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CarbonFiberStone: a new carbon negative and cost-effective alternative to conventional building materials by fusing three different CDR technologies

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Abstract

Unprecedented urbanization has led to a sharp increase in the world's building stock, increasing material consumption and environmental impact. This study introduces CarbonFiberStone (CFS), a novel lightweight construction material, and assesses its carbon footprint in a specific building application. CFS is defined as a millimeter-thin bio-based carbon fiber fabric bonded to compression-resistant stone slabs using an adhesive. CFS is extremely resistant to compression and tension. The resulting stone powder from the stone cutting process is used for enhanced rock weathering. The wall element presented here incorporates a layer of biochar for insulation purposes. Using life cycle assessment and techno-economic analysis, we compare five CFS-based building blocks with two conventional reinforced concrete blocks in single and multi-story residential buildings. The results show that CFS walls achieve a net carbon negative balance of -56.86–65.32 kg CO_{2eq} m^{-2}, sequestering 0.10–0.15 t CO_2 per square meter of living space at similar costs to conventional construction with reinforced concrete. These results show that CFS has the potential to become a viable, sustainable alternative to conventional building materials and thus has the potential to make a significant contribution to the 1.5 °C target of the Paris Agreement.

1. Introduction

Recent decades have seen unprecedented urbanization, which has led to significant growth in the global building stock [1, 2]. This expansion has led to significant material consumption and environmental impacts [3–5]. Man-made buildings and infrastructure now exceed the mass of all living things on Earth [6]. In 2022, for example, global steel production reached around 1.89 Gt yr^{-1} and emitted around 2.6–3.7 Gt CO_{2eq} [7, 8]. Around 50% of this was attributable to the construction sector, the largest consumer of steel. Global cement consumption in 2023

was around 4.2 Gt yr^{-1}, with emissions of around 1.6–2.4 Gt CO_{2eq} [9, 10]. Most of these CO_{2eq} emissions are process-related from the burning of limestone, which cannot be avoided by using renewable energy. A similar problem arises from the use of limestone in the manufacture of steel, which in effect results in a 10% hard-to-reduce share of residual CO_{2eq} emissions, even if steel is decarbonized through the use of energy-intensive hydrogen. Taken together, the production of steel and cement accounts today for more than 10% of global greenhouse gas emissions, underlining the urgent need for decarbonization to achieve the goals of the Paris Agreement [11–13]. At

the same time, the mining and extraction of the necessary resources, including fossil fuels for energy, damages the environment and displaces people worldwide [14, 15]. Further, cement plants emit sulphur dioxide (SO_2), nitrogen oxides (NO_x) and carbon monoxide (CO), which are associated with respiratory diseases (e.g. asthma, bronchitis) as well as acid rain and smog formation [16].

One strategy to reduce these negative impacts is to promote more efficient and intensive use of existing and future infrastructure [5, 17]. This will reduce, but not eliminate, the need for new buildings. Further, emissions could be offset by using the carbon market to support carbon dioxide removal (CDR) projects such as forestry, terrestrial or marine enhanced rock weathering (ERW) or biochar. Such nature-based solutions have a high potential and have several co-benefits. For example, biochar production could provide additional income for farmers and is an alternative to burning agricultural waste [18]. Marine ERW mitigates ocean acidification while terrestrial ERW can improve food security as it can be used as fertilizer [19, 20].

A second lever focuses on optimizing the use of materials and introducing innovative designs to reduce dependence on conventional materials [21]. Here the replacement of reinforced concrete being the most important lever. One material that has received much attention in recent years is timber [22]. In addition to lower embodied emissions, wood has the added benefit of acting as a long-term carbon store [23, 24]. Although the potential of the world's forests to replace reinforced concrete is still estimated with considerable uncertainty [23], it is clear that wood alone cannot be used as a substitute reinforced concrete in all applications, particularly in load-bearing structures such as high-rise buildings, foundations, and some types of bridges and railway sleepers.

