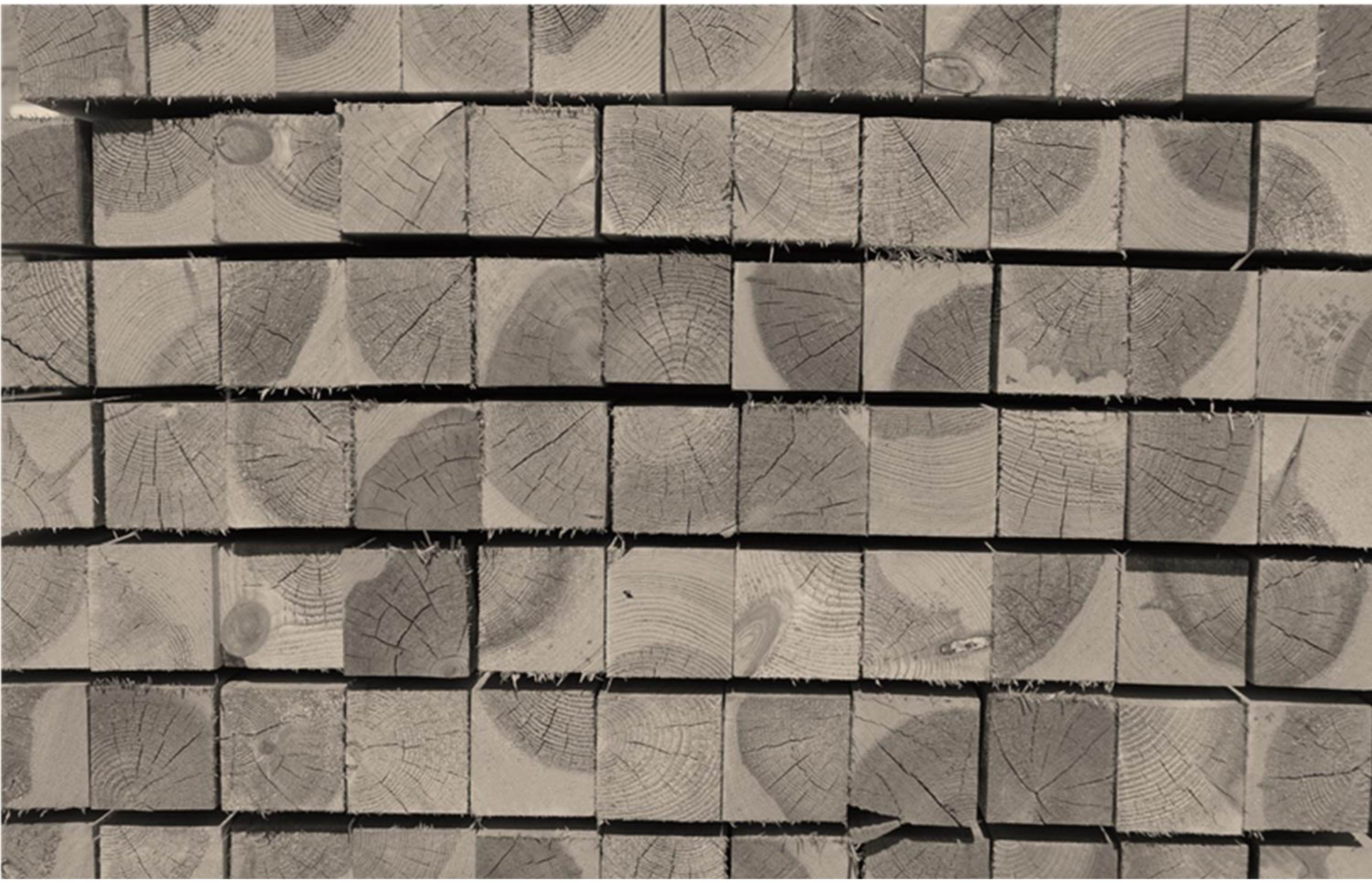
# Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon

## A Contribution to IEA EBC Annex 72

February 2023



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# Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report "Context-specific assessment methods for life cycle-related environmental impacts caused by buildings" " by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of "Assessing Life Cycle Related Environmental Impacts Caused by Buildings" (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

– Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
– Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
– Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
– Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
– Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
– Basics and Recommendations on Influence of Future Electricity Supplies on LCA-based Building Assessments (Zhang 2023);
– Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
– Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al., 2023);
– Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
– Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
– Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

# Summary

There is a general consensus that CO2 emissions contribute significantly to climate change and that mitigation is one of the most important challenges of the current generation. At least since the new EN 15804+ A2:2019, which distinguishes between emissions from fossil and biogenic sources, there has been discussion on how to address emissions from biogenic sources. The current report discusses the different approaches to assessing biogenic carbon. The approaches have different methods to allocate emissions within the observed system.

The report provides an overview and explanation of the most common approaches to assessing biogenic carbon. In LCAs for buildings, biogenic CO2 is typically accounted for using two different approaches: the 0/0 approach (or carbon-neutral approach) and the -1/+1 approach. The 0/0 approach considers only the contribution of greenhouse gases from fossil sources, while the -1/+1approach considers the uptake of CO2 emissions during the growth of biogenic materials and their release at the end of the life cycle. The overall results at the end of the life cycle should be the same, the only difference being that the -1/+1 takes into account fluxes of biogenic carbon. There are also approaches that use time-dependent characterization factors and propose two different possible scenarios: (i) assuming that uptake occurs before the building is constructed, i.e., before the material is harvested, thus following the natural carbon cycle, or (ii) assuming that uptake occurs after the bio-based material is harvested, taking into account the regrowth of trees, thus compensating for exactly the amount of material that was harvested.

The report evaluates biogenic carbon fluxes using the various approaches discussed and provides recommendations for (a) the inventory level and (b) the impact assessment level. The use of wood/biomass materials is desirable, but it is important that the whole life cycle is considered to avoid misinterpretation of results. Requirements should be formulated not only for A1-A3, but should also include the associated disposal modules C3-C4. As an alternative, requirements for A1-A3 should be formulated separately for GWPfossil and GWPbiogen. Due to limited consensus, dynamic modelling of biogenic carbon should be used with caution, while that standards shall be relying on static characterization factors and a net-zero life-cycle balance for biogenic CO2 (Modules A1-C4), unless the biogenic carbon is permanently and safely stored in dedicated underground storage or permanently stored in carbonated cement used in concrete.

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# Abbreviations

| Abbreviations | Meaning |
|---|---|
| **A72** | IEA EBC Annex 72 |
| **CF** | Characterisation Factors |
| **DOCf** | Degradable Organic Carbon Fraction |
| **EoL** | End-of-Life |
| **EPD** | Environmental Product Declaration |
| **GABC** | Global Alliance for Buildings and Construction |
| **GWP** | Global Warming Potential |
| **GTP** | Global Temperature Potential |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **LCA** | Life Cycle Assessment |
| **NZ** | New Zealand |
| **RSL** | Reference Service Life |

# Definitions

**Global Warming Potential (GWP):** Impact category (or characterization factor for climate change) describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over a given period of time. A time frame of 100 years is currently most commonly used and accepted. [kg-CO2eq] (adapted from ISO 14067:2018)

**Carbon content:** refers to the amount of carbon stored in (physically contained in) a product or building. This physical carbon is contained in biogenic products such as timber (called biogenic carbon) as well as fossil-based products such as plastics.

