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RESEARCH

Biogenic carbon in buildings: a critical overview of LCA methods

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Abstract

The increasing pressure to reduce greenhouse gas emissions from buildings has motivated specialists to develop low-carbon products incorporating bio-based materials. The impact of these materials is often evaluated through life-cycle assessment (LCA), but there is no clear consensus on how to model the biogenic carbon released or absorbed during their life-cycle. This study investigates and compares existing methods used for biogenic carbon assessment. The most common approaches were identified through an extensive literature review. The possible discrepancies between the results obtained when adopting different methods are made evident through an LCA study of a timber building. Results identified that land-use and land-use-change (LULUC) impacts and carbon-storage credits are not included in most existing methods. In addition, when limiting the system boundary to certain life-cycle stages, methods using the –1/+1 criterion can lead to net negative results for the global warming (GW) score, failing to provide accurate data to inform decision-making. Deviation between the results obtained from different methods was 16% at the building scale and between 35% and 200% at the component scale. Of all the methods studied, the dynamic approach of evaluating biogenic carbon uptake is the most robust and transparent.

Practice relevance

This critical review identified key methodological differences between the most commonly used methods and recommended standards for biogenic carbon accounting in buildings. This indicates a lack of consensus and guidance for conducting LCAs of bio-based construction products and buildings using bio-based materials. A case study applying four different LCA approaches on a timber building identified the inability to compare results and create proper benchmarks. Moreover, different methods lead designers to pursue different strategies to reduce a building's carbon footprint. Regulators, the construction industry and the construction products industry are directly affected by this lack of comparability. This research highlights the flaws and benefits of commonly used methods. A clear and grounded recommendation is for practitioners to adopt dynamic biogenic carbon accounting for future assessments of bio-based materials and buildings.

Keywords: bio-based materials; biogenic carbon; buildings; dynamic life-cycle assessment (LCA); environmental product declaration (EPD); life-cycle assessment (LCA); product environmental footprint (PEF)

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1. Introduction

The manufacture and transport of construction products currently represents 23% of human-related greenhouse gas (GHG) emissions (Abergel *et al.* 2017), with over half of those as a result of cement and steel production, making its contribution to the climate crisis significant.

Previous research and policy initiatives have concentrated on reducing the operational impacts of buildings, particularly through improving energy efficiency and increasing renewable energy (Lützkendorf *et al.* 2014; Passer *et al.* 2012, 2016a, 2019). Recent studies indicate that the focus now must shift to other stages of the life-cycle, including the embodied impacts associated with manufacturing, transport, construction, maintenance and end of life, in order to further reduce GHG emissions (Röck *et al.* 2020; Lützkendorf *et al.* 2014; Mirabella *et al.* 2018; WGBC 2019; Drouilles *et al.* 2019).

The European Green Deal, which was announced in December 2019 by the European Commission, is a new growth strategy aiming to transform the European Union (EU) into a modern economy where there are 'no net emissions of greenhouse gases in 2050' and where 'economic growth is decoupled from resource use'. A key part of the roadmap is mobilising research and fostering innovation to facilitate scientifically based decision-making, including building and renovating in an energy and resource-efficient way.

Life-cycle assessment (LCA) is a recommended process for measuring GHG emissions associated with constructing and operating buildings. It is a quantitative and objective method of assessing a product or material environmental impact throughout its entire life-cycle (ISO-14040 2006). Environmental product declarations (EPDs) use the LCA methodology with the addition of product category rules (PCR) per product group enabling consistency and comparability. Manufacturers of construction products are increasingly publishing EPDs and other LCA formats (Passer *et al.* 2015). This is in the context of several international and European standards including ISO-14040 (2006), ISO-14044 (2006) and EN-15804 (2019), providing consistency to the methods used to conduct LCA and assess the global warming (GW) score (typically measured in CO_2e).

1.1 Challenges regarding life-cycle-related GHG emissions

Academic research focusing on life-cycle-related GHG emissions of the built environment has significantly increased over the recent years, as identified by Pomponi & Moncaster (2016) and Röck *et al.* (2020). Numerous academic studies look in detail at individual buildings (*e.g.* Lasvaux *et al.* 2017; Kreiner *et al.* 2015, Passer *et al.* 2012; Hoxha *et al.* 2020).

Furthermore, designers are demanding information that will enable them to make informed decisions regarding the carbon footprints of their projects (BRE 2013). Therefore, it is imperative that the information is accurate in terms of its contribution to the total carbon budget.

LCA data, due to their complexity and the long time it can take to collect them for all system boundaries, are difficult for designers to integrate into decision-making (Meex *et al.* 2018). In order to simplify the process, some researchers advocate the reduction in data within LCAs to include only the product manufacturing stages (A1–A3, according to EN-15804 2019), justified by the fact that between 70% and 80% of the GW score is generated during this stage. However, this streamlining process can provide misleading information, as recent research has identified that the other life-cycle stages can have a significant impact on the results.

Reducing the number of flows in a life-cycle inventory (LCI) (*e.g.* not calculating each LCA module) requires careful assessment (Lasvaux *et al.* 2016). Research has identified that the critical flows to track when examining the GW score of mineral-based materials is the extraction and production phases (Lasvaux *et al.* 2014). However, when bio-based materials and products are incorporated in the building LCA, examining only the production phase can lead to significant differences from a full LCA (Fouquet *et al.* 2015; Sandin *et al.* 2014). The end of life is a critical aspect to be considered as well as before extraction during biomass growth (Fouquet *et al.* 2015; Levasseur *et al.* 2013). An additional challenge with bio-based materials is that they belong to multiple systems, each able to claim the benefit of carbon capture. An example is a timber beam: a harvested wood product that can be integrated as an end product of forest industry and calculated as such in a forest LCA (Taverna *et al.* 2007). It is also a bio-based building material that can be taken as an input for the building industry (Head *et al.* 2020). Finally, at the building's end of life, this product may be used by the energy industry to generate heat or electricity (Müller *et al.* 2004). The same matter is produced and used in different technical systems through cascading logic (Mehr *et al.* 2018). If 'double counting' is to be avoided, then the multiple use of the same material requires clarity. An allocation to the different technical systems needs to be defined. There is no obvious solution as it is a question of agreement between the various stakeholders within the supply chain (Habert 2013).

1.2 Assessment of biogenic carbon

A considerable point of contention within LCA is the assessment of biogenic carbon (Levasseur *et al.* 2013; Breton *et al.* 2018). Biogenic carbon is emitted to air as CO_2, CO or CH_4 as a result of the oxidation and/or reduction of biomass by means of its transformation or degradation (*e.g.* combustion, digestion, composting, landfilling). Biogenic carbon can also be captured as CO_2 from the atmosphere through photosynthesis during biomass growth, a process commonly referred to as sequestration (Brandão *et al.* 2013). Bio-based products, such as wood, hemp and straw, contain circa 50% carbon by dry mass (Pittau *et al.* 2018), creating an opportunity to store carbon in buildings constructed with these materials (Churkina *et al.* 2020). Therefore, it is necessary that the assessment of carbon content and related GW score calculations are conducted in a transparent and comparable manner to avoid misleading information.

1.2.1 Biogenic carbon uptake and release

In traditional LCAs used for buildings, two main approaches can be distinguished when assessing the impact of biogenic carbon uptake and release. The first approach, which is referred to as the '0/0 approach' or 'carbon neutral approach', is based on the assumption that the release of CO_2 from a bio-based product at the end of its life is balanced by an equivalent uptake of CO_2 during the biomass growth. As a consequence, there is no consideration of biogenic CO_2 uptake (0) and release (0). The approach is illustrated in **Figure 1** for a wooden product used in a building. A distinction is made between the forest system, the building system and a potential subsequent product system, in the case of wood recycling. The building system is subdivided according to the modular structure of European standard EN-15978 (2011), including the product and construction process stages (module A), use stage (module B) and end-of-life stage (module C). In line with this standard, the subsequent product system is referred to as module D. As shown in **Figure 1**, biogenic CO_2 is not considered in any module. Only the release of biogenic methane (CH_4) is modelled in module C, due to its higher impact on GW compared with biogenic CO_2.