Natural stone has been used alongside wood as a building material for several millennia. Research has shown that natural stone has a low energy footprint, in case they are cut from blocks into slabs. It has a high durability and excellent thermal properties, making it a promising option for reducing the carbon footprint of buildings [25–27]. However, several issues hinder the widespread use of stone as a primary building material. Reinforced concrete, with its wire mesh reinforcement, offers a superior tensile strength and capability to take up shear forces [28]. Stone is more prone to sudden, catastrophic failure once cracks have formed. Another major obstacle is the higher cost of the stone if built in massive form. The unmatched advantage of stone is more than 4x higher pressure resistance compared to normal concrete and its relatively low weight, since the gravity of many hard rock stones come very close to the one of aluminum. In order to increase the attractiveness of stone as a

building material, there is a need to reduce material consumption while improving tensile mechanical performance to compete with reinforced concrete.
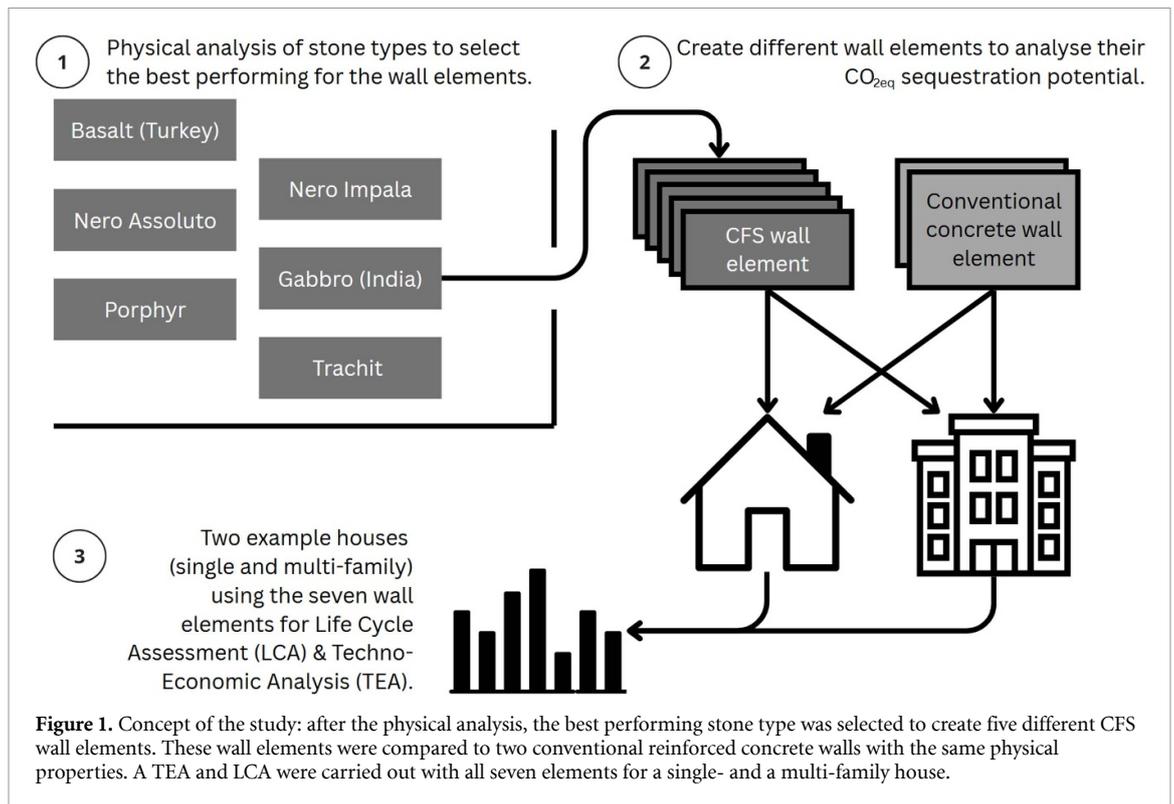
With this study, we therefore propose a novel potential replacement for reinforced concrete that combines the advantages of stone with materials of high tensile strength, with three different carbon dioxide removal (CDR) strategies: ERW, biochar and plant-based biocarbon fiber. Enhanced weathering accelerates the natural process of rock weathering by spreading finely ground silicate rock, created through stone cutting, over terrestrial or marine surfaces. This technique captures atmospheric CO_{2eq} through chemical reactions between rock, water and air. In this study, biochar is used as an insulating material. Carbon fiber is the highest performance material made from highly oriented turbostratic carbon phase and is known for its exceptional tensile strength to weight ratio, stiffness and durability. It is typically used in aerospace, windcraft, automotive, sports and construction industries for highest performance application. Recent advances allow them to be made from renewable, bio-based materials, making it a long-term carbon sink [29–32].

We refer to this new material as 'CarbonFiberStone' (CFS). This study evaluates the physical performance of six types of stone, the carbon footprint of CFS and the architectural performance by analyzing five different building blocks in comparison to conventional reinforced concrete blocks in two building scenarios: a single-family house (SFH) and a multi-story residential building (figure 1). Our investigation addresses the following questions: How does CFS compare to reinforced concrete in terms of mechanical behavior and heat resistance? What is the carbon footprint of CFS compared to the corresponding reinforced concrete elements? And are the costs of CFS comparable to those of similar building materials?