**Energy source:** source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process.

**Energy carrier:** substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes.

# 1. Introduction

The contribution of buildings to global greenhouse gas emissions (GHG) is widely acknowledged (IEA GABC 2018). Many strategies to lower resource consumption and emission intensity during buildings' life cycle have been proposed during the last decades, with varying reduction potentials. Using so-called 'bio-based' products, i.e. materials based on renewable feedstocks that absorb $CO_2$ during their growth, has been increasingly proposed as a climate change mitigation measure (Ministère de la transition écologique, 2020; Pomponi & Moncaster, 2016; Moschetti et al., 2019; Peñaloza et al., 2016, Carcassi et al., 2022). Among the realm of bio-based products used in buildings, wood stands out as a historically adopted structural choice, mostly in light-framed construction or low-rise residential buildings (Churkina et al. 2020) and in recent years, with cross-laminated timber (CLT), in multi-storey apartment and office buildings (Hoxha et al 2020). With the increasing acknowledgement of steel and concrete as energy or GHG emission-intensive products, design decision makers in general gradually opt for using wood as a replacement of the latter traditionally employed structural materials.

Nonetheless, the potential reduction in GHG emissions from replacing minerals or metal-based materials with wood (or other bio-based products) must be properly estimated. Through a range of indicators, the international standardized method of life cycle assessment (LCA) has been used to calculate the impacts of new solutions and projects. The LCA method has four main steps: goal and scope definition, life cycle inventory, impact assessment and interpretation.

Global warming potential (GWP) is the indicator used to translate the effects of emissions of GHG generated during a building's life cycle into their contribution to increased radiative forcing. The most common gases contributing to the GWP indicator are the $CO_2$, $CH_4$, $N_2O$ and CO. $CO_2$ emissions should be distinguished between fossil and biogenic sources. Biogenic $CO_2$ is absorbed during the growth of biobased materials (Carcassi et al. 2022).

In the 6$^{th}$ assessment report of IPCC, it is stated that every tonne of $CO_2$ emission adds to global warming resulting in a near linear relationship between cumulative $CO_2$ emissions and the increase in global surface temperature, irrespective of the time when the emission takes place (Figure 1, IPCC 2021). This is a fact which is important to keep in mind when reading this report.

The modelling of biogenic carbon in life cycle assessments of buildings still lacks methodological consensus (Hoxha et al. 2020). Typically, in building LCAs, biogenic $CO_2$ is accounted for using two different approaches: the 0/0 (or carbon neutral) approach and the -1/+1 approach. The first considers by default that the uptake of $CO_2$ during the growth of the bio-based material is compensated by its release at the end of its service life (Hoxha et al 2020). Consequently, the 0/0 approach considers only the contribution of gases from fossil sources to the GWP calculation. The -1/+1, on the other hand, considers both the uptake during growth and the release at the end of life (Hoxha et al. 2020). Standards (EN 15804:2019) highlight that if the uptake is accounted for, the release must also be considered in end-of-life recycling, landfilling and incineration. The life cycle-based greenhouse gas emissions arising from the two approaches should be equal, the only difference being that with the -1/+1 approach one can track the biogenic carbon flows throughout the full life cycle.

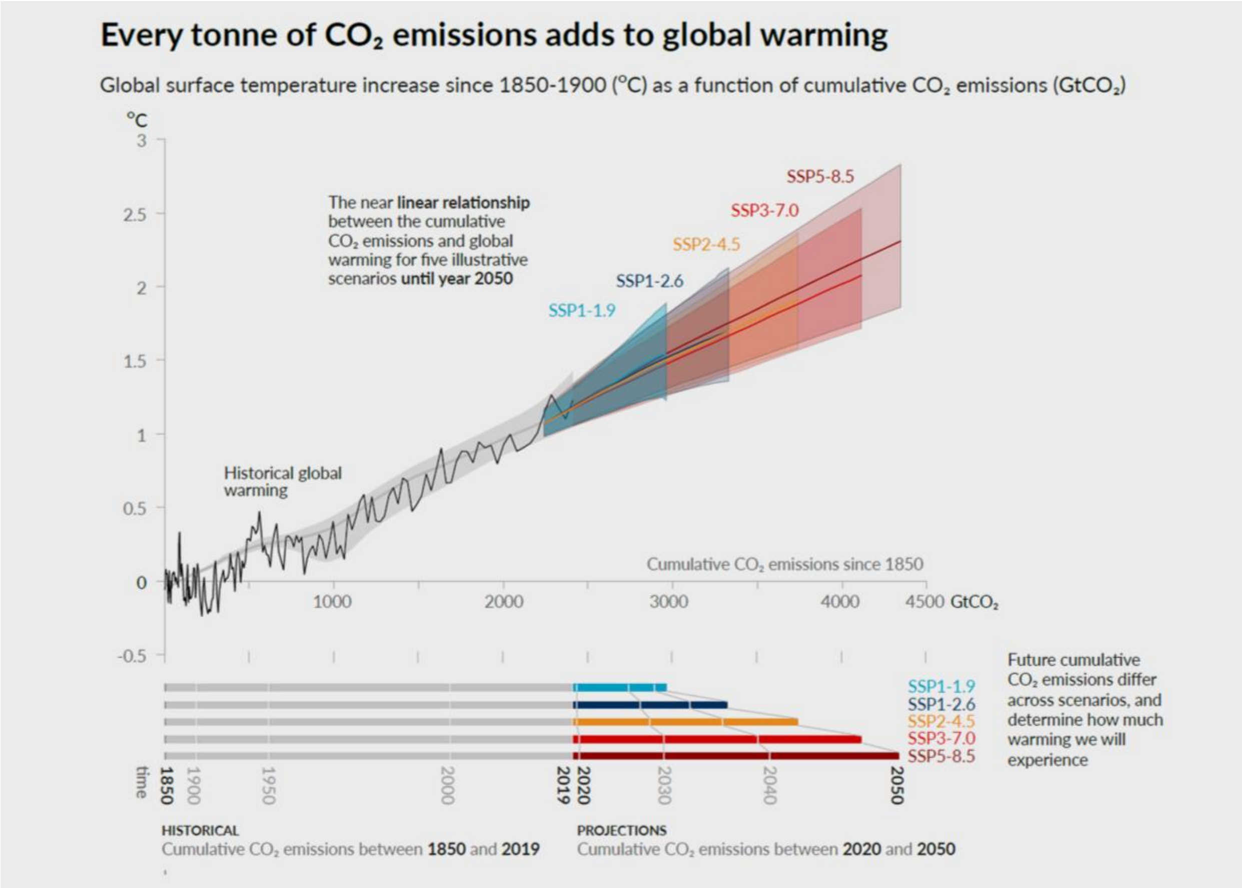


**Figure 1**: Near-linear relationship between cumulative $CO_2$ emissions and the increase in global surface temperature (IPCC 2021).

