When means and ends meet

examining strategies and carbon accounting fit for Our Global Future

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When means and ends meet: examining strategies and carbon accounting fit for Our Global Future

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Abstract:
Global efforts to accelerate the transition towards whole-life carbon (WLC) neutral buildings are key to ensuring humanity's survival in a world beaten by climate change. WLC design is expected to optimize embodied and operational GHG emissions, and corresponding estimates imply that both types are explicitly accounted for. As varied carbon accounting approaches have been used, this paper overviews two promising strategies for carbon removal - biobased materials and mineral carbonation - and discusses the implications of the main calculation approaches applied to them. Crushed concrete carbonation and CO_2 curing can uptake almost 10% of the original emissions each, at low additional cost. Still, both assume continued use of concrete, which has high embodied emissions. Well-established in temperate climates, biobased construction materials are not mainstream and durability challenges in certain exposure conditions prevent their unrestricted contribution as carbon sinks. As to calculation rules, assigning emissions and uptake to the life cycle stage in which they occur can be tricky when recycling, reuse and waste management activities are inherently involved. By design-reduction and compensation measures must be sought for and - if we are to reach Our Global Future - partnerships and resources urgently directed to all nations to play their part in the collective decarbonization.

Keywords: Carbon removal strategies, Carbon Accounting Rules, Whole-life carbon buildings

1. Introduction

The operational energy demand of buildings has decreased steadily as more stringent regulation gradually came into effect. For example, 'nearly zero-energy' buildings are required in the European Union since 2021. Climate change urgency put forward the Paris Agreement, which requires that the anthropogenic greenhouse gas (GHG) emissions released into the atmosphere are balanced by their removal from it by GHG sinks by 2050. Fulfilling such goal thus relies on 'climate-neutral' buildings, for which the emissions generated throughout their lifecycle are (absolute) zero or (balanced or offset) net-zero. Yet, currently reaching absolute zero GHG emissions from operations (including the supply chain) alone, and offsetting emissions embodied in the building itself, in water supply and in wastewater treatment are goals hard to accomplish today. Hence, in the short- and medium-terms, "net zero" emission is a pragmatic goal, for which offsets play a key role (LÜTZKENDORF; BALOUKTSI, 2023).

If only direct GHG emissions (Scope 1) are considered, buildings with absolute zero operational emissions (i.e. completely decarbonised) can be produced in many climates and typologies, without needing offsets (LÜTZKENDORF; BALOUKTSI, 2023), by combining high energy efficiency and exclusive use of distributed generation (onsite) of renewable energy sources. Even so, GHG are still emitted in the upstream and downstream supply chains

(LÜTZKENDORF; FRISCHKNECHT, 2020). Another background pressure refers to the massive demand boost for minerals and metals (in developed countries) and mining (in developing ones) to support the global transition towards a net-zero future, based on renewable energy generation and storage technologies needed to mitigate GHG emissions and deliver SDGs 7 and 13 (THE WORLD BANK, 2020).

A current shift in the net zero debate tends to allow offsetting of unavoidable residual emissions (Scope 3 plus Scope 1 emissions from refrigerant leaks) while the whole economy decarbonises. Offsets for Scope 1 and Scope 2 emissions from operational energy use would be excluded though (LETI & CIBSE, 2022). This way, building design and construction should minimize GHG emissions before seeking to offset residual emissions and balance them down to net zero (LÜTZKENDORF; BALOUKTSI, 2023) or to use technologies that sequester CO_2 and aspire for carbon negative construction. In fact negative emission technologies (NET) are required by all scenarios in the latest IPCC (2021) report.

Indeed, this concept applies to any building project, climate and market. However, for many parts of the world a net zero lifecycle carbon perspective seems very distant. Poorer regions started further behind in the net zero race and find it harder to catch up than others. Narrow net zero visions are sometimes translated into standards that promote 'superefficient HVAC' solutions, while what is needed is buildings that run for as much of the year as possible on local natural energy (solar in winter and natural ventilation in most seasons). High energy efficiency, based on active equipment, comes at a high cost, not affordable to everyone, everywhere.