2. Methods

2.1. The CFS-wall elements

CFS was invented by TechnoCarbon Technologies GbR and is defined as a less than millimeter-thin carbon fiber fabric bonded to pressure-resistant stone slabs using an adhesive [33]. Depending on the application, the tensile carbon fiber fabric is applied on one or both sides, resulting in a lightweight composite material that is extremely resistant to compression, and tension, and can be bent without hair cracks of the stone [34]. In this study, six different types of stone were analyzed to evaluate their compressive strength at room temperature and elevated temperatures up to 1000 °C. The temperature-exposed specimens were heated in a furnace and then allowed to cool. Compressive strength tests were conducted on both the non-exposed and the cooled, previously

Figure 1. Concept of the study: after the physical analysis, the best performing stone type was selected to create five different CFS wall elements. These wall elements were compared to two conventional reinforced concrete walls with the same physical properties. A TEA and LCA were carried out with all seven elements for a single- and a multi-family house.

heated specimens to assess their structural integrity under thermal stress. Further we tested a lightweight and standard reinforced concrete wall with a thickness of 6 cm.

The used carbon fibers were prepared from biomass using acrylonitrile derived from algae oil [29]. The bio-based acrylonitrile was polymerized, spun to fibers and carbonized in the established industrial process without any loss in mechanical properties. For an oven test, two granite slabs were bonded to a carbon fiber layer using a water glass adhesive. Care was taken to ensure that the adhesive penetrated the entire carbon layer and coated each individual fiber by splicing the fiber bundles (rovings). In the case of the house wall, only a minimal proportion of carbon fiber is required (0.2 mm fiber stabilize 20 mm stone slabs, resulting in a ratio of 1:100).

Biochar is the solid residue obtained from the controlled thermal decomposition (pyrolysis) and gasification of biomass under limited oxygen and high temperatures [35]. It therefore has a high heat resistance due to C–C covalent bonds. Biochar has been successfully used as a filler in polymeric materials and for carbon sequestration [36].

Five different CFS-wall panels were analyzed: The CFS wall panels cfs1.1 and cfs1.2 (Supplement A Fig. A1 and Fig. A2) differ in the thickness of the lateral boundary plates (20 mm vs 2 mm) but have no internal stiffening ribs. The CFS wall elements cfs2.1 and cfs2.2 (supplement A figure A3 and figure A4) correspond to variants cfs1.1 and cfs2.2, but with

internal stiffening ribs, which considerably increase the axial moment of inertia of the CFS walls and thus the permissible breaking and buckling load. The CFS wall element cfs.3 (supplement A figure A5) is a semi-finished element that is filled with biochar on site and bonded to the top plate. All elements are filled with biochar. We also measure the surface area of the stone powder (using three different samples) produced during the manufacture of a CFS wall element.

For the comparison with the CFS wall element construction methods, two typical concrete construction methods have been considered so far: the 'classic' *in-situ* reinforced concrete wall (rc1, supplement A figure A6) with thermal insulation on the reinforcement mesh, interior and exterior rendering. In addition, we also analyzed a concrete wall as a semi-prefabricated part (concrete double wall with lattice girders in the cavity), which is cast with *in-situ* concrete on site and finished with insulation, interior and exterior rendering (rc2, supplement A figure A7). Such prefabricated walls have recently become more attractive, as they allow a more efficient construction, show higher quality and minimize material waste [37].

2.2. Example house scenarios
Two stylized reference house models have been defined for the comparison of building types: a SFH and a multi-family house (MFH). The detached house has a footprint of 10×10 m, a net living area of 164 m^2, an internal staircase and a pitched roof. The

floor slabs are of ring beam construction, with only the external walls serving as load-bearing elements. The apartment block has a footprint of 15×65 m, five stories, 40 apartments with a net floor area of 80 m^2 each, four internal stairwells, and a flat roof (see also supplement B).

These models are used to determine the masses, total areas and vertical loads of the external walls, floor slabs and roof. Both models have been designed with maximum simplification, excluding elements such as basements, windows, doors, balconies and bay windows (see supplement B). The gabbro was used as stone material as it performed best in the previous thermal tests (see section 2.1).

2.3. Life cycle assessment (LCA) & techno-economic analysis (TEA)

The analysis focuses on CDR potential. The LCA results, which include the reduction of CO_{2eq} emissions from wall production and carbon sequestration in the wall, could have an economic impact if the EU ETS allowance scheme can be extended to all industrial sectors and the carbon sequestration can be compensated through certificate trading on established CO_{2eq} trading platforms.