Aiming at solving the abovementioned issues, the so-called ‘dynamic’ or ‘time dependent’ approaches for biogenic carbon accounting have been developed with focus on carbonation of recycled concrete with biogenic $CO_2$ and bio-based materials modelling (Guest et al., 2013; Cherubini et al., 2011; Arehart et al., 2021) and others which can be applied to any context, product or system (Levasseur et al., 2010). The definition of time-dependent characterization factors proposed by Levasseur et al., (2010) is based on some key value-based choices when it comes to calculating biogenic carbon uptake in bio-based products used in buildings. Two different scenarios have been addressed in literature: (i) assuming that the uptake happens before the building is constructed, i.e., before the harvesting of the material, following the natural carbon cycle or (ii) assuming that the uptake happens after the bio-based material is harvested, considering regrowth of trees, compensating for the exact amount of material that was harvested (Peñaloza et al., 2016). The dynamic calculation approach has been portrayed as a pertinent way to account for biogenic $CO_2$ uptake and release in buildings LCA (Hoxha et al., 2020), and it has harnessed the attention and interest of policymakers who aim to define rules for wood products modelling in LCAs (Ministère de la transition écologique, 2020; Zibell et al. 2021).

Considering the lack of consensus on the appropriateness of the different currently available methods to account for biogenic carbon in buildings, this chapter aims to discuss the opposing views and derive recommendations based on the calculation guidelines published by the Intergovernmental Panel on Climate Change (IPCC, 2021) and the increasing knowledge on carbon sources, sinks and deriving budgets.

The report is structured in two main parts: discussion and recommendations for biogenic carbon accounting at (a) **the inventory level,** and (b) **the impact assessment level**. The final section of the report presents a brief discussion on the development of non-binding orientation values or binding secondary requirements for greenhouse gases in building products, more specifically wood and biomass-based products.

# 2. The Inventory Level

## 2.1 The 0/0 Approach

The modular structure proposed in the European standard EN-15978 (2019) is used to subdivide the building system, including the product and construction stage (module A), use stage (module B) and end-of-life stage (module C). The subsequent product system is referred to as module D beyond the system boundary. Figure 2, extracted from Hoxha et al (2020), illustrates the 0/0 approach 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 case of wood recycling. As can be seen in the figure, biogenic $CO_2$ is not considered in any of the modules. In the cases where wood is landfilled after reaching the end of its service life, the release of biogenic methane ($CH_4$) is modelled in module C, due to its higher impact on global warming compared to biogenic $CO_2$. Because biogenic $CH_4$ emissions shall be and are taken into account this approach is not to be considered nor called a "climate neutral" approach. Data collection for building LCAs following this approach therefore does not require any consideration of the amount of $CO_2$ absorbed during forest growth, nor released during end of life.

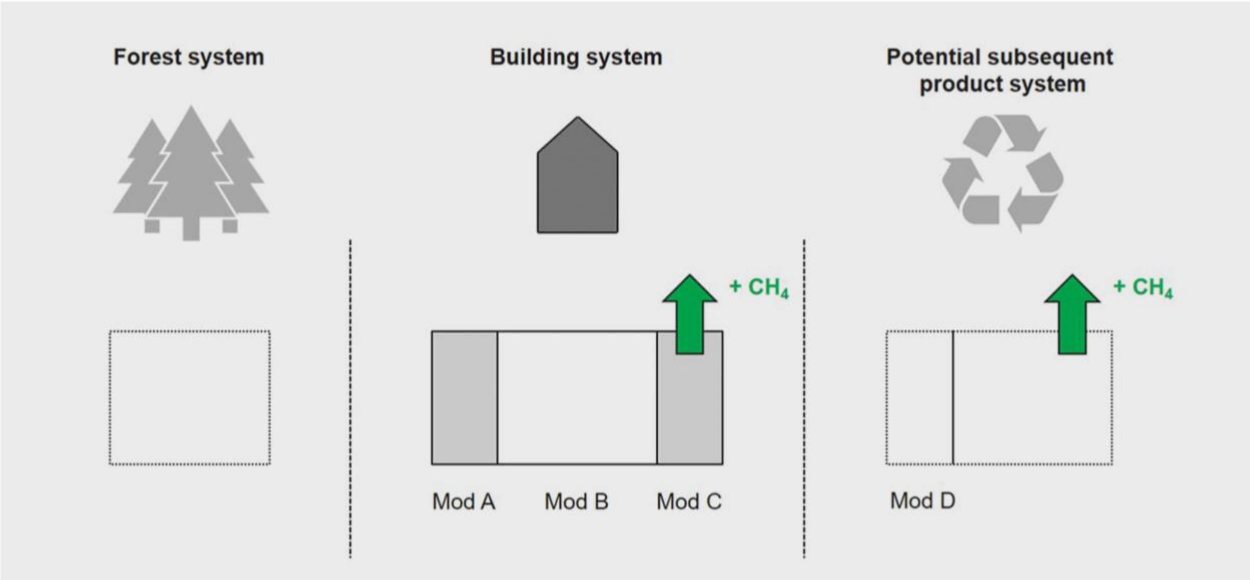


Figure 2: The 0/0 approach to model biogenic carbon uptake and release. The dotted lines indicate the product systems which fall outside the building system boundaries. Source: Hoxha et al (2020).

## 2.2 The -1/+1 Approach

### 2.2.1 General

Figure 3 (Hoxha et al. 2020) illustrates the -1/+1 approach, in which both biogenic $CO_2$ uptake (-1) and release (+1) are considered, as well as the transfers of biogenic carbon between the different systems. 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, whereas 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 case of recycling). In both situations a positive emission is reported in module C. It must be noted that the biogenic $CO_2$ balance should be zero for all product systems. Also, because biogenic $CH_4$ emissions shall be and are taken into account this approach is not to be considered nor called a "climate neutral" approach.