Benefiting from a greener-than-global-average electricity mix, like in Brazil (where electricity is about 16% carbon intensive), indeed facilitates to decarbonise building operation. Gomes et al (2018) confirmed that for a demonstration building. Even so, neutralizing its life cycle emissions would only be accomplished if the whole building plus a considerable surface next to it were wrapped in PV arrays. But such conduct is currently unlikely for regular buildings and off the table for social housing due to cost restrictions. Gomes and Pulgrossi (2021) estimated that removal of each hour of heat-related discomfort in units in three regions and climates in Brazil would require between 10 and 13kg CO_{2eq} and that the active solution (fans) responded by 1,5 to 3 times the sum of annualised embodied emissions of all passive measures considered. With little or no fat to shred, even simple passive improvements are unaffordable, and emissions offset or carbon removal are unthinkable in situations of daily energy poverty. A net neutral whole-life carbon goal seems unrealistic.

This paper examines the literature on trends regarding emissions offset or removal, and discusses how calculation rules and local or building segment limitations influence their applicability and might rerank contribution/climate potential of technological options.

2. Method

Given the above-mentioned challenge, we look at CO_2 removal strategies that store carbon in the built environment, compensating for the residual emissions – which will be adamant to allow reaching a net zero status. An exploratory literature review to identify the most promising/feasible options is followed by a discussion on how different (i) carbon accounting rules applied to identified options interfere with the interpretation of their Global Warming Potential (GWP) and environmental attractiveness and (ii) geographic/climate/construction contexts could limit applicability and challenge the net zero target achievement.

3. What seems promising to reach net zero carbon goals?

Most approaches for storing and/or sequestering carbon within the built environment do so during building use, but mineralization/carbonation also uptake carbon during EOL (KUITTINEN et al., 2023). But the low hanging fruit approaches – biobased building materials and biochar in soils - uptake carbon offsite before building use (and during, if biochar is applied) and stored it on site, during use. Climate potential of options for capturing and storing carbon onsite is lower, despite high applicability of carbonation in concrete and of natural photosynthesis/carbon uptake into soils in urban landscaping. Onsite carbon capture and offsite storage options rely on emerging (e.g. HVAC systems with direct air capture (DAC), artificial or enhanced photosynthesis and on marginal (e.g. living structures, building skins) technological solutions, with low or too variable maturity level, and still strongly restricted by their costs and maintenance requirements.

Kuittinen et al. (2023) ranked the approaches according to their climate potential and current applicability to construction. Three families of solutions stood out: biobased construction (wood, bamboo and straw, plus biochar for landscaping) and composites; carbonation of concrete/cement-based items; and urban landscaping (natural photosynthesis; accumulation in soils). CO_2-cured concrete, and air conditioning with DAC *in offices* would complete the medium to high combinations in both axes.

In their systematic literature review, Maierhofer et al. (2023) found that only materials assigned to the Eurostat categories ‘biomass’ or ‘non-metallic minerals’ had CO_2 storage potential and, based on their findings, proposed a new categorization: ‘biomass - fast growing’, ‘biomass - slow growing’, 'non-metallic mineral - natural' and 'non-metallic mineral - industrial’. The first category consisted of straw, hemp and bamboo but also miscanthus, sheep wool, herbaceous plants, moso bamboo, palm leaves and seaweed. The second category, ‘biomass - slow growing’, contained materials like wood or timber but also cellulose fibre, cork, cardboard and construction paper. The category ‘non-metallic minerals - industrial’ included the large group of industrial alkali wastes such as blast furnace slags, coal fly ashes and municipal solid waste incineration ash, among others, while the category 'non-metallic mineral - natural' included magnesium silicate-based rocks like serpentine and olivine, and also akermanite, pyroxene, tremolite, enstatite, wollastonite, nesquehonite and others (MAIERHOFER et al. 2023). Materials in the categories 'biomass - fast growing' and ‘biomass - slow growing’ have the highest CO_2 storage potential according to the literature (MAIERHOFER et al. 2023).

