Stadt Zürich
Amt für Hochbauten

Carbon storage project

Technical report
Methodology for biogenic carbon accounting and carbonation in LCA of buildings and construction products

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Fachstelle nachhaltiges Bauen

ETH zürich

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Stadt Zürich
Amt für Hochbauten
Fachstelle nachhaltiges Bauen
Postfach, 8021 Zürich
stadt-zuerich.ch/hochbau
Kontaktperson: Niko.Heeren@zuerich.ch

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Autoren
Francesco Pittau, Wissenschaftlicher Mitarbeiter an der ETH Zürich
Guillaume Habert, Professor an der ETH Zürich
Daniel Savi, Dipl. Umweltnaturwissenschafter ETH, Büro für Umweltchemie Matthias Klingler, MSc Umweltingenieur EPFL, Büro für Umweltchemie

ETH Zürich
Institut für Bau- und Infrastrukturmanagement
Professur für Nachhaltiges Bauen
Stefano-Franscini-Platz 5, HIL F 28.2
8093 Zürich
sc.ibi.ethz.ch

Büro für Umweltchemie GmbH
Schaffhauserstrasse 21
8006 Zürich
www.umweltchemie.ch

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Executive summary

The transformation of our society and living standards to meet a zero-carbon society by 2050 is an urgent task that requires targeted investments a prioritization plans able to stop disturbing the climate with human activities. The energy related carbon to operate the buildings as well as the carbon embedded in construction materials are one of the main responsible to climatic disaster we are living nowadays. To preserve the residual carbon budget that should be spent for the transition a radical shift to zero carbon construction is required. Wood materials, and bio-based in general, have been identified as valuable solutions able to regenerate the climate due to the restoration in the land of the carbon stored in buildings and the delayed biogenic emissions at the end of life. Moreover, the substitution of ordinary non-biogenic construction materials with biogenic ones can bring an additional contribution to reduce the fossil carbon emissions from ordinary fossil-based construction processes. While methodologies to evaluate the fossil carbon of construction materials is generally well integrated in LCA databases, the impact of biogenic carbon on global warming potential (GWP) is complex to be evaluated since influenced by time-dependent factors and uncertainties. For this reason, LCA methodology adopted by commonly used databases (KBOB, ecoinvent, etc.), is normally based on IPCC method which excludes biogenic CO_2, assuming a carbon neutral cycle for biogenic material. Similarly, no carbon uptake in cement and lime products is considered due to the difficulty of prediction models.

This technical report aims to support the City of Zurich in identifying the main issues which affect the biogenic carbon calculation in LCA projects, as well as the carbon sequestration in cement products, and to propose and calibrate valid methods to sidestep the obstacles. A state-of-the-art about different existing calculation methods for biogenic carbon cycles (static vs. dynamic) is presented and a novel method, based on the GWP_{bio} concept is proposed and discussed. Similarly, a specific section is dedicated to carbon sequestration in concrete and cement products via carbonation, with the proposition of a novel semi-static methodology able to support building and structural designers in estimating the removal contribution from structures during their operational life in buildings. Finally, an estimation of carbon mitigation potential from implementing wood in construction by 2050 in the City of Zurich is presented and sensitivity of the different calculation methods discussed to define a valuable pathway for the development of a climate neutral city.

1. Background

Fighting against the current climate emergency is the main challenge of these years. Construction sector, in particular construction products manufacturing, products transportation and onsite construction activities, contributes to 23% to the global human-related greenhouse gas (GHG) emissions (UN Environmental and International Energy Agency, 2017). Over half of those is the result of cement and steel production, making its contribution to the climate crisis significant. Previous research and policy initiatives focused on reducing operational emissions of buildings, particularly through improving energy efficiency and increasing renewable energy use (Lützkendorf et al., 2014; Passer et al., 2019, 2012). Recent studies indicate that the focus now must shift to other stages of the life-cycle, including the embodied carbon associated with manufacturing, transport, construction, in order to ensure a full decarbonization of construction (Drouilles et al., 2019; Mirabella et al., 2018; Röck et al., 2020).