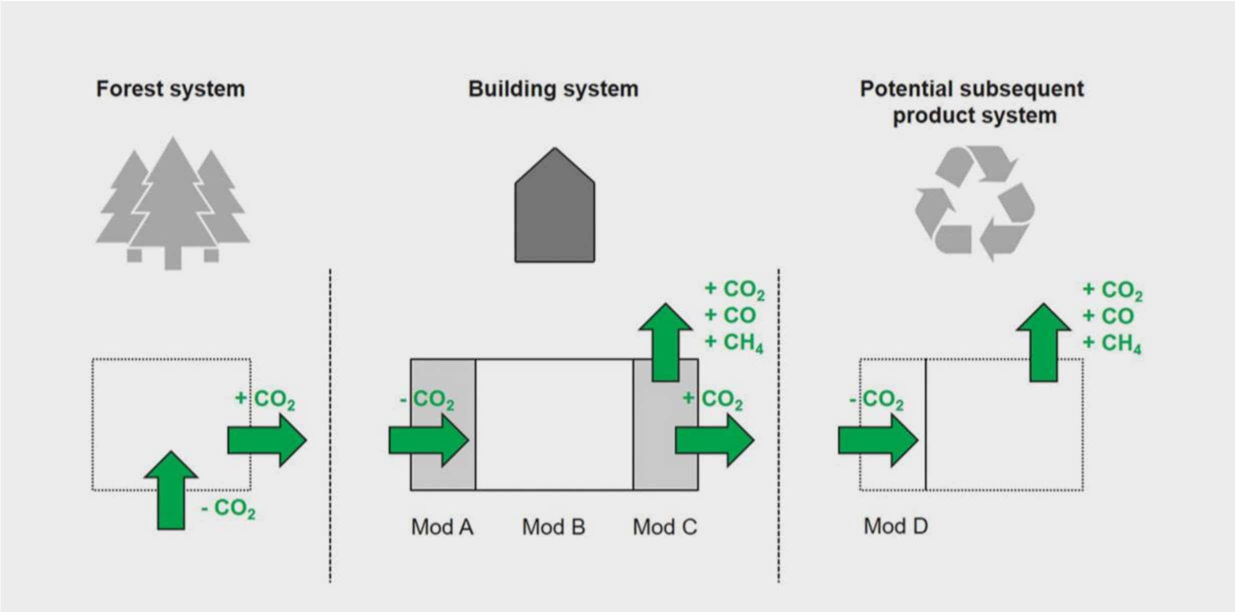


**Figure 3**: The -1/+1approach to model biogenic carbon uptake and release. The dotted lines indicate the product systems which fall outside the building system boundaries. Source: Hoxha et al (2020).

Building LCAs conducted with the -1/+1 approach therefore require the calculation of the amount of $CO_2$ absorbed by the wooden product(s) used in the building, which – at the end of life – will be considered as released in its entirety. It is noteworthy, however, that typical life cycle databases currently do not include detailed, mass-balanced information on the biogenic $CO_2$ content absorbed by biobased materials during their growth. In fact, when encountering biogenic $CO_2$ information in life cycle databases, practitioners must ensure that the carbon balance is maintained, which might entail in some efforts regarding data adaptation.

### 2.2.2 The -1/+1* approach

In some countries, variations of the -1/+1 approach are observed, which are not allowed in others. A noteworthy variant is the -1/+1* approach, in which the right-hand-side depends on the end-of-life fate case of the product and on whether or not landfills are considered a permanent sequestration, or specifically whether it is recycled, sent to landfill (>0) or incinerated (+1) (Figure 4). The -1/+1* means that the fixation of biogenic carbon is considered, but no or not all biogenic carbon is modelled as an emission at the end of life. In Australia, Canada, France and New Zealand, wood sent to landfill gets a GWP factor close to zero but substantially lower than +1. Wood that exits the system boundary, e.g. for reuse, recycling gets a "+1" in NZ, and then the potential benefit of its reuse, recycling is calculated in module D. The interpretation of landfills as a permanent or temporary sequestration varies among countries. In Australia and New Zealand, two values of degradable organic carbon fraction (DOCf) for softwood timber are allowed: NZ applies the lower value of 0.1% while AU could use either 0.1% or applies the higher value of 10% (Australian Government, 2016; Wood Solutions, 2020), which results in 99.9% and 90 % assumed permanent sequestration in NZ and AU, respectively. The comparison between New Zealand and Australia shows the impact of applying two different DOCf scenarios in landfilling, because the share of biogenic carbon released at end-of-life by incineration and degraded carbon in landfills is nearly the same (AU: 10.5%, NZ: 10.1%). Both countries use the same EPD datasets, which supply two different DOCf values for landfilled softwood timber: one option is a DOCf value of 10% estimated from Australia's National Greenhouse Accounts (Australian Government 2016), and the other option is a DOCf value of 0.1% based on the bioreactor laboratory research on Australian Radiata Pine (Wang et al., 2011).

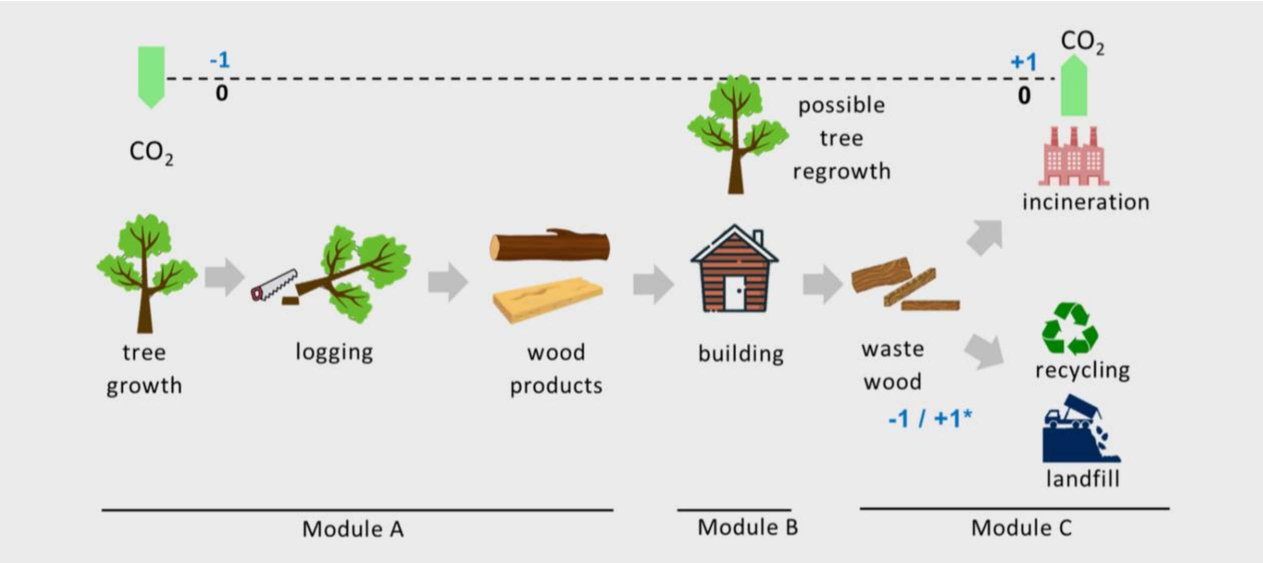


Figure 4: Methods applied on modelling biogenic carbon in the LCA bio-based products. Carbon fixation is assumed to happen either before the construction stage or carbon fixation during the use stage of the building life cycle.

It should be noted that extensive research in Australia over many years involving both bioreactor laboratory research and actual landfill studies of several softwood timber species and various types of engineered wood products (Ximenes et al., 2019) have largely supported the earlier results of (Wang et al., 2011). Summing up numerous studies and accounting for uncertainties, Ximenes at al. (2019) recommended a 1.4% carbon loss for wood in landfills in Australia and noted that "disposal of wood in landfills in Australia results in long-term storage of carbon, with only minimal conversion of carbon to gaseous end products".