4. Unpacking most promising strategies

Considering both potential for applicability in buildings (associated to technology readiness level and material availability) and potential for CO_2 storage, the literature points to two major classes of promising strategies to help to compensate for life cycle embodied CO_2 emissions in buildings, namely: biobased materials use and mineral carbonation. The following subsections further introduce these classes, while the next section discusses how their performance towards a net zero whole life carbon target is challenged by rules and context.

4.1 Biobased materials

Biobased materials absorb atmospheric CO_2 as they grow, through photosynthesis. Their potential to temporarily store CO_2 removed from the atmosphere coupled with their renewable nature has significantly increased their attractiveness as a building material. The CO_2 absorbed by these materials during growth is assumed to be enough to not only compensate the emissions associated with their own production and distribution, but also

emissions associated with other materials and activities that take place within a building's life cycle.

While timber is the most used biobased material in the built environment, "fast-growing biobased materials" are mostly employed for their thermal properties as insulation and stands out for their carbon storage potential (MAIERHOFER et al., 2023). Typically covering herbaceous plants like straw and hemp, these materials do not require long rotation periods. In other words, the period between establishment of the crop and final harvest or regeneration is many times shorter than for timber. When one takes into account that buildings last for decades and fast growing biobased material crops can be replenished in much less than a decade (in some cases less than a year), their storage potential becomes more significant than that of forest products (PITTAU et al. 2018). Another well-known biobased material that falls within the fast-growing category but is not used for thermal properties is bamboo. Despite its rapid growth and lightweight features, bamboo exhibits a high strength-to-weight ratio and is able to withstand significant structural loads (SHU et al. 2020).

4.2 Mineral carbonation

Construction products containing cement and/or lime, such as concrete, mortar and bricks, have the potential to absorb CO_2 when their surfaces are exposed to the air and the contained calcium oxide (CaO) and calcium hydroxide ($Ca(OH)_2$) react with the CO_2 in the atmosphere. This natural process is known as carbonation. In this case, the carbon sequestered qualifies as a permanent storage as it will stay in the form of calcium carbonate within mineral products until they are heated to high temperatures by humans or an unlikely geological process.

Carbonation rates depend on the duration of exposure, concrete designation and the exposure conditions including any concrete surface treatments. Therefore, carbonation only affects untreated/uncoated exposed concrete elements. Moreover, there is a maximum CO_2 that can be absorbed by any given quantity of cementitious material under certain circumstances, and once reached, no further carbonation occurs.

According to studies, natural carbonation of cement products during the use stage typically plays a minor role, i.e. about 1-5% of the GHG emissions of a massive concrete building (RESCH et al., 2021; ALIG et al., 2020) and hence may be ignored. Carbonation effects in bricks are less studied, but Sambataro et al. (2023) recently found that the carbonation of calcium silicate bricks can offset 5% of building GHG emissions, for maximum carbonation potential and disregarding e.g. the presence of a render layer that would most likely reduce carbonation values.

In this context, CO_2 mineralization via curing in cementitious and lime-based products during manufacturing, and natural carbonation at the end of life have gained attention, as more promising potential carbon removal solutions associated with mineral products.

The carbonation rate of construction and demolition aggregates is faster than during service life, since the exposed surface drastically increases after demolition. As such, CO_2 uptake after demolition can be up to 50% higher in comparison with the concrete structures in service (MAIA PEDERNEIRAS et al., 2022). Saade et al. (2022) found that, on a macro-scale, if 80% of used concrete is assumed to be crushed into smaller particles and 20% to be landfilled, the cumulative proportion of carbon uptake in 2050 amount to over 9% of the cumulative global warming effect of concrete manufacturing. This places the carbonation of crushed concrete among the most promising mitigation strategies in some contexts.