IPCC has investigated different scenarios for global warming and related 'emission reduction pathways' (IPCC, 2018), and in total 80% of the global carbon should be saved by 2040 to ensure a relatively safe transition to Zero-carbon society. Unfortunately, construction is a problematic sector to decarbonize, compared to other industrial compartments, due to massive investments needed to transform its fossil-dependent infrastructure and the cross interactions existing with other sectors (e.g., mobility, energy, etc.). Based on this scientific evidence, policymakers have agreed to use 2°C target as important objective for international climate policy (UNFCCC, 2015). However, higher GHG concentration levels than those consistent with long-term temperature targets may be possible if negative emissions technologies, also called carbon capture and storage (CCS) reabsorb this concentration excess before 2100 (van Vuuren et al. 2013). Unfortunately, the investment needed to develop CCS technologies able to actively remove the carbon from the atmosphere and store it in the natural pools (i.e. ocean or land) are extremely high and their fast implementation in a very short period is questionable (Smith et al., 2015). It is therefore time to go beyond the conventional concept of sustainability based on "do less bad" to pave the way to a new regenerative concept based on "provide more good". In construction, alternative solutions out of local resources, such as earth, bio-based and reused materials are emerging all over the world and are triggering regenerative output, thanks to their capacity to contribute to the restoration and improvement of the surrounding natural and social environment. In particular, forest products and bio-based materials in general, especially fast-growing (e.g. straw fibres, hemp, flax, etc.) can positively contribute to climate regeneration through the capacity of restoring the carbon in the land (Pittau et al., 2018). However, their use is not widespread in the construction sector due to lack of information on the side of decision makers and lack of competence on the side of practitioners. Moreover, focusing on climate restoration, the positive effect due to biogenic CO_2 storage and delayed emissions are not included in standard methodology for carbon footprint calculation (SIA 2032 and ISO 14067) and their fast promotion in the market is difficult due to the lack of incentives.

Forest ecosystems store a large amount of carbon. It is estimated that more than 650 billion tons of carbon is stored in the forests all over the world, almost 20% of the carbon contained in the earth's biosphere (Olson et al., 2001). In Europe, the forest net-change area grows at a rate of 0.5% each year (FOREST EUROPE, 2015). It has been demonstrated that an efficient and sustainable management of the forests (by means cutting mature trees for the production of bio-based products, harvesting

residues for energy production and replanting young trees for afforestation and carbon uptake) can contribute to improve the carbon storage capacity in the biosphere(Eriksson et al., 2007).

In Switzerland, the building stock is expected to undergo important structural changes in the next decades. While this will lead to a reduced number in new constructions, material flows will increase, mainly due to insulation materials that will be needed to renovate the aged buildings (Heeren and Hellweg, 2018). Thus, the renovation of existing buildings, as well as the material supply for new construction, can become a valuable opportunity to store carbon in the built environment by promoting the use of bio-based construction materials (Churkina et al., 2020). In fact, , as shown in Figure 1, when the wood is harvested from the land, the carbon embedded in the biomass is not emitted into the atmosphere, as when used as biofuel, but stored for a long period in the building. During the storage period in building, the carbon is slowly regenerated in the forest, contributing to negative emissions.

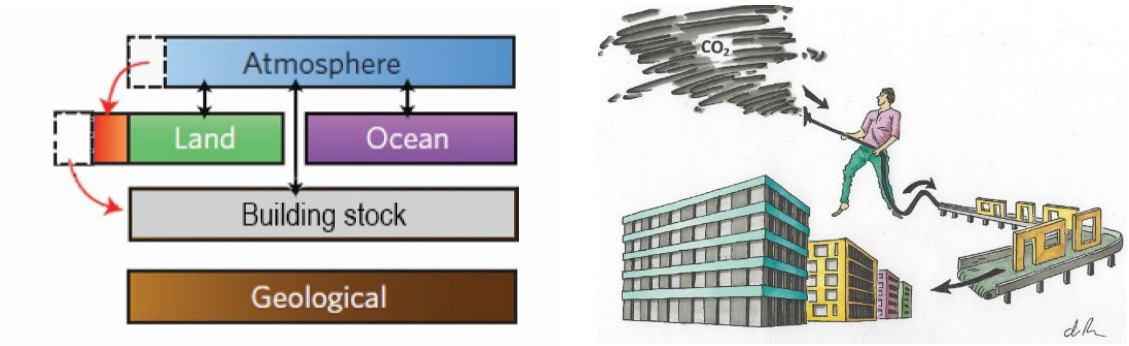


Figure 1. Carbon capture and storage in the built environment by using forest and agricultural bio-based products.