In the French EQUER method (Table 1), negative biogenic $CO_2$ emissions are accounted for in the production stage if a new tree is growing which is the case for wood from certified forests. If the wood stems from non-certified forests, the same amount of carbon is stored in the building as if it were stored in the forest. Therefore, no carbon fixation is considered ("0" instead of "-1"). At the end of life, the quantity of biogenic $CO_2$ is emitted if the wood is incinerated, but not if the wood is landfilled or recycled (see Table 1). In France a 0/+1 approach is used if no tree is regrowing (i.e. the forest is transformed to agricultural or built-up land) or if the wood stems from native forests (EN 15804+A2) and the wood is incinerated at the end of life (meaning that no fixation of biogenic carbon is considered, but emissions do happen at the end of life).

Table 1: Biogenic carbon accounting according to the French Equer method

| Timber harvesting | Production/ EoL-Incineration | Production/ EoI-Landfill, recycling or reuse |
|---|---|---|
| **Sustainable forest management (a new tree is growing)** | -1 / +1 | -1 / >0 |
| **Other case (non-certified forest)** | 0 / +1 | 0 / >0 |

## 2.3 The Time-dependent Approach

The time-dependent approach is most frequently adopted by using the calculation procedure proposed by Levasseur et al. (2010). The following figures illustrate the two scenarios that can be considered related to the timing of biogenic carbon sequestration in the forest: (a) assuming that trees grow before the use of the harvested wood product, following the natural carbon cycle (Figure 5), or (b) 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 6) (Peñaloza et al., 2016; Pittau et al., 2018). Results may vary considerably between the two approaches (Peñaloza et al., 2016) - this issue is further detailed in the next section, related to the impact assessment level.

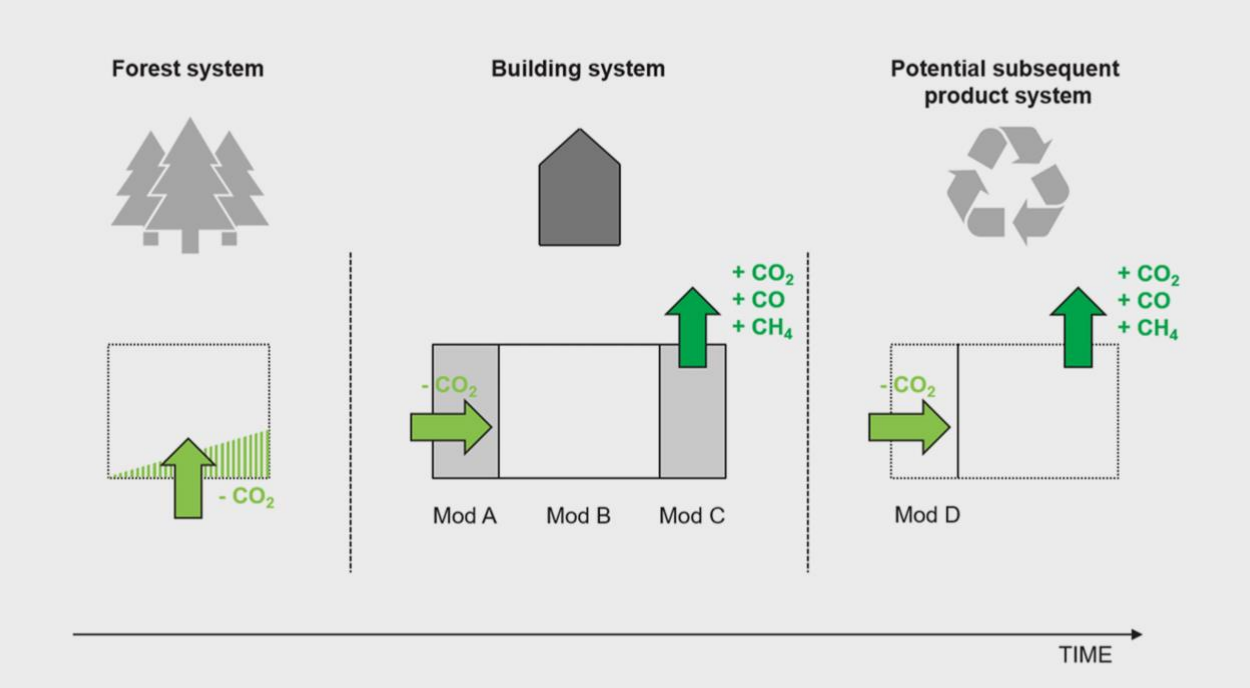


**Figure 5**: The time dependent approach, considering that trees grow before the use of the harvested wood product. The dotted lines indicate the product systems which fall outside the building system boundaries. Source: Hoxha et al (2020).