In addition to influencing factors such as particle size, cement content and relative humidity (e.g. thinner recycled aggregates carbonate faster than the others), the time that the recycled aggregate has been stockpiling before being used as a ground filling material

significantly affects the carbonation rate (PICCARDO; GUSTAVSSON, 2021); the more time crushed concrete is in contact with the air, the more fully carbonated the particle will be. For example, a study from the Institution of Structural Engineers (GIBBONS; ORR, 2022) suggests that up to 5% of A1-3 concrete carbon emissions can be re-absorbed at EoL (module C3) but based on the assumption that concrete crushed on site at EoL sits on site for 26 weeks before being removed. The calculation of carbon removal potential of this EoL scenario would necessitate specifying the time of carbonation to be assumed, which is what defines the level of overall importance of this effect. In the absence of national scenarios, the Swedish Environmental Research Institute (IVL) proposes fixed CO_2 uptake values of 10kgCO_2/m3 of concrete, or 20kg CO_2/m3 with improved end-of-life handling procedures (CAPON; de SAULLES, 2023).

Table 1 shows examples of commercialised cement and concrete construction products that use CO_2 in their production. Such accelerated carbonation process can have great potential not only to reduce impacts of concrete but to generate carbon negative footprints for precast elements (the effect of CO_2 curing on reinforced concrete and potential risk of steel reinforcement corrosion needs further examination). For example, this can be the case when the use of alternative binders, like steelmaking slags, which typically already leads to low carbon concrete, is combined with curing with waste CO_2, given that the transport distances also are reasonable. In the Finnish context, Mäkikouri et al. (2021) compared the A1-3 impacts of conventional concrete (243 kg CO_{2e}/m^3) to that of CO_2-cured blast furnace slag concrete using purified CO_2 or flue gas CO_2, and the carbon footprint was negative in both cases (-157 and -187 kg CO_{2e}/m^3, respectively). However, not all CO_2 utilization methods adopted in concrete production to date necessarily result in climate benefits (Ravikumar et al., 2021). Comprehensive LCAs are required that include the CO_2 impact of capturing, transporting and utilizing CO_2 to determine the benefits.

Table 1: Examples of commercialised cement and concrete construction products use CO_2 in their production, representative of (a) concrete production via CO_2 curing of cement-based materials (CarbonCure, Solidia Technologies and CO_2-SUICOM), and (b) production of blocks from industrial wastes such as steel slag (CarbiCrete and Carbstone). Information taken from Li and Unluer, 2022, and Hanifa et al., 2023. Note: "CO_2 uptake" indicates the absorbed CO_2 during the curing and not the overall reduction potential of these products due to improved mixes compared to typical concrete products.

	Technology	CO_2 absorption method	Country	TRL	Commercialization/ application phase	CO_2 uptake	Final product
CO_2 curing	Carbon Cure	Injection of CO_2 in the concrete mix	Canada	8–9	installed in over 300 concrete plants worldwide with most ready-mix concrete producers using this technology located in Alberta	100–200 kg CO_2/ton of aggregate	Concrete
	Solidia	CO_2 curing cement concrete	Canada	8	The first precaster using Solidia cement and concrete solutions was manufactured in the USA. Compliance with durability and other requirements in the USA and EU under investigation	250–300 kg CO_2/ton of cement.	Cement and concrete
	CO_2-SUICOM	γ-C2S and fly ash to reduce cement, and CO_2 curation	Japan	9	already been applied to building elements in Nakano Central Park Residence (i.e. balconies)	109 kg/m^3	Concrete
Carbonated coproducts	Carbstone	Carbonation of steel slag (CO2 from flue gas)	Belgium	9	test plant in Wallonia that produces building blocks	180–200 g CO_2/kg of steel slag	Carbonated blocks, roofing tiles
	Carbicrete	Carbonation of steel slag to replace cement (cement free concrete)	Canada	6-7	it partnered with Patio Drummond in 2021 to scale up production, and blocks are currently being produced in Quebec	1kgCO_2/ block (18 kg cinder block)	Carbonated blocks