The second approach, which is referred to as the '−1/+1' approach, consists of tracking all biogenic carbon flows over the building life-cycle. In this approach both biogenic CO_2 uptake (−1) and release (+1) are considered, as well as the transfers of biogenic carbon between the different systems. This is illustrated in **Figure 2**. The uptake of biogenic CO_2 during the forest growth is transferred to the building system and reported as a negative emission in module A. At the end of life of the building, biogenic CO_2 (or CO or CH_4) is released or the carbon content is further transferred to a subsequent product system (in the case of recycling). In both cases a positive emission is reported in module C. An important aspect in this approach is that the biogenic carbon balance should be zero for all product systems. Compared with the 0/0 approach, the main advantage of the −1/+1 approach is to provide an overview of all biogenic carbon flows. However, there is a risk of biased and misleading results when only the impact of the product and construction

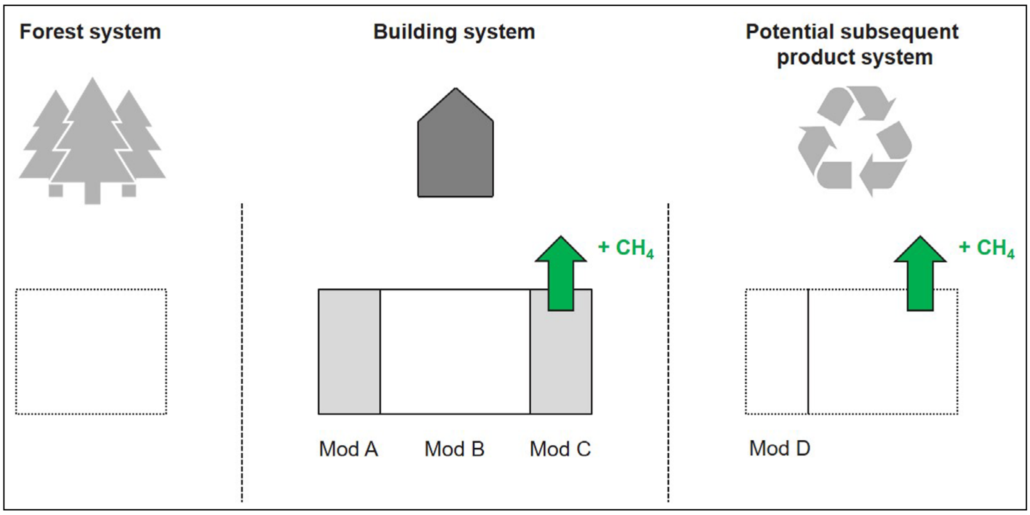


Figure 1: The 0/0 approach to model biogenic carbon uptake and release. Dotted lines indicate the product systems that fall outside the building system boundaries.

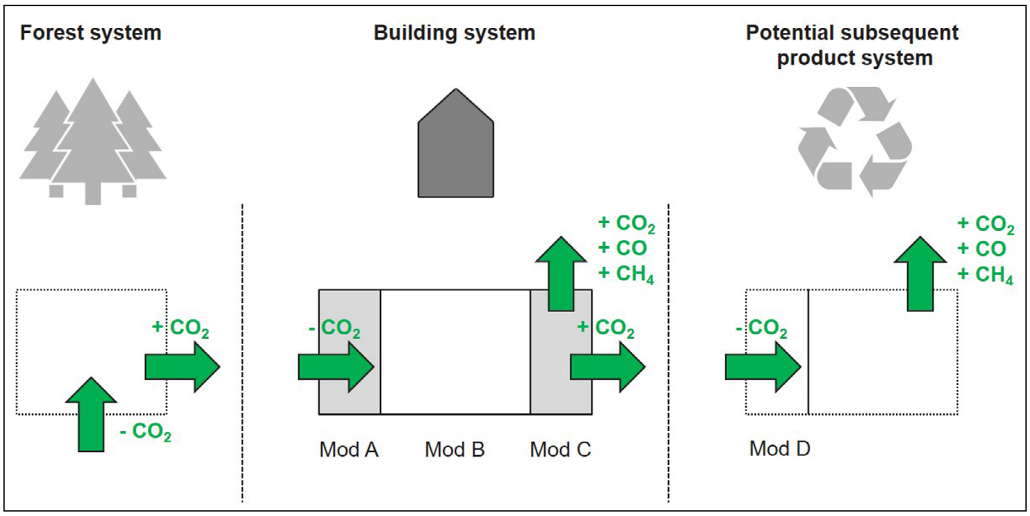


Figure 2: The −1/+1 approach to model biogenic carbon uptake and release. Dotted lines indicate the product systems that fall outside the building system boundaries.

process stages (module A) is assessed, considering the positive effect of biogenic CO_2 uptake but without reporting the release at the end of life.

The main criticism of traditional LCA approaches is that they do not consider the impact of the timing of the carbon emissions and the influence of the rotation periods related to the biomass growth. This can be problematic when assessing the impact of bio-based products. Studies such as that by Pittau *et al.* (2018) demonstrate that not all bio-based products can be considered as carbon neutral. Specifically, timber products (*e.g.* wood that has been processed into beams or planks) have a longer rotation period due to slow forest growth periods, so they cannot be considered as carbon neutral, in a short time horizon. Conversely, fast-growing bio-based materials, such as straw and hemp, have a short rotation period and can provide an effective mitigation effect on GHG emissions by rapidly removing carbon from the atmosphere (Pittau *et al.* 2018).

To better capture the impact of time, dynamic approaches have been developed. Levasseur *et al.* (2010) proposed an approach based on time-dependent characterisation factors. Cherubini *et al.* (2011) developed specific characterisation factors for biogenic CO_2 considering the rotation period of biomass. The longer the rotation period, the longer the mean stay of CO_2 in the atmosphere and therefore the higher the biogenic GW score. Guest *et al.* (2013) extended the method proposed by Cherubini *et al.* (2011) to assess the impact of carbon storage in wooden products. Based on this research, it was found that carbon neutrality is achieved for a storage time of about half of the rotation period.

Within the dynamic approach of Levasseur *et al.* (2010), two scenarios can be considered related to the timing of biogenic carbon sequestration in the forest: (1) assuming that trees grow before the use of the harvested wood product, following the natural carbon cycle (**Figure 3**); or (2) accounting for the so-called 'regrowth' after harvesting, assuming an equal amount of the harvested trees would start growing right after the production process (**Figure 4**) (Peñaloza

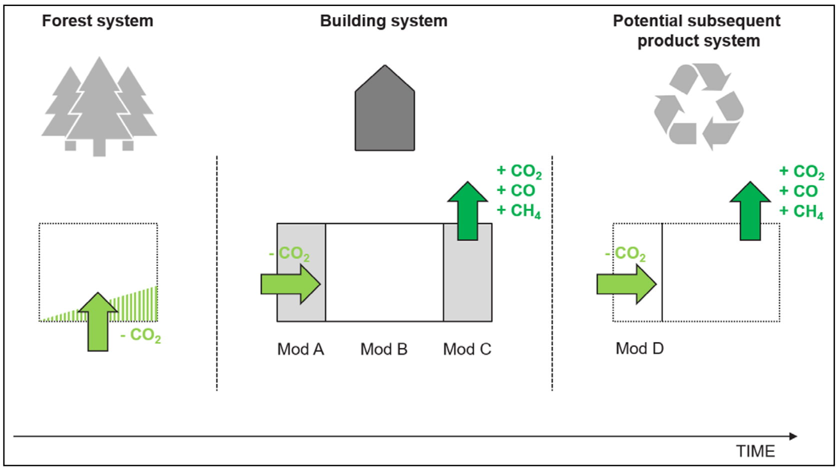


Figure 3: The dynamic approach, considering that trees grow before the use of the harvested wood product. Dotted lines indicate the product systems that fall outside the building system boundaries.