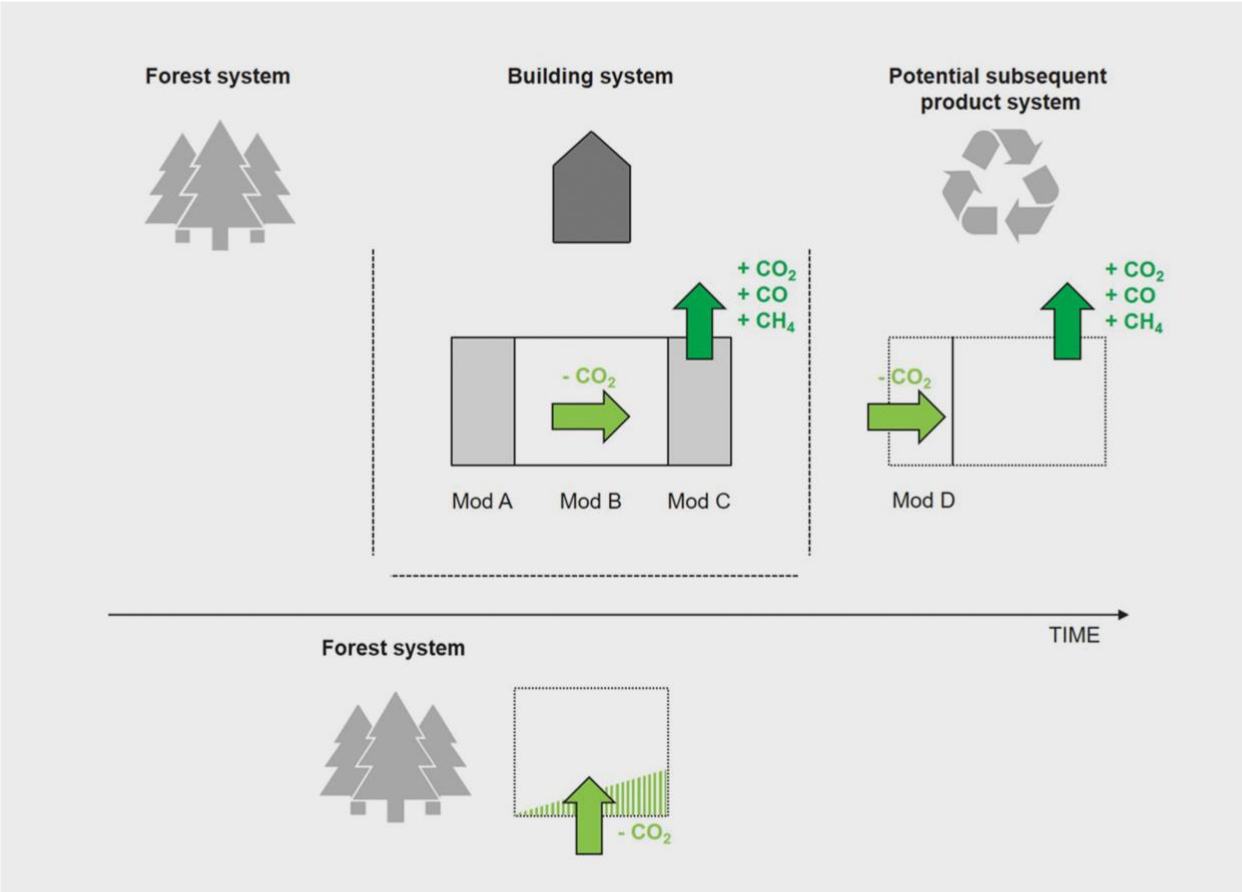


**Figure 6**: The time dependent approach, considering that trees regrow after harvesting. The dotted lines indicate the product systems which fall outside the building system boundaries. Source: Hoxha et al (2020).

Analogously to the -1/+1 approach, the time-dependent approach requires that all biogenic $CO_2$ considered to be absorbed during trees' growth is released at the end of life. The data requirements in this approach, however, are more complex than in the previous one, because the practitioner would need to determine (i) a yearly amount of $CO_2$ being absorbed during material growth, instead of the full content of $CO_2$ in the wooden product, and (ii) the rotation period of the forest, i.e. the time it takes for the trees to reach maturity and be felled. It is not uncommon to find building LCA studies relying on detailed forestry models to determine the latter parameters (Hoxha et al. 2020, Pittau et al. 2020, Carcassi et al. 2022). In these cases, care must be taken to account only for the $CO_2$ that is actually transferred to the building system, i.e. "stored" within the mass of wooden product.

## 2.4 Key Messages and Recommendations at the Inventory Level

Considering the data and inventory modelling needs of these approaches, we hereby draw recommendations that should be considered regardless of the biogenic carbon accounting approach adopted:

a. The physical, life cycle-based balance of biogenic carbon contained in construction products, building elements and buildings shall be net zero. This may require significant adjustments in currently available life cycle inventories of materials based on renewable feedstocks such as wood. In particular, the allocation of raw material inputs shall reflect the physical flows irrespective of the allocation approach chosen. (Both 1 kg of wood beam and 1 kg of sawdust require an input of at least 1 kg of wood each.)
b. When construction materials containing biogenic carbon are either expected to be recycled or landfilled at the end of life of the building or the building element, an amount of biogenic $CO_2$ emissions equivalent to the biogenic carbon content shall be accounted for. Biogenic $CO_2$ safely and permanently removed and stored in dedicated underground facilities shall be treated differently.
c. If an existing building is replaced by a new one, the biogenic carbon stored in the existing building and the subsequent release of biogenic $CO_2$ shall be taken into account.
d. Natural flows of biogenic carbon in forests and on agricultural land (i.e. biogenic carbon not transferred into harvested products) left in forests such as branches, leaves and other residues shall be disregarded and not allocated to the products harvested.
e. The absorption of $CO_2$ shall not be accounted for, if the wood stems from forests which sold $CO_2$-emission certificates based on $CO_2$ absorption to third parties.

# 3. The impact assessment level

## 3.1 The 0/0 Approach

The calculation of the global warming potential (GWP) for the 0/0 approach follows Equation 1, which depicts the sum of the products of each greenhouse gas emission and their respective characterization factor, as defined by the IPCC. For simplification purposes, only $CO_2$, CO, $N_2O$ and $CH_4$ emissions are considered in the equation. Since no biogenic $CO_2$ is accounted for in this approach, only fossil $CO_2$ emissions take part in the GWP calculation.

$$GWP_{0/0} = \sum_t g_{CO2,fossil}(t) * GWP_{CO2} + \sum_t g_{CH4,fossil+biogenic}(t) * GWP_{CH4} + \sum_t g_{CO,fossil}(t) * GWP_{CO} + \sum_t g_{N2O,fossil}(t) * GWP_{N2O} \quad (1)$$

With:

$g_{CO2,fossil}(t) = emissions\ of\ fossil\ CO_2\ at\ time\ t$

$g_{CH4,fossil+biogenic}(t) = emissions\ of\ fossil\ and\ biogenic\ CH_4\ (methane)\ at\ time\ t$

$g_{CO,fossil}(t) = emissions\ of\ fossil\ CO\ at\ time\ t$

$g_{N2O,fossil}(t) = emissions\ of\ fossil\ N_2O\ at\ time\ t$

$GWP_{CO2} = IPCC\ characterization\ factor\ of\ CO_2$

$GWP_{CH4} = IPCC\ characterization\ factor\ of\ CH_4$

$GWP_{CO} = IPCC\ characterization\ factor\ of\ CO$

$GWP_{N2O} = IPCC\ characterization\ factor\ N_2O$

## 3.2 The -1/+1 Approach

### 3.2.1 General

The calculation of GWP when adopting the -1/+1 approach must also consider the uptake and emissions of biogenic $CO_2$, along with other greenhouse gas emissions (Equation 2). The sign used for the uptake of $CO_2$ shall be negative.

$$GWP_{-1/+1} = \sum_t g_{CO2,fossil+biogenic}(t) * DOCf_{CO2} * GWP_{CO2} + \sum_t g_{CH4,fossil+biogenic}(t) * DOCf_{CH4} * GWP_{CH4} + \sum_t g_{CO,fossil+biogenic}(t) * DOCf_{CO} * GWP_{CO} + \sum_t g_{N2O,fossil+biogenic}(t) * DOCf_{N2o} * GWP_{N2O} \quad (2)$$

With:

$g_{CO2,fossil+biogenic}(t)$ = emissions and removals of fossil and biogenic $CO_2$ at time t

$g_{CH4,fossil+biogenic}(t)$= emissions of fossil and biogenic $CH_4$ (methane) at time t

$g_{CO,fossil+biogenic}(t)$= emissions of fossil and biogenic CO at time t

$g_{N2O,fossil+biogenic}(t)$= emissions of fossil and biogenic $N_2O$ at time t

$GWP_{CO2}$ = IPCC characterization factor of $CO_2$

$GWP_{CH4}$ = IPCC characterization factor of $CH_4$

$GWP_{CO}$ = IPCC characterization factor of CO

$GWP_{N2O}$ = IPCC characterization factor of $N_2O$

$DOCf_{CO2}$ = degradable organic carbon fraction of $CO_2$ (for the -1/+1 approach the value is 1)
$DOCf_{CH4}$ = degradable organic carbon fraction of $CH_4$ (for the -1/+1 approach the value is 1)
$DOCf_{CO}$ = degradable organic carbon fraction of CO (for the -1/+1 approach the value is 1)
$DOCf_{N2O}$ = degradable organic carbon fraction of $N_2O$ (for the -1/+1 approach the value is 1)

### 3.2.2 The -1/+1* approach

The calculation of GWP when adopting the -1/+1* approach must also consider the uptake and emissions of biogenic $CO_2$, along with other greenhouse gas emissions (Equation 4). The sign used for the uptake of $CO_2$ shall be negative. The formula for the -1/+1* approach is the same as the formula for the -1/+1 approach expect that the emissions and removals of the greenhouse gasses are multiplied by the degradable organic carbon fraction (DOCf) that is not equal 1. For further information about the DOCf used for the -1/+1* approach see also 2.2.2.