5. What about calculation and impact assignment rules?

The potential solutions to offset residual CO_2 emissions are many-fold, and the range of compensation possibilities, technological readiness and cost deeply affect their applicability. But the complexity of addressing carbon offset solutions does not stop there. The balance of generated and avoided or removed Scope 1, 2 and 3 emissions is ideally determined through Life Cycle Assessments (LCA). As a comprehensive methodology to estimate potential environmental impacts of a product, process or service throughout its entire life cycle, LCAs

provide valuable insight into carbon hotspots which not only supports reduction of environmental impact but also helps point out the most effective CO_2 compensation efforts that lead to minimal trade-off.

Conceptually, a negative environmental impact score may sound counterintuitive at first, and possibly caused the many calculation rules and approaches within the LCA method to address carbon dioxide removal (CDR) proposed to address it. While in the built environment their use has been mostly explored for biobased materials such as timber, the quest for offsetting options has turned the scientific community's gaze towards other carbon uptake possibilities, such as the ones explored in the previous sub-section. As the number of options for carbon removal grows, a similar effect is observed in the methodological framework, widening the calculation spectrum.

The European standard EN 15804 determines the rules for life cycle-based Environmental Product declarations (EPD) of construction products. It attempts to regulate the carbon balance of some of the mentioned offset solutions, following the "modularity principle" to assign emissions (and uptake) to the life cycle stage in which they occur. Still, such assignment is challenging for certain solutions, as is the interpretation as to which product's life cycle could receive the uptake benefit, especially when recycling, reuse and waste management activities are inherently part of the solution. The EN 15804 standard also introduces specific rules for the accounting of CO_2 uptake by timber and other forest-related products that have been recently revised. As the research direction shifts, further revisions may be expected, so an international consensus will most likely not be reached anytime soon.

5.1 Biobased materials

Until recently, in traditional LCA, the timing of GHG emissions was unaccounted for, which rendered the benefits of temporary storage and the differences between varying storage periods meaningless. The cycle of biogenic CO_2 - i.e. the CO_2 absorbed by biobased materials during growth - is typically considered to be neutral, as the CO_2 absorbed is expected to be released when these materials reach their end of life, either through incineration or decomposition. This approach (known as the 0/0 approach) receives criticism for neglecting the impact of rotation periods on global warming assessments and overlooking potential storage-related benefits (HOXHA et al., 2021), and for assuming carbon neutrality, as biogenic carbon emissions are expected to occur from decomposing roots, reduced soil carbon content, and a loss in carbon storage potential resulting from non-harvesting practices (PENG et al., 2023).

The so-called -1/+1 approach is another biogenic carbon accounting approach that has gained traction in built environment LCAs. While the initial principle of carbon neutrality remains, the calculations allow consideration of the biogenic CO_2 that was absorbed during growth of the biobased material, which - according to the EN 15978 standard on buildings LCA - shall be equal to the amount of biogenic CO_2 released during the end of life of the material, regardless of the scenario considered (landfilling, incineration, recycling, etc.). The main difference between the -1/+1 and the 0/0 approach is that the former provides an overview of the biogenic carbon flows which are completely disregarded in the latter (Hoxha et al 2021). Still, the previously mentioned critique remains.