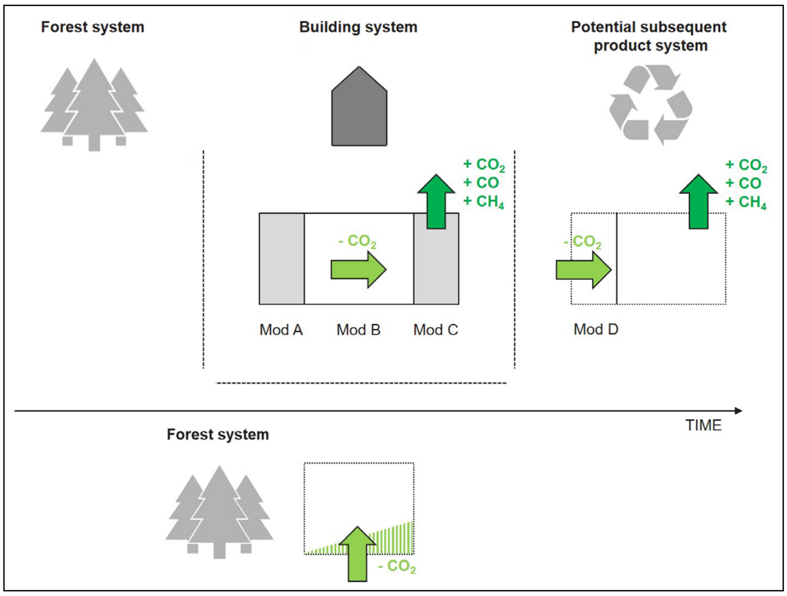


Figure 4: The dynamic approach, considering that trees regrow after harvesting. Dotted lines indicate the product systems that fall outside the building system boundaries.

et al. 2016; Pittau *et al.* 2018). Results vary considerably between the two approaches (Peñaloza *et al.* 2016), so the selection must be justified and clearly declared.

1.2.2 Carbon storage

Carbon storage can be defined as the sequestration of carbon in products for a certain period of time, resulting in a (temporary) reduction of the CO_2 concentration in the atmosphere (Brandão *et al.* 2013). In most LCA standards, there is a distinction between temporary carbon storage (within a 100-year period) versus permanent carbon storage (more than 100 years). In order to account for the positive effect of carbon storage, some LCA methods, namely the British Publicly Available Specification (PAS) 2050 (2011) and the European Commission's International Reference Life Cycle Data System Handbook (ILCD 2010) allow the calculate of a credit for temporary carbon storage.

1.3 Land use and land-use change (LULUC)

While the carbon stocks in bio-based materials are well researched, recent publications have identified that land use has an important effect on carbon sequestration, and has often been underestimated in the literature. Erb *et al.* (2018) concluded that with current climate conditions, if there was no human managed land, potential vegetation could store 49% more carbon than it does currently. Therefore, the contribution of LULUC for carbon sequestration has now become a subtopic of GW score calculation. One of the challenges of increasing biomass into the material, products and energy industries is that harvesting timber, for example, reduces forest biomass stocks compared with their potential. Therefore, those who manage the forests would need to both maintain and increase biomass productivity and stocks in order to maintain and increase carbon storage at a global level.

The more recent ISO-21930 (2017) and Draft EN-15804/prA2 (2017) provide characterisation factors for LULUC change based on the sustainability of forest management. An unsustainably managed forest has a characterisation factor of 1 kg CO_2e/kg CO_2, while the sustainably managed forest has a characterisation factor of 0 kg CO_2e/kg CO_2. As indirect land-use change methods are still under development, the calculation of indirect land-use change is not required by the standards.

1.4 Research objectives

Considering the variety of LCA methods and the current growth in bio-based products in the construction industry, the objective of this study is to critically analyse the different methodological approaches to assess biogenic carbon in buildings. The critical analysis consists of two parts: (1) a literature review of the existing methods; and (2) key LCA methods are applied to a building constructed with timber-based products, in order to analyse and understand the diverging LCA outcomes.

2. Material and methods

2.1 Literature review

A wide research question was formulated to guide the initial literature search:

- What are the most common methods to account for biogenic carbon in building materials?

Six additional research questions were formulated to determine the particulars of each accounting method:

- Which life-cycle stages are considered? Are the studies cradle to gate or cradle to grave?
- How is biogenic carbon uptake modelled in module A?
- Which approach is followed for temporary biogenic carbon storage, or delayed emissions of biogenic carbon in module B?
- How is biogenic carbon release modelled in module C?
- Is direct land-use change included or not? How?
- Is indirect land-use change included or not? How?

The literature sample was initially composed of studies knowingly important to answer the research questions according to experts' opinion (following the so-called 'snowball approach', as predicted by Littell *et al.* 2008 and Wohlin 2014). The sample was then enriched by performing a literature review on matters poorly addressed in the studies identified in the aforementioned way.

The 58 sources of literature selected include 14 peer-reviewed journal papers, 25 EPDs, 12 standards and seven research reports from a wide range of geographical locations and covering various construction typologies in order to obtain a holistic understanding of this topic. A matrix was developed to compare the key data from the literature review—enabling both quantitative and qualitative analyses guided by the previously defined research questions. This structured and wide review framework allowed research gaps to be identified and provided assurance of adequate coverage of qualified published information.

2.2 LCA methodology

Three biogenic carbon accounting methods identified as the most common through the critical review were applied to a highly energy-efficient timber building, which was part of a pilot project in Plus Energy districts in the city of Graz, Austria (Staller *et al.* 2015). The influence of addressing carbon uptake and release through (option 1) the 0/0 approach (*i.e.* carbon neutrality); (option 2) the −1/+1 approach and through a dynamic modelling approach (options 3 and 4) was investigated. For the dynamic approach, two scenarios were considered: (option 3) biogenic carbon uptake by the forest before extraction and (option 4) biogenic carbon uptake by the forest after extraction.

2.2.1 Whole-building LCA

The building life-cycle was modelled using the modular structure defined in EN-15978 (2011). The following life-cycle modules were considered in this research (**Figure 5**):

- Product stage (A1–A3).
- Construction process stage (A4 and A5).
- Use of the installed products (used here to report the impact of biogenic carbon uptake after construction) (B1).
- Operational energy use (B6).
- End-of-life stage (C1–C4).

Other life-cycle modules were not included as they were not influenced by the modelling choices and parameters investigated. For simplification, all materials and components were assumed to have the same reference service life as the building, *i.e.* 50 years. This assumption was adopted as the literature has demonstrated that the lifetime of many building components can exceed 50 years (Hoxha *et al.* 2014). The materials (*e.g.* paint), mechanical and electrical equipment and systems that have a reference service life of less than 50 years were not considered in the system boundary of the study.

The Swiss Ecoinvent database v.3.5 was used for the LCI (Wernet *et al.* 2016). The Ecoinvent system model 'Allocation, recycled content', which is also referred to as 'cut-off approach', was selected to be in line with the rules applied in EN-15978 (2011). With regards to the selected data records, preference was given to Western European processes to ensure they were representative for the Austrian context. When Western European processes were lacking, Swiss data records were used. Specific unit processes adopted for the research purposes are listed in the supplemental data online. The life-cycle impact assessment method IPCC 2013 (Ciais *et al.* 2014) was used for calculating the GW score.

A detailed list of quantities and types of materials was extracted directly from the building plans, enabling a calculation of the environmental impacts of the product stage (*i.e.* A1–A3). Transportation distances (to be used in modules A4 and C2) calculated for a building located close to the case study were used as a proxy. Results from the operational energy simulations performed by the designers of the case study provided the values for module B6. Simulation methods and associated input parameters can be found in Staller *et al.* (2015). The environmental impacts of modules A5 and C1 were considered equal to 5% of the impact of the product stage (A1–A3) (Hoxha *et al.* 2016). For the end-of-life calculations, modules C3 and C4 were modelled based on Austrian average scenarios. As a general rule, landfill processes were

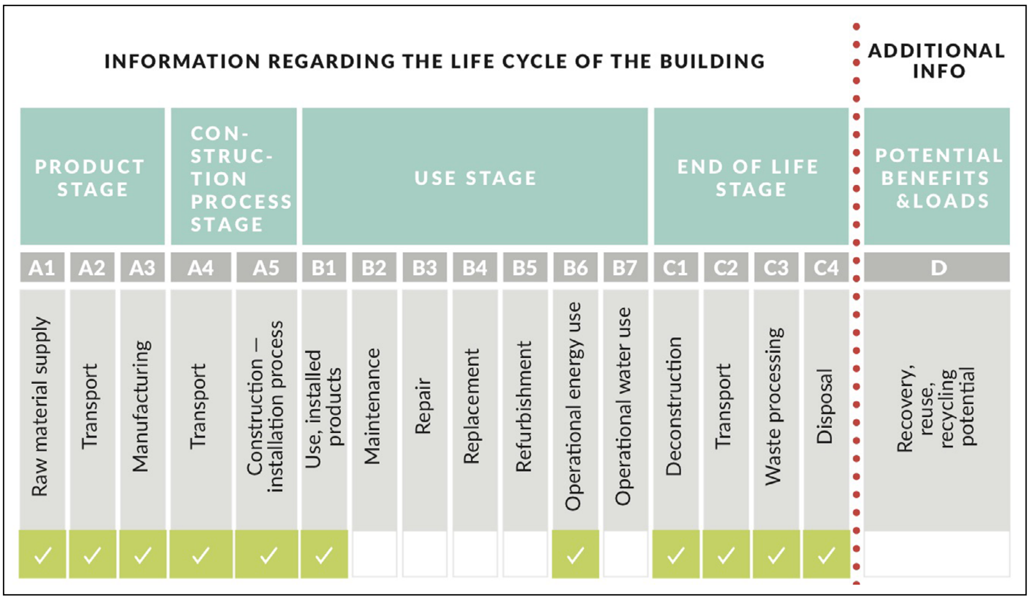


Figure 5: Life-cycle modules according to the EN-15978 (2011) standard. The life-cycle modules considered in this research are indicated in green.