## 3.3 The Time-dependent Approach

To properly comprehend the dynamic characterization factors proposed by Levasseur et al. (2010), one must understand how the traditionally employed characterization factors are calculated. Two main factors have to be considered: (a) the radiative efficiency of the gas (Hartmann et al. 2013), or, in very simple terms, its capability to absorb solar radiation; and (b) the decay pattern of the gas, which indicates how the concentration of a certain gas in the atmosphere changes with time after an emission pulse. The calculation approach consists in multiplying the decay equation (time-dependent) of each GHG by their specific radiative forcing per unit of mass, which is represented by the division of the radiative efficiency (assumed to be constant) by the GHG concentration. The resulting equation (Equation 3) – still a function of time – coupled with the amount of GHG emitted, governs the instantaneous radiative forcing curve, indicating how much an emission of a certain quantity of that GHG can increase the radiative forcing in the atmosphere.

$$IRF = A_i \cdot C_i(t) \qquad (3)$$

Where Ai is the radiative forcing per unit mass. For the $CO_2$, $CH_4$ and $N_2O$ the values are respectively: $A_{CO_2} = 1.76 \cdot 10^{-15}$Wm-2kg-1; $A_{CH_4} = 1.28 \cdot 10^{-13}$Wm-2kg-1; $A_{N_2O} = 3.9 \cdot 10^{-13}$Wm-2kg-1.

Ci is the decay equation of each GHG (represented by i). For $CO_2$ emissions and assuming a background concentration of 378 ppm, the Bern carbon cycle-climate model is used. It presents the decay in time of the initial unitary impulse at t = 0 (Joos et al. 2001):

$$C_{CO_2}(t) = a_0 + \sum_{i=1}^{3} a_i \cdot e^{\frac{-t}{\tau_i}} \qquad (4)$$

$C_{CO_2}(t)$ is the decay pattern of a CO2 pulse emission.

$a_i$ are the coefficients for the calculation of CO2 fractions remaining in the atmosphere. They have the values: $a_0 = 0.217$; $a_1 = 0.259$; $a_2 = 0.338$ and $a_3 = 0.186$.

$\tau_i$ are the perturbation time. They have the values $\tau_1 = 172.9$; $\tau_2 = 18.5$; $\tau_3 = 1.186$ years.

For the other GHGs, the first order exponential decay function is used as described by Equation 5:

$$C_{CH_4,N_2O}(t) = e^{\frac{-t}{\tau}} \qquad (5)$$

The perturbation times for $CH_4$ and $N_2O$ gases are respectively $\tau = 12$ years and 114 years (Shine et al., 2007).

Then, one must calculate the cumulative effect in radiative forcing, by integrating the instantaneous radiative forcing curve (described by Equation 6) for a certain period of time. The definition of the time in which the curve is integrated is called the 'time horizon' of the GWP calculation, and equals the moment in which the warming effect is observed. Typically, a 100-year time horizon is adopted as this is the time horizon applied in the Kyoto protocol and all international negotiations.

$$CRF = \int_0^t A_i \cdot C_i(t) \qquad (6)$$

To quantify the cumulative radiative forcing of the emission of 1 kg of a greenhouse gas in relation to that of 1 kg of $CO_2$, the result for the cumulative radiative forcing of a certain amount of GHG is divided by the cumulative radiative forcing effect of a same amount of $CO_2$ (Equation 7).

$$GWP_{TH} = \frac{\int_0^{TH} A_i \cdot C_i(t)}{\int_0^{TH} A_{CO_2} \cdot C_{CO_2}(t)} \qquad (7)$$

In typical GWP calculations, the IPCC determines the cumulative effect of 1kg of each GHG, in relation to that of $CO_2$, for a set of fixed time horizons (20 and 100 years for the GWP and 20,50 and 100 for GTP- while the GWP is a measure of the heat absorbed over a given time period due to emissions of a gas, the GTP is a measure of the temperature change at the end of that time period relative to $CO_2$), obtaining the so-called characterization factors (CF). That allows an LCA practitioner to obtain an aggregated value of the GHGs emitted during the life cycle of a product or system by using these official CFs. This is the exact approach used in Equations 2, 3 and 4, for 0/0, -1/+1 and -1/+1* approaches, respectively.

The proposal of time-dependent CFs by Levasseur and colleagues (2010) was based on these authors' judgement that when applying the fixed CFs to emissions happening at different times, one would get the cumulative effect of global warming at different moments in the future. Adding up these values to represent the full life cycle GWP is perceived by the cited authors as an inconsistency and a breach of the LCA's time horizon. Claiming to adjust this, Levasseur et al (2010) proposal consists on integrating the instantaneous radiative forcing function (Equation 3) in yearly time steps instead of applying a fixed time horizon – therefore getting a CF for each year in an analysis. These yearly CFs are multiplied by the emission (or uptake) happening in that respective year, and eventually added up to represent the total global warming effect at a certain (arbitrarily fixed) time horizon. The cause and source of emissions (reference study period (RSP) of building) and impacts of those emissions are independent of each other and thus (may) have different time periods.

This latter time horizon is a choice to be made by the LCA practitioner. The results will vary quite significantly depending on this arbitrary choice. If calculating the overall warming effect 100 years after the building was built, the effect of emissions associated to the end of life of the building (say 75 years after it was built) is significantly underestimated – because 25 years later there is a "cut-off" of that effect due to the time horizon adopted.

Since the time-dependent approach moves away from the agreed upon reasoning behind the calculation of CFs by the IPCC, valid questions can be raised as to its robustness and/or relevancy:

a. there are no recommendations for time dependent CFs in any official IPCC documents, despite the proposal having been published over ten years ago;

b. the concept of time zero for GWP calculation is different than time zero for a specific LCA: the IPCC assumes that time zero for GWP calculation is the time of emission, regardless of whether it is happening today or a few decades from now;
c. the setting of the time horizon for time-dependent LCAs seems to carry a political weight: a short TH decreases the relevance of emissions happening at a later stage, pointing to a stimulus on short-term solutions to control climate change, whereas a very long TH allows for the perception that delaying emissions for a few decades has a negligible effect on the overall warming of the atmosphere.