Based on CFS wall construction, the corresponding CFS components are determined. For each component, a cost and global warming potential (GWP) calculation is made for the process steps of block preparation, sawing, calibration, CF coating, and transport to the prefabrication plant. This is followed by the assembly of the components and the filling of the CFS wall elements in the factory. The transport of the prefabricated elements to the construction site and the assembly work on site are also considered. The entire process chain is summarized in a calculation of the building walls (and optionally ceilings) for a reference building (see also supplement C for data collection details). The carbonation of the cement is not explicitly considered for the concrete elements, as modern houses have covered walls that exclude contact with water. This reduces the carbonation process to a negligible level. The system boundary has been aligned with a 'cradle to construction-site' approach, as stone and biochar can be reused many times even after hundreds of years, making it difficult to compare to the much shorter lifetime of concrete. In addition, the separation and recycling of the CFS wall components—stone, carbon fiber and biochar—are still in the early stages of research, so there is a lack of reliable and comprehensive data.

For the TEA and LCA calculations a complex dynamic model system with an object-oriented, modular model structure based on an integrated modeling approach (fully integrated TEA-LCA modeling) was developed by AHP GmbH & Co. KG in Berlin. The model system comprises a Monte Carlo simulation shell for probabilistic and risk analysis purposes [38]. At the lowest level of the static model, each CFS component has a sub-model for calculating manufacturing costs and GWP values. There are also sub-models for the construction costs and GWP values of the wall elements, again with the ability to easily add future designs. These models access data repositories and standardize prices using construction price indices. Construction costs and GWP values for the building are derived from the wall element models. It is also possible to model floor slabs as CFS structures, using initial assumptions. The dynamic modeling system that follows this static first part determines the cost differences between the construction methods and derives a complete financial plan, including profitability figures using the discounted cash flow method. GWP values are also calculated. Further details of the methodology and the Monte Carlo simulation (with 10 000 random samples) are described in [38]. Confidence intervals are derived from worst, base and best cases for input variables [38]. See also supplement C and F for simulation details and input variables. Sensitivity analyses were performed for costs and GWP.
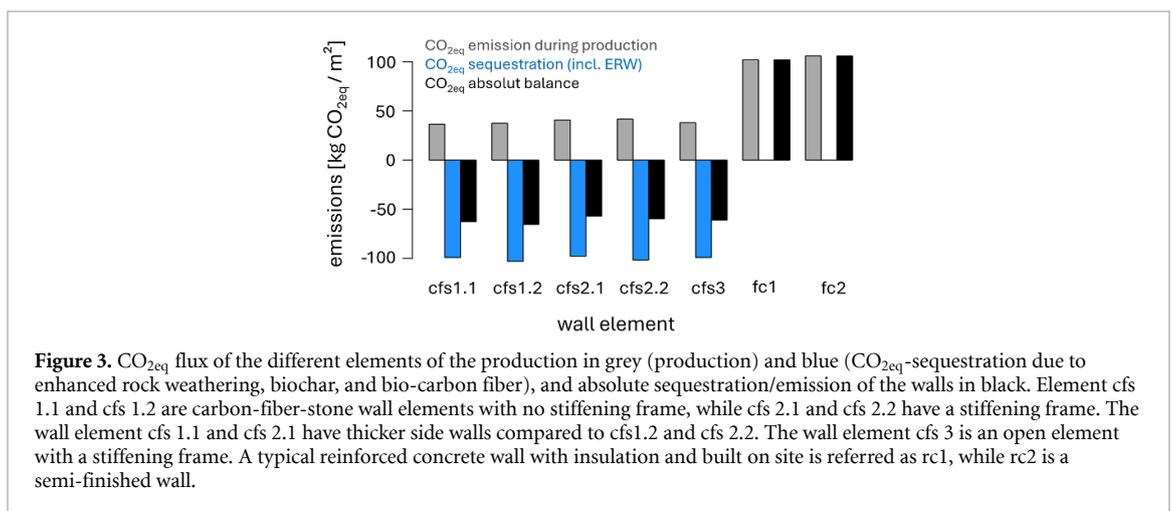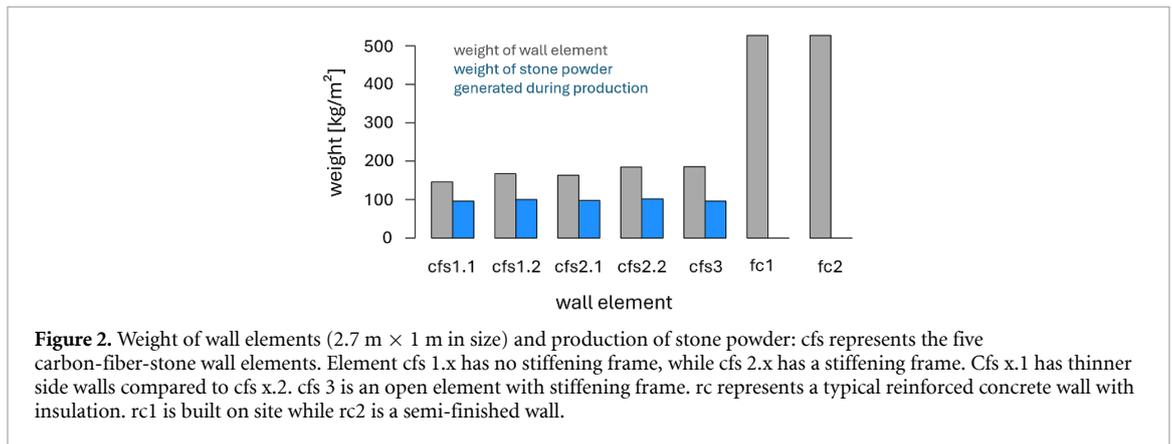
3. Results