selected for inert materials such as brick, concrete and plaster, while wooden products were assumed to be incinerated for waste to energy generation. For the dynamic calculation, the biogenic CO_2 uptake by trees regrowth was allocated to B1 for uptake after construction, and to A1 for uptake before construction. A specific non-linear biomass regeneration model was developed based on forest primary data collected by Masera *et al.* (2003) in order to calculate the annual carbon absorption of Nordic pine growth.

LCAs were supported by the software SimaPro v.8.5 (Pré Consultants 2018), which allows for a detailed analysis of the impact contributors. Furthermore, calculations from the software were coupled with additional calculations in Excel in order to model the impact of biogenic carbon uptake and release.

2.2.2 Biogenic carbon accounting

Regarding the traditional LCA approaches (static modelling), the GW score for the 0/0 approach is calculated as the sum of all fossil CO_2 CO and N_2O emissions and the sum of all fossil and biogenic CH_4 emissions, multiplied by their respective GWP factor, based on equation (1):

$$\begin{aligned} GW_{0/0} = & \sum\nolimits_t g_{CO_2,fossil}(t) * GWP_{CO_2} + \sum\nolimits_t \left(g_{CH_4,fossil}(t) + g_{CH_4,biogenic}(t)\right) * GWP_{CH_4} \\ & + \sum\nolimits_t \left(g_{CO,fossil}(t) + g_{CH_4,biogenic}(t)\right) * GWP_{CO} + \sum_t \left(g_{N_2O,fossil}(t) + g_{N_2O,biogenic}(t)\right) * GWP_{N_2O} \end{aligned} \tag{1}$$

The GW score for the −1/+1 approach, on the other hand, is calculated as the sum of all fossil and biogenic CO_2 emissions minus removals and the sum of all fossil and biogenic CH_4, N_2O and CO emissions, multiplied by their respective GWP factor, based on equation (2):

$$\begin{aligned} GW_{-1/+1} = & \sum\nolimits_t \left(g_{CO_2,fossil}(t) + g_{CO_2,biogenic}(t)\right) * GWP_{CO_2} + \sum\nolimits_t \left(g_{CH_4,fossil}(t) + g_{CH_4,biogenic}(t)\right) * GWP_{CH_4} \\ & + \sum\nolimits_t \left(g_{CO,fossil}(t) + g_{CO,biogenic}(t)\right) * GWP_{CO} + \sum\nolimits_t \left(g_{N_2O,fossil}(t) + g_{N_2O,biogenic}(t)\right) * GWP_{N_2O} \end{aligned} \tag{2}$$

where:

t = discrete time steps (year of impact occurrence)
$g_{CO_2,fossil}(t)$ = emissions of fossil CO_2 at time t
$g_{CO_2,biogenic}(t)$ = emissions minus removals of biogenic CO_2 at time t
$g_{CH_4,fossil}(t)$ = emissions of fossil CH_4 at time t
$g_{CH_4,biogenic}(t)$ = emissions of biogenic CH_4 at time t
$g_{CO,fossil}(t)$ = emissions of fossil CO at time t
$g_{CO,biogenic}(t)$ = emissions of biogenic CO at time t
$g_{N_2O,fossil}(t)$ = emissions of fossil N_2O at time t
$g_{N_2O,biogenic}(t)$ = emissions of biogenic N_2O at time t
GWP_{CO_2} = GWP factor of CO_2
GWP_{CH_4} = GWP factor of CH_4
GWP_{CO} = GWP factor of CO
GWP_{N_2O} = GWP factor of N_2O

The calculation of credits for carbon storage was not considered in the traditional LCA approaches as it is not recommended by most common standards.

For the dynamic approach, the modelling of carbon uptake during forest regrowth is based on the dynamic characterisation factors developed by Levasseur *et al.* (2010). While the model can be applied to all GHGs, the assessment in this paper is restricted to CO, CO_2, N_2O and CH_4 as these are the greatest contributors to radiative forcing impact. The decay pattern $C_{GHG}(t)$ of a GHGs' pulse emission in the atmosphere can be represented by the impulse response function (Timma *et al.* 2020). For CO_2 emissions and assuming a background concentration of 378 ppm, the Bern carbon cycle-climate model (equation 3) is used. It presents the decay in time of the initial unitary impulse at $t = 0$ (Joos *et al.* 2001):

$$C_{CO_2}(t) = a_0 + \sum_{i=1}^{3} a_i * e^{\frac{-t}{\tau_i}} \tag{3}$$

where:

$C_{CO_2}(t)$ is the decay pattern of a CO_2 pulse emission (*e.g.* 1 kg CO_2)
a_i are the coefficients for the calculation of CO_2 fractions remaining in the atmosphere. They have the values: $a_0 = 0.217$; $a_1 = 0.259$; $a_2 = 0.338$; $a_3 = 0.186$
τ_i are the perturbation time. They have the values: τ_1 = 172.9 years; τ_2 = 18.5 years; τ_3 = 1.186. years

For the other GHGs, the first-order exponential decay function is used as described by equation (4):

$$\mathrm{C}_{CH_4,N_2O}(t) = e^{\frac{-t}{\tau}} \tag{4}$$

The perturbation times for CH_4 and N_2O gases are respectively τ = 12 years and 114 years (Pittau *et al.* 2018; Shine *et al.* 2007). CO rapidly oxidises when it is released into the atmosphere and for this reason it is accounted for as CO_2.

The next step is the calculation of instantaneous dynamic characterisation factors (DCF_{inst}). The formulation conceived by Levasseur *et al.* (2013) for a given GHG in the time step between its occurrence t_j and time t is calculated using equation (5):

$$DCF_{inst,GHG}(t - t_j) = \int_{t_j}^{t} A_{GHG} \cdot C_{GHG}(t)\,dt \tag{5}$$

where A_{GHG} are the specific radiative forcing per unit mass. For the CO_2, CH_4 and N_2O the values are respectively: $A_{CO2} = 1.76 \times 10^{-15}$ Wm^{-2} kg^{-1}; $A_{CH4} = 1.28 \times 10^{-13}$ Wm^{-2} kg^{-1}; $A_{N2O} = 3.90 \times 10^{-13}$ Wm^{-2} kg^{-1}. Specific radiative force per unit mass is calculated by the division of radiative efficiency coefficients with the concentration of GHGs.

According to Hartmann *et al.* (2013), the radiative efficiency coefficients have the values: $RE_{CO2} = 1.37 \times 10^{-2}$ Wm^{-2} ppm^{-1}; $RE_{CH4} = 3.63 \times 10^{-1}$ Wm^{-2} ppm^{-1}; $RE_{N2O} = 3.03$ Wm^{-2} ppm^{-1}. While the concentration of GHGs are: $7.773 \cdot 10^{12}$ kg CO_2/ppm; $2\ 83 \cdot 10^{12}$ kg CH_4/ppm and $7.773 \bullet 10^{12} \mathrm{kg} \frac{\mathrm{N_2O}}{\mathrm{ppm}}$ (Ciais *et al.* 2014).