## 3.4 Key Messages and Recommendations at the Impact Assessment Level

Considering the opposing views on the calculation of GWP in so-called "static" (0/0 and -1/+1) and time-dependent approaches, we hereby draw important messages to be considered in building LCAs containing wood products:

a. If opting for a time-dependent assessment of biogenic carbon flows, the time horizon at least be set to 100 years plus the final year of the reference study period (let's say, 50 or 60 years after the construction). With this time horizon, the results of the dynamic assessment and of the -1/+1 approach (if the carbon balance mentioned in section 2 is assured) are identical.
b. Renewable materials used in building elements and buildings store biogenic carbon temporarily1. The temporary biogenic carbon storage has hardly any effects on the overall cumulative radiative forcing nor on the overall temperature increase. However, it offers a few decades of time to develop technologies to separate biogenic carbon and store it permanently after the end of life, either in buildings or in dedicated final carbon repositories.

Considering the need for clear practical guidelines in building LCAs that shall allow for harmonization and benchmark creation, the recommendations of the authors are:

c. Since the publication of Levasseur et al. (2013) scientific knowledge regarding climate change and $CO_2$ emissions progressed. While annual budgets were discussed in the past, global total budgets are considered relevant today (IPCC 2021). Hence, the time of release of a ton of $CO_2$ does not matter and has hardly an influence on its ultimate effect on the longterm rise of global mean surface temperature (which should not exceed 1.5°C). Hence, the GWP of an emission of $CO_2$ shall be independent of time and equal 1 kg $CO_2$-eq per kg.
d. The integration time (usually 100 years) used to determine the global warming potential (GWP) and the global temperature increase potential (GTP) applies independently of the time of release of $CO_2$ and other greenhouse gases. The integration time on one hand and the reference study period and the lifetime of a building on the other are fully independent. A fixed time horizon (of e.g. 100 years) shall not be reasoned with the (fixed) integration time used to determine GWP and GTP.
e. Still, acknowledging the importance of benchmarks and of increasing $CO_2$ uptake and storage, it is recommended to introduce legally binding benchmarks on biogenic carbon content (minimum biogenic carbon content in a building, >XX kg $C_{biogenic}/m^2$), since it is justified to believe that during the period of temporal carbon storages new technologies will be developed that will provide the possibility of permanent storage. Such a benchmark shall be kept separate from a carbon footprint benchmark (maximum fossil greenhouse gas emissions, <XX kg $CO_2$-eq/m$^2$ and/or < xx kg $CO_2$-eq/m$^2$a). The next section further discusses binding benchmarks and recommendations thereof.

[1] Considering the fact that landfilling is forbidden. Since there are also special cases, like the -1/+1* notes herein and in the submitted journal paper (i.e., esp. the conclusions and recommendations therein), this report recommends that jurisdictions about landfill practice and measure/present DOCf values are developed. As an international guideline, this report should recognize that some (or many) countries use landfills primarily (or where incineration is not the main or only practice, etc. and should also provide recommendation how to handle these cases.

# 4. GWP as a Requirement in Legislation

In connection with funding conditions and legislative initiatives to limit greenhouse gas emissions in the life cycle of buildings, represented as GWP, the question arises as to whether and to what extent GHG emissions as a result of the production (and construction) of the building (i.e. embodied emissions) can and should be introduced in the form of non-binding orientation values or binding secondary requirements for modules A1-A3 or A1-A5.

According to EN 15804 A2 and EN 16643, the information on GWP should be additionally subdivided into $GWP_{fossil}$, $GWP_{biogenic}$ and $GWP_{luluc}$. This makes it possible to distinguish between fossil and biogenic greenhouse gas emissions. The -1/+1 approach is part of $GWP_{biogenic}$. Emissions of biogenic methane are also accounted for in the latter indicator. Shares caused by land use or land use change (luluc = land use and land use change) are usually neglected. In addition, the content of biogenic carbon in the material, product and structure shall be reported in "kg C", as briefly mentioned in the previous section.

If partial characteristic values for A1-A3 are taken from life cycle assessments for buildings, this part corresponds to the -1 approach for A1-A3. Shares according to +1, to be assigned to module C, are then not visible. In the case of above-average use of products made of wood or biomass in the production and construction of the building, the sub-value A1-A3 for $GWP_{total}$ can assume very small or even negative values. Larger amounts of fossil GHG emissions are supposedly compensated by negative $GWP_{biogenic}$ contributions. The question arises as to the steering effect of corresponding effects.

Annex 72 experts identify three separate positions on how to handle the issue:

**Position A:**

Low or negative values for A1-A3 with above-average use of wood/biomass are desirable and are intended to have a steering effect in the direction of increased use of renewable raw materials.

In a national view of greenhouse gas emissions in annual slices, they show that $CO_2$ is removed from the environment in the growth phase. However, assigning this to the time of construction of the building is a gross simplification and does not apply to wood in particular. The situation is different for fast-growing biomass, where there is approximately a temporal correspondence. However, the time of storage of $CO_2$ (as well as its release) is not decisive for the overall global temperature increase.

When considering annual emissions in annual slices at the national level, two additional considerations would have to be made: (1) How many GHG emissions will be released this year by the end-of-life of dismantled products? (2) How many GHG emissions will be released at what point in time by the end of life of products now in use and can this point in time be delayed by further use/cascade use? Again, it is pointed out that this is not important with regard to global warming effects as a whole.

There is a (small) risk of using wood/biomass beyond necessity in the interest of low values at A1-A3. There is also a risk of false incentives. In particular, negative values would suggest that more extensive construction measures benefit the environment. This can only be put into perspective by including other indicators and makes it clear once again that an isolated consideration of greenhouse gas emissions is not a solution.

**Position B:**

The use of values according to -1/+1 for sub-values (as orientation values, secondary requirements or as main requirements) to A1-A3 is considered methodologically not permissible. In particular, the lack of visibility of emissions at the end of the life cycle is met with criticism. The use of the 0/0-approach for an isolated presentation of A1-A3 is discussed. In this way, corresponding products are included in the consideration as "greenhouse gas neutral" in the area of biogenic GWP.

On the other hand, however, this can be interpreted as a methodological break and produces problems of presentation when dividing an LCA into phases A, B and C.

**Position C1:**

Requirements should not be formulated for A1-A3 alone, but mandatorily take into account the associated disposal modules C3-C4.

**Position C2:**

As an alternative to C1, requirements for A1-A3 should be formulated separately for $GWP_{fossil}$ and $GWP_{biogenic.}$ In addition, land register entries must be made to ensure that the quantities of biogenic and fossil carbon used in buildings are separated and permanently sequestered during demolition.

# 5. Conclusions

Considering the current state of knowledge on dynamic modelling of biogenic carbon in buildings, the scientifically questionable application of a fixed time horizon and the derivation of time dependent GWP factors, the variability and uncertainty due to choices of important (newly introduced) parameters, and the lack of consensus on the latter, standards and regulations for LCAs of buildings shall rely on static characterisation factors and on a net zero biogenic $CO_2$ balance over the full life cycle (modules A1-C4) unless the biogenic carbon is permanently and safely stored in dedicated underground storage facilities[2] or permanently stored in carbonated cement used in concrete.

[2] Certain jurisdictions and national authorities have published documented/measured values on the degradable organic carbon fraction in landfills, which allows to determine the share of landfilled biogenic carbon released back to the atmosphere. Some countries such as Australia and New Zealand use this information to determine the net sequestration of biogenic carbon in the life cycle of buildings.

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