Gabbro stone retained about 26% of its original strength after exposure to 850 °C and 19% after 1000 °C (the temperature limit we could test with our oven equipment), while basalt retained only 9% after 850 °C (table 1). The lightweight standard reinforced concrete wall start crumbling at temperatures of 650 °C because the embedded aggregates have different coefficients of thermal expansion, leading to internal stresses and material disintegration.

Carbon fibers can remain stable in an oxygen-free environment up to 2000 °C (30, 31 when water glass adhesives are used to embed the carbon fibers, the water glass begins to release oxygen at temperatures of 700 °C, which reacts with the carbon fibers to form CO_2. When sandwiched between two stone plates to prevent oxidation, the carbon fibers remain intact up to 700 °C. Further, the carbon fibers have low thermal expansion. The pre-stressed carbon fiber fabric counteracts the thermal expansion of the natural stone, resulting in minimal expansion of the entire structure during temperature changes.

During the production of CFS, around 60% of the mass of the final stone slab is produced as fine-grained stone powder with a grain size of 2.40 ± 0.02 m^2 g^{-1} (figure 2). This stone powder is used for enhanced weathering sequestering 45 kg of CO_{2eq} per 100 kg.

Table 1. Bending stress in $(N\ mm^{-2})$ for different types of rock and concrete.

	Room temperature	850 °C	1000 °C
Basalt (Turkey)	25.1	2.2	—
Nero Assoluto	33.5	8.5	—
Porphyr	15.5	3.3	—
Nero Impala	14	2.5	—
Gabbro (India)	42.6	11.1	8.2
Trachit	5.4	3.3	3.7
Concrete	5.0	—	—

Figure 2. Weight of wall elements (2.7 m × 1 m in size) and production of stone powder: cfs represents the five carbon-fiber-stone wall elements. Element cfs 1.x has no stiffening frame, while cfs 2.x has a stiffening frame. Cfs x.1 has thinner side walls compared to cfs x.2. cfs 3 is an open element with stiffening frame. rc represents a typical reinforced concrete wall with insulation. rc1 is built on site while rc2 is a semi-finished wall.

Figure 3. CO_{2eq} flux of the different elements of the production in grey (production) and blue (CO_{2eq}-sequestration due to enhanced rock weathering, biochar, and bio-carbon fiber), and absolute sequestration/emission of the walls in black. Element cfs 1.1 and cfs 1.2 are carbon-fiber-stone wall elements with no stiffening frame, while cfs 2.1 and cfs 2.2 have a stiffening frame. The wall element cfs 1.1 and cfs 2.1 have thicker side walls compared to cfs1.2 and cfs 2.2. The wall element cfs 3 is an open element with a stiffening frame. A typical reinforced concrete wall with insulation and built on site is referred as rc1, while rc2 is a semi-finished wall.

Further CFS walls have significantly lower CO_{2eq} emissions during production compared to reinforced concrete, primarily due to reduced energy requirements. Only the electrical cutting and milling processes as well as oven temperatures of 100 °C for the fiber coating process consume energy. Low emissions from the carbon fibers production process add a low amount of unavoidable CO_2 emissions. In contrast, steel and limestone production require temperatures exceeding 1000 °C. Additionally, there are also no CO_{2eq}-emissions, as there is no need for lime calcination (figure 3). Lower energy consumption, ERW of the stone powder and sequestration due to the utilized biochar for insulation result in a net carbon negative balance for CFS walls ranging from -56.86 kg CO_{2eq} m^{-2} to -65.32 kg CO_{2eq} m^{-2} of the wall element.