The instantaneous global warming impact $GW_{Iinst,GHG}(t - t_j)$ can be calculated according to equation (6):

$$GWI_{inst,GHG}(t - t_j) = \sum_{GHG} g_{GHG}(t_j) \bullet DCF_{inst,GHG}(t - t_j) \tag{6}$$

And the cumulative GWI under a given horizon (t) is calculated with equation (7):

$$GWI_{cum}(t) = \sum_{t_j=0}^{t} GWI_{inst,GHG}(t - t_j) \tag{7}$$

Finally, the dynamic global warming ($GW_{dynamic}$) can be evaluated according to the IPCC method, which provides the cumulative radiative forcing caused by emissions/removals of a given GHG over a given time, divided by the absolute global warming potentials (AGWP) of 1 kg CO_2 pulse emission over the same time (equation 8):

$$GW_{dynamic}(t) = \frac{GWI_{cum}(t)}{AGWP_{CO_2}(t)} = \frac{\sum_{t_j=0}^{t} GWI_{inst,GHG}(t - t_j)}{\int_0^t A_{CO_2} C_{CO_2}(t)\,dt} \tag{8}$$

The biogenic carbon uptake due to trees regrowth, to replace the biomass used for the construction of the timber building, was assumed under two conditions: (1) before harvest, and accounted for in module A; and (2) after harvest during the building service life and beyond, accounted for in module B1. In this study the rotation period of the forest was assumed to be 100 years (Masera *et al.* 2003).

2.2.3 Case study

The 'timber building' case study belongs to a pilot project entitled '+ERS-Plus Energy Network Reininghaus Süd'. This project, designed by Nussmüller Architekten ZT GmbH, aims to create an 'economic, technical and organisational solution for a self-sufficient energy network', and is part of a larger initiative to establish a new, highly energy-efficient city district called 'Reininghaus' (Staller *et al.* 2015).

The project comprises 17,000 m^2 and is composed of two typologies: a multifunctional, low-energy concrete building and 12 residential multi-family massive wood buildings. The project achieves a plus-energy standard due to an innovative holistic approach: the office and commercial complex interact with the housing units by exchanging energy, in a synergetic approach that allows for the different users and load profiles of these typologies to compensate each other, effectively reducing energy demand (Staller *et al.* 2016).

This paper focuses on the LCA of one of the multi-family timber buildings, designed as a passive building with nine apartments (**Figure 6**). The building has a heating energy demand of 8.83 kWh/m^2/yr and a final energy demand of 37.58 kWh/m^2/yr.

3. Results

3.1 Literature review: general statistics of documents reviewed

The evaluated literature was composed of peer-reviewed papers, EPDs, reports and standards. Of the 11 standards reviewed, five were EN standards (EN-15804 2013; Draft EN-15804/prA2 2017; EN-16449 2014; EN-16757 2017; EN-16485 2014), four were ISO standards (ISO-14040 2006; ISO-14044 2006; ISO-14067 2018; ISO-21930 2017) and two were product environmental footprint (PEF) documents (EC 2013b; EC 2017b). The 25 EPDs came mostly from North America and Europe: North America (10), Germany (five) and Austria (four), and the 14 peer-reviewed papers were published in 10 different journals, with *Building and Environment* carrying the largest sample (three), followed by the *International Journal of LCA* (two) and *Wood and Fiber Science* (two). The vast majority of all analysed sources came from Europe (32), followed by North America.

The system boundaries reviewed identified that most (32) documents used (or recommended, in the case of standards) a cradle-to-gate 'with options' approach, *i.e.* covering the product stage and possibly the end-of-life stage (C1–C4) with or without assessing the recovery, reuse and recycling potential in module D (**Figure 7**). A total of 14 documents considered a full life-cycle approach (*i.e.* cradle-to-grave) approach, while six assessed a different scope altogether, either forest growth/regrowth, maintenance and/or end of life. This lack of consistency in terms of scope, along with differing functional units and methods to account for biogenic carbon, made a direct comparison between the studies unfeasible.

Figure 6: Case study building under construction. Source: Martin Grabner, TU Graz.

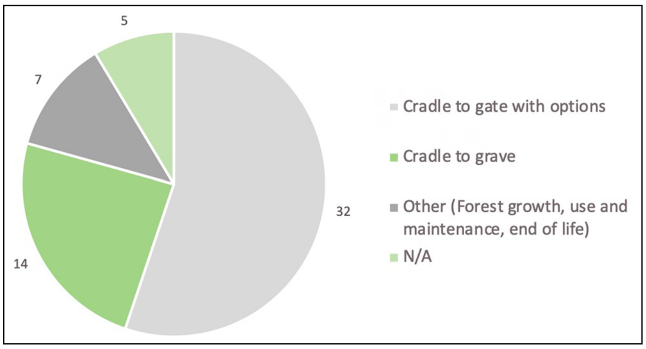


Figure 7: Life-cycle stages considered in the evaluated literature.

3.2 Literature review: biogenic carbon assessment

Within the documents assessed, 24 considered the uptake of CO_2 as a credit during the product stage (A1–A3). Carbon neutrality (*i.e.* 0/0 approach), however, was dominant, as it was adopted in 34 documents. The European EPDs assessed were often cradle to gate (with options), mostly applying the –1/+1 approach.

In terms of standardised recommendations and guidance, EC (2017a) recommends a 0/0 approach, while ILCD (2010), PAS 2050 (2011), EC (2013b), EN-15804 (2019), EN-16485 (2014), ISO-14067 (2018) and ISO-21930 (2017) recommend a –1/+1 approach.

The documents that considered the uptake as a negative emission in the product stage through a dynamic LCA approach present peculiarities in terms of the temporal boundaries adopted for carbon sequestration. As documented by Peñaloza *et al.* (2016), one can consider that biomass growth (and consequent CO_2 sequestration) occurs before the use of the biomass-based product, or that an equal amount of the harvested biomass regrows after the product is extracted and processed for use.

As for carbon storage, the literature indicates that it is considered permanent if carbon is expected to be emitted again more than a century after its uptake. In contrast, emissions expected to occur within a century (delayed emissions or temporary storage) are modelled as if emitted now (EC 2013b). Delayed emissions are emissions that are released over time, *e.g.* through long use or final-disposal phases, versus a single emission at time *t* (EC 2013b). In most standards, there is a distinction between temporary carbon storage (within a 100 year period) versus permanent carbon storage (more than 100 years). Most of the applied approaches do not consider carbon storage. It is usually reported as additional information. However, EC (2017b) does provide a credit of –1 for permanent carbon storage (EC 2017a). In PAS 2050 (2011) and ILCD (2010), temporary carbon storage may be calculated based on linear discounting, an approximation for the non-linear atmospheric decay of CO_2.

Finally, none of the EPDs assessed included land-use change, be it direct or indirect. Direct land-use change guidelines are provided in the IPCC guidelines for national GHG inventories and PAS 2050 (2011). There are requirements in the ISO-21930 (2017) and the Draft EN-15804/prA2 (2017) to apply a characterisation factor of 0 for sustainably managed forests and 1 for non-sustainably managed forests. Vogtländer *et al.* (2014) is the sole peer-reviewed paper to cover the subject. The absence of assessment and guidance on indirect land-use change is due to the ongoing development of methods and data requirements.

An overview of the main approaches recommended by several important documents is listed in **Table 1**.

3.3 Case study results

The GW scores of the timber building obtained using the evaluated methods are presented in **Figure 8**. The overall impact of the building calculated with the approaches 0/0 and –1/+1 equals 20.7 kg-CO_2e/m^2/yr. Although the final results appear to be the same, the impact of the product and construction process and end-of-life stages vary significantly between both approaches. The impact of the product and construction process stages (A1–A5) assessed with the 0/0 approach is 6.58 kg-CO_2e/m^2/yr, while with the –1/+1 approach it is 1.92 kg-CO_2e/m^2/yr. The difference of 4.66 kg-CO_2e/m^2/yr corresponds to the biogenic carbon uptake in the timber-based components. While the 0/0 approach does not consider any benefit of sequestered biogenic carbon, the –1/+1 approach does within the product and construction process stages. Thus, the carbon emissions of the product and construction process stages are lower. Within the end-of-life (C1–C4) stage of the building, the timber-based components are assumed to be incinerated and subsequently biogenic carbon is released. For this reason, the impact of wood combustion is attributed to the end-of-life stage of the building. Consequently, the impact of the end-of-life stage calculated with the –1/+1 approach is 4.66 kg-CO_2e/m^2/yr higher than the value calculated with the 0/0 approach.

