusions:

- BFRP bars were shown to have the lowest environmental impact of all considered materials (steel, stainless steel, galvanised steel and GFRP), scoring the lowest across all 18 midpoint categories.
- Global warming potential of 6 mm BFRP bars, measured as kg CO_2 eq, excluding transport, is 74% lower than that of steel, 22% lower than steel with 100% recycled content, 49% lower than galvanised steel, 88% lower than stainless steel and 44% lower than GFRP.

Finally, a comparative assessment of RC beams was conducted, showing that:

- The environmental impact of BFRP reinforced beams is lower than total impact of steel reinforced beams, with 8% lower GWP. This is the minimum saving achieved by replacing only the bottom reinforcement with BFRP; much higher savings can be achieved by replacing all longitudinal and shear reinforcement with BFRP reinforcement.
- BFRP RC beams score lower across all 18 midpoint indicators even when taking into account the worst-case transport scenario of BFRP bars.

4.1. *Limitations and further recommendations*

The authors would like to incentivise further LCA studies on various reinforcement options, providing independent source of information to structural engineers faced with the challenge of designing for net zero carbon future. Due to the limitations imposed by the current unavailability of data on use and EoL life cycle stages for BFRP reinforced elements, future expansion and improvement of the current analysis is recommended. Subsequent study should aim to include a comparative assessment of durability of BFRP reinforced elements and steel reinforced elements, with implications for maintenance/rebuild cycles. Additionally, recyclability of BFRP and opportunities for reuse of fibres should be further elaborated based on real-life data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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