A comparison between two types of housing shows that the use of CFS elements for walls and ceilings can turn buildings into carbon sinks, with a sequestration rate of 0.10–0.15 t CO_{2eq} per square meter of living area. Due to the favorable ratio of walls and ceilings to living space, the CO_2-sequestration per square meter is higher in SFHs, while it is worse for the CO_{2eq} emissions in case of reinforced concrete (tables 2 and 3). The tolerance ranges for effective CO_{2eq} flux and CO_{2eq} flux per living area in tables 2 and 3 refer to the related 95% confidence intervals as result of the Monte Carlo simulations.

The area-specific construction costs (production and transport) for the cfs 2.2 are about 10% lower than for the *in-situ* concrete wall rc1 and about 5% lower than for the precast concrete wall rc2 (table 4). Considering the price of CO_2, the effective

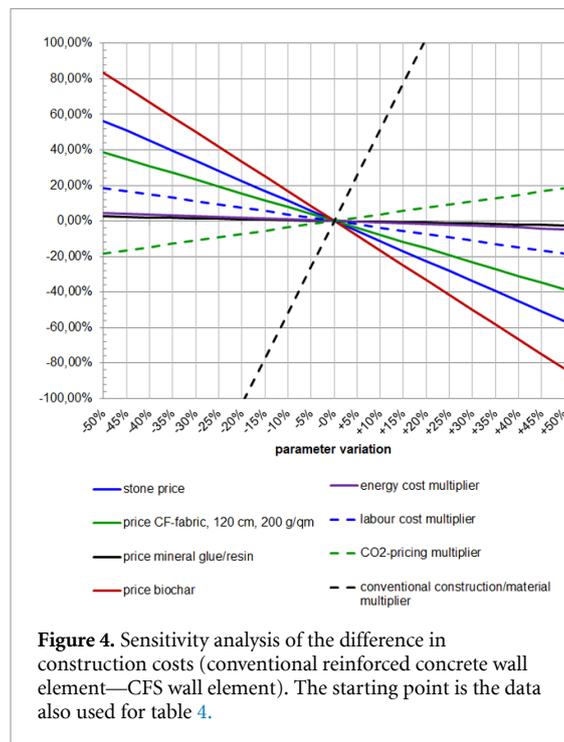**Table 2.** CO_{2eq} emissions of single-family house construction with CFS and reinforced concrete wall elements.

	SF-house made of cfs2.1	SF-house made of cfs2.2	SF-house made of rc1	SF-house made of rc2
CO_{2eq} emissions (t CO_{2eq})	16.56	17.02	41.57	43.20
CDR (t CO_{2eq})	39.70	41.31	0	0
Absolute CO_{2eq} flux	$-23.14 \pm 17.1\%$	$-24.29 \pm 18.2\%$	41.57	43.20
CO_{2eq} flux per living area (t CO_{2eq} m^{-2})	$-0.14 \pm 17.1\%$	$-0.15 \pm 18.2\%$	$+0.25$	$+0.26$

Table 3. CO_{2eq} emissions of multi-family house construction with CFS and reinforced concrete wall elements.

	MF-house made of cfs2.1	MF-house made of cfs2.2	MF-house made of rc1	MF-house made of rc2
CO_{2eq} emissions (t CO_{2eq})	219.77	225.92	551.89	573.42
CDR (t CO_{2eq})	525.99	548.43	0	0
Absolute CO_{2eq} flux	$-307.21 \pm 17.3\%$	$-322.51 \pm 17.7\%$	551.89	573.42
CO_{2eq} flux per living area (t CO_{2eq} m^{-2})	$-0.10 \pm 17.3\%$	$-0.10 \pm 17.7\%$	$+0.17$	$+0.18$

Table 4. Costs of CFS and reinforced concret wall elements using the default values of the TCA.

	cfs 2.1	cfs 2.2	rc1	rc2
Construction costs (€ m^{-2})	303.60	302.70	335.66	318.38
CO_{2eq} emission-related costs (€ m^{-2})	3.61	3.71	9.05	9.41
Credits from CDR due to biochar and ERW (€ m^{-2})	13.35	13.89	0	0
Total costs (€ m^{-2})	293.86	292.52	344.71	327.78
Cost reduction compared to rc1 (%)	14.75	15.14	—	4.91

Figure 4. Sensitivity analysis of the difference in construction costs (conventional reinforced concrete wall element—CFS wall element). The starting point is the data also used for table 4.

construction cost of both CFS walls is approximately 15% lower than the *in-situ* concrete wall rc1 and approximately 11% lower than the precast concrete wall rc2.