Figure 8 also presents the environmental impact of the building calculated with the dynamic approach by considering an uptake of the biogenic carbon after construction. In this case the GW score is 26.67 kg-CO_2e/m^2/yr, or 29% higher than the values obtained with the 0/0 and –1/+1 approaches. The difference of values for the use phase (B6) are due to the 'time' parameter that the dynamic approach employs, having a significant influence on the final results (Levasseur

Table 1: Overview of the most common standards and their proposal in terms of biogenic carbon assessment.

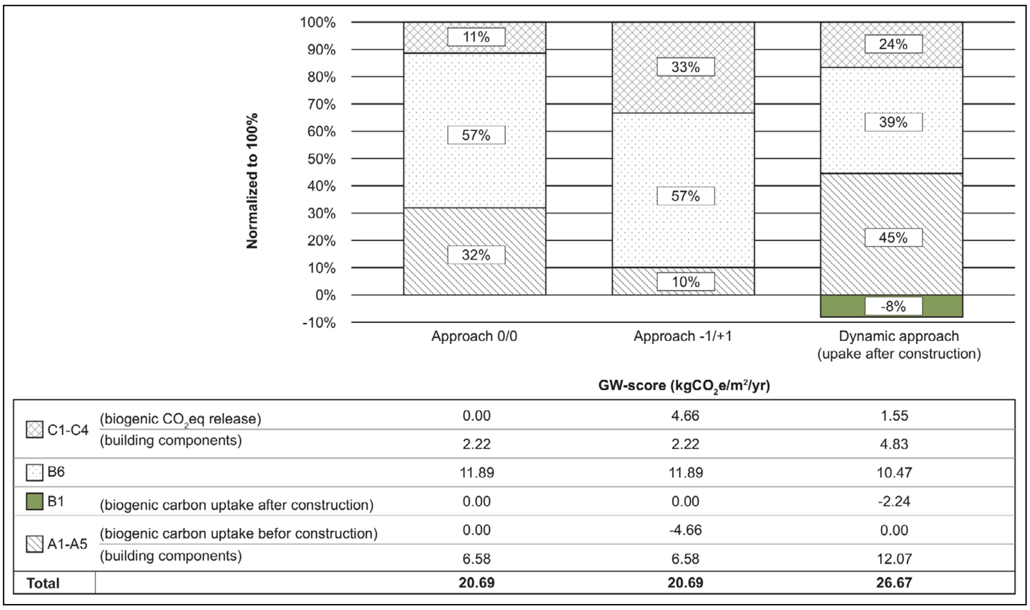
Main documents (reference)	Type of approach	Biogenic carbon uptake	Biogenic carbon storage	Biogenic carbon release	Direct land-use change	Indirect land-use change	Additional life-cycle inventory (LCI) indicators on biogenic carbon
		Module A	**Module B**	**Module C**	**Module A**	**Module A**	
EC (2013b)	−1/+1	Yes, CF = −1 CO_2e for CO_2. Reported separately in the Resource use and Emissions Profile	No, credit for temporary carbon storage may be included as additional information	Yes, CF = +1 CO_2e for CO_2 and 25 for CH_4. Reported separately in the Resource use and Emissions Profile	Yes, assessed based on Ciais *et al.* (2014). Land-use changes that occurred within a period of 20 years or a single harvest period	No, unless the product environmental footprint category rules (PEFCRs) require to do so	No requirements
ISO-14067 (2018)	−1/+1	Yes, CF = −1 CO_2e for CO_2. Reported separately in the Resource use and Emissions Profile	No, impact of carbon storage (>10 years) may be documented separately	Yes, CF = +1 CO_2e for CO_2. Reported separately	Yes, assessed in accordance with internationally recognised methods such as Ciais *et al.* (2014). Land-use changes that occurred within a period of 20 years or at least a full rotation period. Reported separately	No, methods and data requirements under development	If calculated, the biogenic carbon content will be documented separately
ISO/DIS-14067 (2018)	−1/+1	Yes, CF = −1 CO_2e for CO_2. Reported separately in the Resource use and Emissions Profile	No, delayed emissions and removals are not allowed; impact of carbon storage (>10 years) may be documented separately	Yes, CF = +1 CO_2e for CO_2. Reported separately	Yes, assessed in accordance with internationally recognised methods such as Ciais *et al.* (2014). Land-use changes that occurred within a period of 20 years or at least a full rotation period. Reported separately. Included changes in carbon stock. Land use defined as a different category (different land-use change)	No, methods and data requirements under development	If calculated, the biogenic carbon content will be documented separately. Land use for greenhouse gas emissions and removals occurring as a result of land use through changes in soil and biomass carbon stocks which are not the result of changes to the management of land should be assessed and included

(Contd.)

Main documents (reference)	Type of approach	Biogenic carbon uptake	Biogenic carbon storage	Biogenic carbon release	Direct land-use change	Indirect land-use change	Additional life-cycle inventory (LCI) indicators on biogenic carbon
		Module A	**Module B**	**Module C**	**Module A**	**Module A**	
EC (2017a, 2017b)	0/0	No, CF = 0 CO_2e for CO_2	No temporary carbon storage (within 100 years). Credit (−1) for permanent carbon storage (>100 years)	Partially, CF = 0 CO_2e for CO_2 and CO, 34 CO_2eq for CH_4. Included under the subcategory 'Climate change-biogenic'	Yes, assessed based on default land-use change values from PAS 2050 (2011) or Ciais *et al.* (2014). Land-use changes which occurred within a period of 20 years or a single harvested period. Included under the subcategory 'Climate change-land use and land transformation'	No, methods and data requirements under development	Biogenic carbon content reported as additional technical information
PAS 2050 (2011)	−1/+1	Yes, CF = −1 CO_2e for CO_2.	No, weighting factor for delayed emissions (within 100 years) may be calculated based on linear discounting (2 equations for the storage from 0 to 25 years and from 25 to 100 years). >> applied to bio-based and fossil-based product (polymer). Carbon storage of >100 years considered as permanent carbon storage (permanent negative credit)	Yes, CF = +1 CO_2e for CO_2 and 25 for CH_4	Yes, based on default land-use change values for selected countries. Land-use changes which occurred within a period of 20 years or one harvest period.	No, methods and data requirements under development	No requirements
ILCD (2010)	−1/+1	Yes, CF = −1 CO_2e for CO_2.	No, credit for delayed emissions (within 100 years) may be calculated based on linear discounting. Applied to bio-based and fossil-based products (polymer). Delayed emissions beyond 100 years included in 'Carbon dioxide, biogenic (long term)'	Yes, CF = +1 CO_2e for CO_2	No specified	No, methods and data requirements under development	No requirements

(Contd.)

Main documents (reference)	**Type of approach**	**Biogenic carbon uptake**	**Biogenic carbon storage**	**Biogenic carbon release**	**Direct land-use change**	**Indirect land-use change**	**Additional life-cycle inventory (LCI) indicators on biogenic carbon**
		Module A	**Module B**	**Module C**	**Module A**	**Module A**	
ISO-21930 (2017)	−1/+1	Yes, CF = −1 CO_2e for CO_2 in the case of sustainable forest management, and 0 otherwise	No, delayed emissions may be reported as additional information	Yes, CF +1 CO_2 for CO_2	Yes, CF = 1 CO_2e/kg CO_2 for non-sustainably managed forest, and 0 otherwise	Not specified	Carbon uptake and emissions reported as LCI indicator (kg CO_2) for both biogenic carbon and carbonation
EN-15804 (2013)	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
EN-15804 (2019)	−1/+1	Yes, CF = −1 kg CO_2e/kg CO_2 included removals, transfers and emissions of biogenic carbon. Biomass from all sources except native forests	No, temporary or permanent carbon storage	Yes, CF = +1 CO_2e for CO_2 (as in ISO-14067 2018)	Yes, CF = +1 CO_2 for CO_2	Not specified	Not specified
EN-16485 (2014)	−1/+1	Yes, CF = −1 CO_2e for CO_2 in the case of sustainable forest management, 0 otherwise	No, effect of delayed emissions may be calculated based on PAS 2050 (2011) or Ciais *et al.* (2014) and reported as additional information	Yes, CF = +1 CO_2e for CO_2	Yes, assessed in accordance with Ciais *et al.* (2014) for national greenhouse gas inventories	No, methods still under development	Biogenic carbon content will be reported in addition elsewhere
Levasseur *et al.* (2013)	New approach	Dynamic life-cycle analysis approach with time-dependent characterisation factors for all emissions (fossil and biogenic), allowing for the consideration of the effects of delayed emissions and carbon storage					
Vogtländer *et al.* (2014)	New approach	Approach based on the global carbon style-benefit of carbon sequestration when there is a global growth of forest and a simultaneous growth of wood					
Cherubini *et al.* (2011); Guest *et al.* (2013)	New approach	Biogenic global warming potential (GWP bio) considering the effect of forest regrowth and carbon storage					