Some approaches that claim to better capture the impact of time in biogenic carbon accounting have been proposed in the specialised literature. These approaches focus mostly on proposing adjustments in the determination of global warming potential, which, very simply put, relies on "characterisation factors" that consider the different greenhouse gases' ability to increase heat in the atmosphere. Levasseur et al. (2010) introduced a time-dependent characterisation factor approach, which is based on the decay of each GHG in the atmosphere, while Cherubini et al. (2011) developed specific characterisation factors for

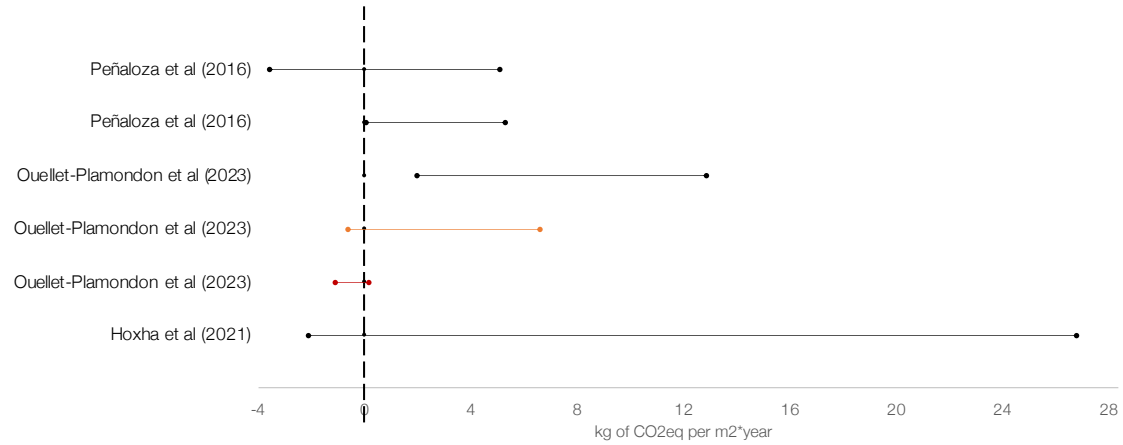
biogenic CO_2, considering biomass rotation periods. A longer rotation period leads to a higher biogenic global warming score due to the increased duration of CO_2 in the atmosphere. Building upon Cherubini et al.'s work, Guest et al. (2013) extended the method to evaluate carbon storage in wooden products, finding that carbon neutrality is achieved when storage lasts approximately half of the rotation period.

The first mentioned approach (by Levasseur et al, 2010) has been employed assuming two different scenarios to account for uptake: (1) trees growing before the use of harvested wood products, following the natural carbon cycle; or (2) accounting for "regrowth" after harvesting, assuming the same amount of harvested trees would start growing immediately after production (PEÑALOZA et al., 2016; PITTAU et al., 2018). The regrowth approach has been favoured because, from the carbon storage perspective, if using the first scenario, the biobased material would “receive” the full benefit of CO_2 uptake even if the product is short-lived. From a sustainability perspective, preferring consideration of biogenic carbon uptake after construction would encourage future forest regrowth (Hoxha et al 2021).

The different biogenic carbon accounting approaches lead to varying outcomes, not uncommonly leading to diametrically opposed conclusions. Hoxha et al (2021) assessed a timber building in Austria using the static approaches 0/0 and -1/+1, and the dynamic approach proposed by Levasseur et al. (2010) considering the biogenic CO_2 uptake by timber *before* and *after* harvest. While the result indicated that with both static approaches the overall life cycle GWP of the building was the same, when employing the dynamic approach results varied significantly. Most interestingly, when comparing the life cycle global warming scores of that same building considering the uptake before and after harvest, the result at the end of the service life of the building changed from a negative GWP, in the former case, to a positive GWP in the latter case. The same building could therefore be perceived as a net negative whole life carbon design, which would even act as a potential offset for emissions arising elsewhere, or as a net positive design, which would require compensation to meet carbon neutrality.

Ouellet-Plamondon et al. (2023) showed the results of LCAs of the same multi-residential building carried out by experts from sixteen countries, using biogenic carbon accounting methods typically employed in their practice. One specific biogenic carbon calculation approach stood out, the so-called “-1/+1*”, a variant of the -1/+1 approach which assumes permanent storage of a portion of the absorbed CO_2 if a biobased material is recycled or landfilled. The authors showed the results at the material level (a softwood beam), at the element level (the building’s superstructure), and at the whole building level. At the material and element levels, the whole life carbon when employing the -1/+1* approach could reach a net negative value, which was not the case with the 0/0 and -1/+1 approaches, for which either a neutral or a net positive whole life carbon score would be obtained. Again, decision making processes relying on such results would vary considerably.