This cost advantage has the potential to reduce the overall construction cost per square meter of living space. Assuming that CFS elements are used not only for external walls but also for floor slabs—which

are estimated to have similar square meter costs and specific GWP values as the CFS wall—further savings can be achieved. When the benefits of greenhouse gas emission reductions under the EU Emissions Trading Scheme and the carbon storage potential of walls and floors are also taken into account, and these costs are compared with those of conventional *in-situ* concrete construction, the result is a reduction in comprehensive construction costs per square meter of living space of 5.7% for SFHs and 3.9% for MFHs with the default values of this analysis. The highest sensitivity of CFS-wall economic viability was observed for the prices of biochar, granite blocks, and carbon fiber at the factory entry point, as well as for the cost of conventional materials, which has been highly volatile in recent years (figure 4). This sensitivity analysis shows that even a significant increase in stone and biochar prices keeps the price in the same range as the reinforced concrete elements. Further sensitivity analysis can be found in the Supplement.

4. Discussion

We are introducing CFS walls, which combine high-strength gabbro rock with algae-based carbon fibers to create wall elements that are filled with biochar for insulation. This combination of three CDR technologies creates a substantial and durable carbon sink and provides a cost-effective alternative to reinforced concrete.

Algae-based carbon fibers are an active area of research. Microalgae, which provide the oil for these

fibers, are much more efficient at sequestering carbon dioxide than land plants and produce about ten times more biomass per unit area over the same period. However, growing microalgae in seawater farms on an industrial scale would require extensive land use for tank facilities. Such technologies will be part of a future scalable bio-based carbon fiber production. In the short term, however, fossil-based fibers could be used because the change in the carbon balance of the wall is nearly negligible. A sustainable and scalable alternative for biomass-based fiber production could be Lignin [39, 40]. Lignin, a by-product of the paper industry that is currently largely incinerated, holds great promises. Lignin is available as byproduct in significant quantities and can be converted into affordable carbon fibers with sufficient quality using low-cost technologies that have already been developed [32]. This offers a viable short-term solution until algae farms of the required scale are established.

Gabbro is found on all continents and is mined in regions such as the Bushveld Complex in South Africa and the Duluth Complex in the USA, as well as large amounts in China and Australia. Other quarries are located in Scandinavia, Scotland, and the Deccan Traps in India. Quarrying techniques are well developed and many existing plants can be efficiently scaled up to produce significant quantities of stone powder in the coming decades.

A significant proportion of the CO_{2eq} sequestration potential comes from the weathering of the stone dust produced during the cutting of gabbro slabs for the wall. The measured surface area of the powder is 2.4 m^2 per gram is six times greater than that normally reported in recent ERW studies for basalt, which traps 300 g CO_{2eq} per kg and has a specific surface area of 0.5 m^2 per gram in average [41]. This increased surface area significantly accelerates weathering rates, increasing the value of carbon credits compared to estimates based on basalt weathering using conventional milling techniques. The use of diamond rope cutting produces ultrafine particles, further increasing weathering efficiency through super-linear acceleration.

The long-term trade-offs of different ERW approaches on soil ecosystems and biogeochemical cycles are becoming better understood [42]. ERW can effectively remove CO_{2eq} from the atmosphere, and may offer land restoration and improved fertility [43]. However, some rock types used in ERW, such as basalt or silicate rocks, may contain heavy metals (e.g. nickel, chromium) or other toxic elements. These can leach into soils and water systems during weathering, posing risks to soil health, aquatic ecosystems, and human food safety through bioaccumulation [44]. Further ERW research is needed to explore the

interactions between environmental sustainability and the sustainable development goals, as well as the potential benefits and trade-offs with other sustainability goals [43].

Using biochar on a large scale as CDR in the context of construction and resource generation would still leave 71% of agricultural by-products available for other applications and could therefore generate an additional income for farmers [18]. A potential co-benefit of using biochar is that the process of producing it through pyrolysis could coproduce valuable by-products, such as syngas and bio-oil [45]. However, biochar production can also produce toxic gases, which can be captured by various sorption methods [46]. The current production and use of biochar is very limited. Roughly 0.4 Mt of biochar was produced in 2021, while the potential only from crop residues alone is estimated to reach 360 Mt per year [13, 47]. Mixing the biochar with rock wool could compensate for any shortage of biochar in the coming years.