		GW-score (kgCO$_2$e/m^2/yr)		
▦ C1-C4	(biogenic CO$_2$eq release)	0.00	4.66	1.55
	(building components)	2.22	2.22	4.83
⬚ B6		11.89	11.89	10.47
🟩 B1	(biogenic carbon uptake after construction)	0.00	0.00	-2.24
▧ A1-A5	(biogenic carbon uptake befor construction)	0.00	-4.66	0.00
	(building components)	6.58	6.58	12.07
Total		**20.69**	**20.69**	**26.67**

Figure 8: Global warming (GW) scores calculated by different biogenic carbon accounting approaches.

et al. 2013). The significant difference of values for the product and construction process (A1–A5) and end-of-life stages compared with static approaches is due to the biogenic carbon emissions from bio-based material used in the timber building. In particular, in the dynamic approach a large proportion of biogenic carbon in A1–A5 is emitted from wood residues during forest product processing in sawmills, which contributes to a doubling in GW score compared with static approaches. The total mass of wood (including the residues from wood processing) is accounted for in B1 to calculate the carbon uptake from tree regrowth. Due to the long period assumed for forest rotation, only a partial share of CO$_2$e stored in the building is recaptured in the forest, which contributes in 100 years to −8% of the total GW score.

The discrepancies between the share of the contribution of the life-cycle stages to the overall impact come as a result of the hypotheses used by the different approaches for the calculation of the biogenic carbon uptake. The 0/0 approach does not consider any benefits of carbon uptake and consequently the carbon release as a result of wood-burning is also not considered as an impact. The −1/+1 approach considers the benefits of biogenic carbon uptake in the product and construction process stages and its release in the end-of-life stage of the building. For this reason, the product and construction process stages present lower values of environmental impacts because they are shifted to the end-of-life stage. The most comprehensive approach is the dynamic approach (uptake after construction). This method allocates the impacts of carbon release of burning wood based on the timing of emissions and the results are presented separately in the stage B1. In that case, the benefits of carbon uptake are also considered based on the situation of the forest. If the forest is regrown at the end of life of the building, then carbon neutrality can be considered. The comparison of the results evaluated with the different approaches shows that the environmental impact of the timber building calculated with the dynamic approach when the uptake is considered after construction is considered to be more transparent and reliable.

For a more detailed analysis, **Figure 9** shows the GW score results at the component level. The contribution of the life-cycle stages to the overall impact is also highlighted. At the component scale, the results calculated with the 0/0 and −1/+1 are the same. Results evaluated with the dynamic approach, on the other hand, vary considerably with the final values calculated with the 0/0 and −1/+1 approaches. As stated above, the logic behind these differences is mainly due to the 'time parameter' and influence of wood residues from wood processing. The largest relative discrepancy in the final results is obtained for the floor slab where the difference between values is of the range of around 3 kg-CO$_2$e/m^2/yr, or 200%. These findings point out that the comparison of building components can be misleading when the various approaches are used for the assessment of their environmental impacts. Even more misleading is the comparison of environmental impacts of building components when only the product stage is considered in the system boundary. However, a more detailed analysis of environmental impacts of life-cycle phases shows negative values for the product and construction process stages (A1–A5) calculated with the −1/+1 approach. For this reason, limiting the system boundaries of LCA studies to the product stage provide incomplete results and therefore misleading information to inform decision-making. Additionally, at the component level the more reliable and transparent method for the calculation of biogenic carbon is the dynamic approach when the uptake is assumed to happen after construction.

In order to better understand how the carbon impact of the building evolves over time, **Figure 10** presents the results of the GW score as a function of time based on the dynamic approach by considering the scenario when the biogenic carbon uptake is considered before construction and when it is considered after construction. In order to compare both scenarios, the period of analysis is extended to −100 years in order to include the impact of forest regrowth

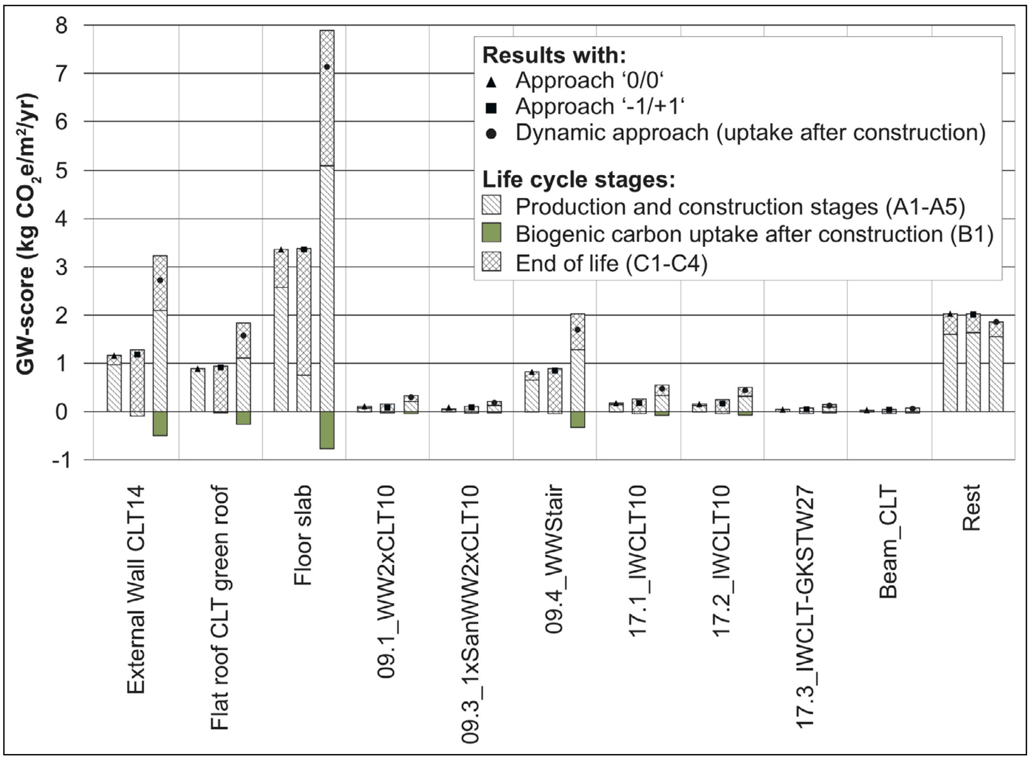


Figure 9: Global warming (GW) scores of building components using static and dynamic approaches.

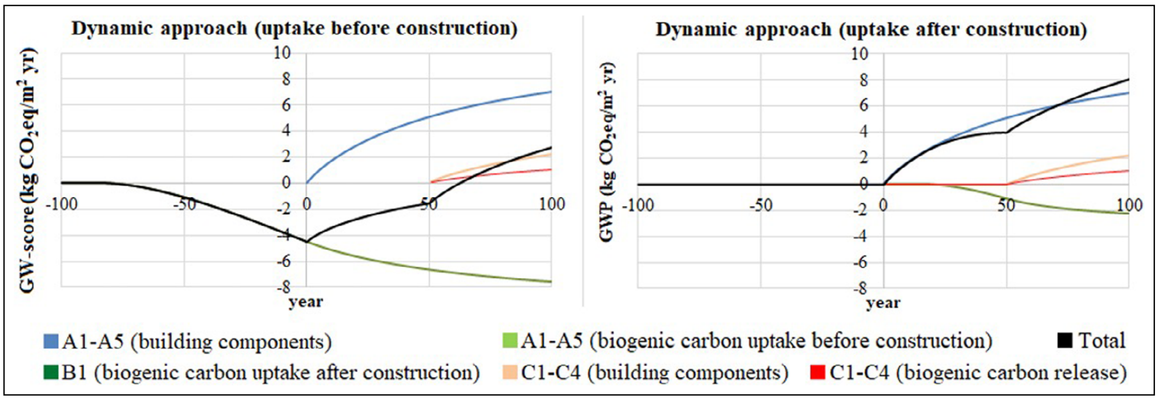


Figure 10: Global warming (GW) scores of the analysed building as a function of the reference service life (year 0 is the construction of the building).

before construction. The results show the influence of the time parameter in the evolution of the impacts over time for the stages of product and construction process (A1–A5) and end of life (C1–C4) for building components and for the biogenic carbon uptake. When the uptake occurs before the construction, the amount of biogenic carbon uptake from forest is significantly larger. This is due to two reasons: the first is the fact that the wood in the forest has been harvested when the rotation period of the forest has been completed. The second reason is the 'time' parameter considered in the dynamic approach. The graph shows that even though the wood is harvested after 100 years, the effect on the GW score indicator for the continuing years continues to be positive. For the scenario when the uptake occurred after construction, the quantity of the biogenic carbon uptake is lower, and its release in the atmosphere happens after 50 years when the building comes to the end of its design life. Compared with the first scenario, the consideration of biogenic carbon uptake after construction should be preferred from a sustainable point of view to stimulate future forest regrowth.