Peñaloza et al. (2016) compared the global warming potential of a hypothetical building block in Stockholm with three design variations: (i) a concrete structure, (ii) a cross-laminated timber (CLT) structure and (iii) a design referred to as “increased bio”, where mineral-based insulation and cladding from the CLT design were replaced with bio-based products, namely cellulose fibre and oriented strand boards. When employing the static 0/0 approach to model the building’s GWP, the two biobased designs reduced over 40% of the GWP relatively to that of the concrete building. When employing the dynamic approach considering uptake *after harvest*, the GWP reduction increased to 68% for the CLT building and 88% for the increased bio building. Finally, the dynamic approach with uptake *before harvest* resulted in a net negative GWP score for the “increased bio” design, positioning it as a potential carbon offset solution (Figure 1).



** GWP results for building and element level are shown per m2*year, while the result on the material level is given per kg of material - in this case, softwood.*

Figure 1: Oscillation of GWP of buildings (black lines), material (red line) and element (orange line) around the net zero target, depending on the approach used for biogenic carbon accounting.

The observed variation indicates that the quest towards carbon neutrality is hindered by a lack of harmonised rules, which is an additional layer of complexity to an already incredibly challenging undertaking.

5.2 Mineral carbonation

The most used model to determine the CO_2 uptake of concrete due to carbonation, especially by European manufacturers and industry, is the standardised model provided in EN 16757. The natural carbonation process occurs over the life of the concrete or brick products and is therefore accounted for in the use module B1 in the various EPDs. When it comes to EoL uptake the rules on when and how to consider it are loose. The benefit can be considered as part of waste processing (C3), otherwise it goes onto the next life cycle and is reported in module D – hence, no compensation is considered for the concrete's first user. In the case of bricks, the specific standardised rules that determine how to develop an EPD for that material class do not specify carbonation rules as clearly as the EN 16757. However, a few brick EPDs list negative CO_2 values due to carbonation in B1 (e.g. SwissModul from p + f Sursee, 2018) and C3 (e.g. the sector EPD of the Federal Association of the German Brick Industry, IBU 2021).

Similar to biogenic carbon accounting for wood, carbonation is a time-dependent process and, as such, can be taken into account in a dynamic way (e.g. PITTAU et al., 2018; SAADE et al., 2022). The time dynamic is that carbonation occurs fast at first and then at a slower rate as more depth is carbonised. After deconstruction, the material is crushed and the exposed surface increases which leads to another rapid rise in carbonation rate and a subsequent levelling off. A simplified approach (different than the previously mentioned studies) is followed by the Norwegian FutureBuilt Zero method (RESCH et al., 2022) which starts from the following assumptions: an uptake of 94 kg CO_2 per tonne of cement after a service life of 100 years, that most storage is considered to happen in the first years, and the absorptions decrease exponentially over the years. According to these assumptions, after 25 years, approximately half of the uptake that takes place over a 100-year period will have taken place. Following a square root function, the uptake that takes place in the years that are part of the building's lifetime is attributed to the building. This approach is characterised as simplified as it does not consider the different concrete strength classes and exposure levels to air.

In the case of CO_2-cured concrete the carbon removal from the atmosphere or when separated from biogas must be recorded as a negative value in A1-3 for the indicators GWPfossil (and consequently GWPtotal) according to the EN 15804+A2. The CO_2 absorbed

during the curing process is not released at the end of the concrete component's life, which leads to a -1/0 allocation, if one refers to the same nomenclature for biogenic carbon accounting as previously described. As the use of such products is at an early stage, the availability of life cycle data is sparse. Therefore, clear guidelines for robust life-cycle analyses and transparent datasets are needed to inform net zero target. Furthermore, when carbon uptake of CO_2-cured concrete is sold as carbon offset to third parties, such carbon savings should not be reported as part of the building's whole life carbon to avoid double counting, for having already been collected by a third party that purchased it as an offset.