CFS has a specific weight comparable to aluminum, making it a lightweight material, whereas steel is more than twice as heavy for comparable load bearing. Consequently, the use of CFS structures, especially cfs 2.2, offers significant energy and weight savings and reduces the vertical load on the base of ground floor walls, opening new possibilities for construction and design.

It is worth noting that hard rock only achieves elasticity comparable to that of aluminum when combined with the high tensile strength and elasticity modulus of carbon fibers. The elasticity of stone is a measurable and exploitable phenomenon, yet it remains poorly understood scientifically. With CFS, the elasticity of the stone can be adjusted from highly flexible to extremely rigid by changing the proportions and adhesion between the stone and carbon layers. While the carbon component provides the tensile strength and stiffness, the stone component provides the flexibility. This new insight could open up new mechanical possibilities in the future, for example in the field of earthquake-resistant constructions.

The weather resistance of natural stone varies with its type. The used gabbro, characterized by low porosity, exhibits high resistance to weathering but may sustain damage under intense chemical, physical, or biological stress. In contrast, carbon fibers and mineral adhesives are chemically corrosion-resistant and, crucially, remain unaffected by corrosion in CFS applications under exclusion of UV-light.

CFS has a significantly higher CO_{2eq} binding capacity compared to other building materials. The optimum cement binder, consisting of magnesium oxide from forsterite and carbonate with 15% biochar as a filler, achieves a CO_{2eq} binding of 0.9 kg per kg of

cement binder [13]. When applied to reinforced concrete, this corresponds to a CO_{2eq} binding of around 0.15 kg per kg of construction material. In contrast, CFS walls achieve CO_{2eq} capture rates of between 1.16 kg per kg (cfs 1.1 wall) and 0.87 kg per kg (cfs 2.2 wall).

Compared to a mature forest, which binds around 55 kg of CO_{2eq} per m^2, the CO_2 binding per residential unit in a MFH built with CFS is twice as high and in a SFH even three times as high. In a four-story MF house, for example, the CO_{2eq} sequestration per house area could reach around 400 kg m^{-2}, which corresponds to an eight-fold increase in sequestration capacity compared to a reforested area.

Recent IPCC reports emphasize the critical role of CDR and long-term carbon utilization technologies in achieving the climate goal set out in the Paris Agreement. The construction sector, which is a major contributor (more than 10%) to greenhouse gas emissions due to steel and cement production, has been identified as a priority area for climate research [11, 12]. The urgency of tackling climate change has led to emission reduction commitments and regulatory measures in many regions, such as the recent Californian legislation requiring net-zero emissions from the cement industry by 2045 [48], while major producers from across the globe (representing 80% of total production outside China) affirm their commitment to net zero concrete by 2050 and agree to an ambitious intermediate goal of preventing 5 billion tons or 25% of CO_{2eq} emissions by 2030 [49]. Carbon storage in building materials is therefore particularly attractive to policy makers, as building materials often come from regional sources—as is the case with CFS. In contrast to problems such as sand shortages in cement production [50] or increased health risks for the local population [51], such problems are avoided when CFS is used as a building material. CFS also promotes local economic development and job creation.

However, DIN standards and approval procedures require extensive analysis and quality control, which makes approval cost- and time-intensive and hence more difficult. In addition, new building products are now often subjected to more stringent tests for approval than in previous approval procedures for building materials that are regularly used today. These hurdles can make alternative materials less attractive in terms of cost, particularly at the beginning, especially in comparison to conventional building materials. As a result, they have received little support from investors. Funding mechanisms or incentive systems could give developers planning security and room for maneuver to bring CO_{2eq}-negative building materials to market maturity. Such measures can help to make the new technologies competitive with the established, more climate-damaging products and process chains. Integration of ERW into national and international climate policies,

carbon markets, and funding mechanisms is essential. Additionally, efforts must be made to gain social acceptance and engage stakeholders [52, 53].

To achieve such broader acceptance and fast usage, these materials could, as a first step, be immediately suitable for non-loaded or low-loaded applications, such as insulation, floor coverings, non-load-bearing walls, which make up a significant proportion of the built environment in terms of weight. In the medium term, railway sleepers or bridge constructions as well as wind power stations and frames of PV-modules made of CFS would also be possible in addition to houses.

5. Conclusion

This study demonstrates that lighter CFS walls offer both cost savings and reduced environmental impacts, as evidenced by LCA and TEA evaluations. These findings underscore the potential of innovative, lightweight materials as sustainable alternatives to traditional construction materials. When scaled up, CFS could play a significant role in achieving the Paris Agreement's 1.5 °C target.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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