In conclusion, the dynamic approach allows for a proper attribution of the impacts to the stages when the emissions occur. It demonstrates the degree of benefits that the LCA practitioner should account for in their projects based on the quantity of the carbon uptake occurring during the building's lifetime. Moreover, the approach allows for a clear identification of the time-dependent effect that GHG uptake and release has on the atmosphere, which is a very welcome feature when applying LCA to long-lived products and systems, such as buildings and forestry products.

4. Discussion

This paper presents the results of the GW score of an advanced timber building, due to its passive house nature, and is a representative case for future building trends striving for net-zero carbon. The impact of this building is within the range of 20.7 kg-$CO_2e/m^2/yr$, where the embodied impacts account for 8.8 kg-$CO_2e/m^2/yr$ and the operational impacts account for 11.9 kg-$CO_2e/m^2/yr$ (based on the 0/0 and –1/+1 approaches). A comparison of these results with those of other Austrian buildings (Passer *et al.* 2012, 2016b) revealed an improved environmental profile from a carbon perspective: the calculated GW score for this case study was 75% lower than the value found for current buildings and about 50% lower than the value documented for low-energy buildings. This reduction comes mostly from the operational phase, where the improvement is of the range of 60%, both in comparison with the current and low-energy Austrian buildings, while for the embodied impacts the improvement is around 10–40% (Passer *et al.* 2012, 2016b). However, the GW score is still higher than the targets sets for 2050 (Röck *et al.* 2020), and the next step is the reduction of embodied impacts.

The GW scores were calculated with three methods that treat the biogenic carbon content in timber building components in different ways. A comparison of the results obtained from these methods concluded that the dynamic approach is the most reliable, giving 26.7 kg-$CO_2e/m^2/yr$. At a building level, the gap between the final results was 29%.

It must be noted that the mechanical and electrical equipment, appliances and furniture were not included in the system boundaries of the study. Previous studies have found that in advanced and passive buildings this equipment can have a contribution of between 5% and 30% (Hoxha *et al.* 2017; Passer *et al.* 2012; Hoxha & Jusselme 2017). If these components were to be considered, the deviation would likely be lower.

The significance of methodological choices related to the assessment of biogenic carbon is expected to increase as future buildings will continue to reduce their operational GHG (Röck *et al.* 2020). However, the environmental impacts of building components present significant discrepancies when they are evaluated with different methods. These differences can range to up of 3 kg-$CO_2e/m^2/yr$, or 200%. Finally, at the building level, the variation and potential to provide misleading information pertaining to biogenic carbon calculations is significant and requires attention.

Calculations can be misrepresentative if building GW scores are compared based on the product stage solely. The case study assessment revealed that the product and construction process stage had a lower contribution to the overall impacts of the building when the assessment was made with the –1/+1 approach. As most standards (ILCD 2010; EC 2013b; EN-16485 2014; ISO-14067 2018; ISO-21930 2017) recommend the –1/+1 approach for the evaluation of the benefits of biogenic carbon uptake, it is important to not limit assessments to the product stage, which most EPDs reviewed do.

This study illustrates the difficulty in defining who shall claim the benefit. The question of how the benefits are allocated will radically affect the GW score. In most standards, the –1/+1 approach is considering that the benefit (–1) is able to be claimed from the first stage of the life-cycle, while the burden (+1) is taken at the end of this same life-cycle. But who planted the tree that will be used in the building which is currently being built? And who will deconstruct, incinerate or landfill this building? Buildings are long-lasting artefacts. The life-cycle of a building spans at least three human generations: the first generation who planted the tree, the second who built the house and the last one who inherited it. Most standards compress these transgenerational processes within one life-cycle with immediate benefits and burdens associated with it. This is due to the fact that buildings are also the result of an industrial activity. Therefore, the situation is reframed as different industrial sectors, one in charge of producing trees every year, the other of building houses every year and the last one of deconstructing and reusing/recycling the house. In this configuration the question of burden and benefits is not shared between generations, but between industrial sectors. Should it be to the forest industry to claim the carbon benefit of growing trees and to the facility management sector to absorb the burden of maintaining and dismantling buildings, while the construction industry would remain essentially neutral? Most standards, by considering a –1/+1 approach for building construction, are integrating these transgenerational and trans-sectorial questions within the construction sector. This may simplify the calculation and certification, but fails to consider the specific complexity of time. Furthermore, there is a risk of double-counting if multiple sectors are claiming the same benefits.

The variability from the methodological choices were found to be higher at the component level. This study found a result range between 35% and 200%. With the –1/+1 approach for some components, the impact of the product stage had a negative value. The negative values of environmental impacts of components motivate LCA practitioners, designers and developers to use these components in their buildings. However, this is misleading information because the final impact of components is not negative. The overestimation of biogenic carbon uptake benefits when only the product stage is considered is also corroborated by Vogtländer *et al.* (2014).

The 0/0 approach was also a highly recommended method in the literature (EC 2017a, 2017b; Draft EN-15804/prA2 2017). In a previous study, this method is found pertinent because the allocation issues related to the biogenic carbon content are neutralised (Frischknecht *et al.* 2010). However, the method does not link the rotation time period of the forest with the reference service life of the building. The case study shows the reference service life of the building, considered to be 50 years, is only half the rotation time period of the forest, considered to be 100 years. Due to this discrepancy, the results evaluated with the 0/0 approach can be 29% lower than the dynamic approach. Due to the consideration of time aspects and forest rotation time, the dynamic approach can be considered as the most reliable method for the assessment of the biogenic carbon content in timber building components.

Previous studies suggested the product stage is the largest contributor to a building's life-cycle environmental impact, and the end-of-life stage as the lowest. Some studies even propose that the impacts of the end-of-life stage should be omitted from consideration (Häfliger *et al.* 2017). In contrast, the present study found the contribution of the end-of-life stage to the overall impacts can be as significant as that of the product stage when using a –1/+1 approach. The authors therefore advocate that if practitioners choose to use the –1/+1 approach, the inclusion of emissions associated to end of life stage must be mandatory.

5. Conclusions

Three approaches are extensively used for the assessment of biogenic carbon. The majority of current standards recommends the –1/+1 approach, while environmental product declarations (EPDs) are mainly following the 0/0 approach. The dynamic approach of biogenic carbon calculation is mostly recommended in scientific papers, but it presents challenges in terms of the temporal boundaries adopted for carbon sequestration.

A comparison of the results obtained from the different approaches identified the dynamic approach as the most pertinent and transparent. The rotation time period of the forest is a crucial parameter that is poorly considered in static approaches (*e.g.* 0/0 and –1/+1). Disregarding this parameter in the static approaches can lead to errors in determining a global warming (GW) score. For the case study, this was 29%. The deviation becomes larger in the GW score assessment of building components. The error found at a component level between different LCA approaches was in the range of 35–200%. In the case of the –1/+1 approach, the results are misleading when the system boundaries of the study are limited to the product stage. Additionally, the approaches 0/0 and –1/+1 do not consider the trees' typology, a factor fully considered in the dynamic approach.

The recommendation to building practitioners is to use the critical assessment herein performed which leads to dynamic life-cycle assessment (LCA) approaches for future assessments of construction bio-based products and materials. As biogenic materials for construction typically require land use and land-use change (LULUC), further investigation is warranted on how the impacts or carbon-storage credits due to these can be assigned.

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Competing interests

The authors have no competing interests to declare.

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