6. And what about context?

Using biobased materials like wood, bamboo and straw does not always suit all building typologies, and their durability is particularly challenged by a high temperature-high humidity combination. In such conditions, components require pre-treatment, which has a high-impact from production to end of life. Earth construction does not suit all typologies either, but has benefits and the indisputable advantage of being low-cost and can be an adequate temperature and humidity regulator for certain climates, which would otherwise demand energy to ensure habitability. Advanced use of biochar also seems promising anywhere, but has just begun. Performance of natural materials is more difficult to predict and control, and the lack of codes of practice/standards creates uncertainty and perceived risk, which can make financing harder. Such issues should be addressed urgently, to enable these elements and techniques to also play a part in the final carbon equation.

The ubiquitous use of concrete makes carbonation strategies also not limited by geography, but land-consuming swift carbonation (to allow for spreading out the crushed concrete for) without backfiring in transportation emissions might be impractical in certain situations. Contrastingly, carbonation cure has been used in countries like Canada, the United States, the United Kingdom and Japan, with increased interest across Europe. Adding this process to existing block plants is feasible at relatively low additional cost: 4-14%, for a study in Brazil (FORTUNATO et al., 2022). Those authors estimated that approximately 168,780 ton of CO_2/year would be sequestered if all Brazilian concrete block plants implemented it (smallest absorption rate considered). That CO_2 mass corresponds to roughly 10% of the emissions of the national concrete block industry.

Biochar use in soils, carbonation of cement-based materials and natural photosynthesis contribution depend on surface area, which can be limited in dense urban areas. Also, the omnipresence of cement/reinforced concrete based construction elements and techniques, which require low cost and low skilled labour, are deeply rooted in many constructive cultures, despite their impact, maintenance and waste intensities, and make it more difficult for other approaches to advance. Hence, though theoretically applicable anywhere, local limitations might rerank contribution/climate potential of technological options. It was not possible to cast an in-depth analysis in this direction herein.

Good old design plays a cheaper role and best practices should be enforced in contexts where financial resources are limited. In disadvantaged cases, reducing embodied carbon of current techniques (e.g. through enhanced earth construction or others) and smart use of passive measures to minimize operational emissions can be more reasonable to reach overall carbon neutralization than aim for financially unfeasible net zero and NET techs to all. Some embodied carbon must even be needed - "invested" in passive measures - and still make more sense towards collective goals.

7. Final remarks

As we approach the 2050 deadline to become a carbon neutral society, many unanswered questions remain. A careful portfolio of measures will have to be delineated, but ultimately

cherry-picked on a case-specific basis. There is no one-size-fits-all solution, which adds challenges and complexity, but supports creativity. Compensation measures like negative emissions technologies (NET) or carbon dioxide removal (CRD) shall become increasingly sought for.

This paper does not perform an exhaustive assessment of strategies but rather focuses on how certain methods can affect estimations of the most common/promising ones and how context can even cause some rank reversal. From a methodological perspective, if we are to meet the ambitious targets, not only is harmonization key – to provide a common benchmark or benchmarking procedure, but scientific robustness must be assured.

To support global efforts in making life-cycle carbon-neutral buildings, data, and context-based benchmarks are also needed, but are still scarce and far from driving or influencing mainstream practice. Moreover, from a context perspective, regional specificities must be further studied to allow for a tailored roadmap. Recent research, regulatory frameworks and financial incentives to boost net zero initiatives are predominantly related to the global North, but, if we are to reach our Global Future, political, financial and technological partnerships and resources must be urgently directed to all nations to play their part in the collective decarbonization.

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