At the end of the building service life, the carbon stored in the bio-based construction products is in large part emitted as CO_2 in the air, but since the biomass has been regenerated in the forest, the same amount of carbon can be assumed to be sequestered when the regrowth of trees is completed (Gustavsson and Sathre, 2006). For this reason, bio-based construction products are generally considered as “carbon neutral”. But how much the carbon neutrality of wood products leads to a climate neutrality is questioned by many authors (Brandão et al., 2012; Cherubini, 2015; Negishi et al., 2019). When biomass is used for buildings, the effects of dynamics of biogenic carbon dioxide cycles affect multiple activity systems: forestry and agriculture, energy sector, construction industry, building and waste management. Several researchers in the last twenty years have developed models and methods to assess these cycles and include the benefits of delaying the biogenic carbon emissions from storing carbon in buildings. Nevertheless, a recognized standard methodology for biogenic carbon accounting is still missing. Moreover, the fundamental question “which system is taking benefits (credits) from the use of biogenic materials in construction?” still needs to find a definitive answer. On one hand, forestry contributes to the restoration of the carbon in the land, with the direct CO_2 uptake in the biomass and forest soils. On the other hand, the regenerative effect from carbon restoration in the forest is not effective if the harvested carbon is not temporarily fixed in long life products, as buildings and building products. The risk of assigning the same credits to both systems can bring to a dangerous double counting with a consequence of overestimating the carbon benefits from biogenic construction.

2. Goals and scope of the work

The scope of this report is to illustrate and discuss different methodologies for biogenic carbon accounting and CO_2 uptakes in building and to propose a validated method, based on scientific evidence, to include its contribution on GWP calculation for timber, biobased and cement-based construction products.

3. Glossary

In the following Table 1, a list of the main key terms and definitions to discuss temporal considerations for biogenic carbon within the LCA framework is presented. These terms are collected to ensure a consistent and non-ambiguous understanding of the further sections of the report. It is also the authors' hope that this glossary might bring some uniformity during discussions.

Table 1. List of the main terms used in LCA and carbon footprint framework and definitions.

Term	Definition
Dynamic LCA (DLCA)	LCA studies where relevant dynamic of systems and/or temporal differentiation of flows are explicitly defined and considered.
Biogenic carbon	The emissions related to the natural carbon cycle, as well as those resulting from the combustion, harvest, digestion, fermentation, decomposition, or processing of biologically based materials.
Biogenic carbon content (CC)	Biogenic carbon content, also simply called “carbon content” is the mass of carbon fixed in biogenic materials (vegetal or animal fibres). It is commonly measured in percentage of C per unit of mass.
Biogenic CO_2 storage	Biogenic CO_2 storage, also simply called “carbon storage”, is the equivalent mass of CO_2 stored in biogenic materials. It depends on the carbon content and is normally measured in kg of CO_2 per unit of mass or unit of volume.
Biogenic CO_2 uptake or removal	Biogenic CO_2 uptake or removal, also simply called “carbon uptake or removal”, is the mass of CO_2 captured by a plant via photosynthesis during its growth which contribute to a (temporary) reduction of the CO_2 concentration in the atmosphere. It can be measured as annual or cumulated value and it is normally expressed in kg of CO_2 per unit of mass or unit of volume.
Dynamic characterization factor (DCF)	Characterization factor (CF) for a given temporal scope or period of occurrence. It results from the dynamic of systems in the ecosphere and can be calendar-specific, relative to the length of the temporal scope, or defined by a TH. Period-specific CFs are modelled as constant over the chosen period.
Dynamic Global Warming Potential (dynGWP)	Heat absorbed over time by a greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed over the same time horizon (TH) by the same mass of carbon dioxide (CO_2).
Dynamic LCI (DLCI)	Life cycle inventory (LCI) that is calculated from supply and value chains where dynamic of systems or temporal differentiation is considered, resulting in temporal distributions to describe elementary flows.
Dynamic LCIA (DLCIA)	Characterization models of environmental mechanisms that account for the dynamic of ecosphere systems and can therefore use temporal information of *DLCIs*. The chosen temporal differentiation (e.g. day, season, and year) can depend on the impact categories. Both case specific and calendar-based characterization models can be used, depending on the chosen indicators.

Dynamic of systems	System modelling that considers inherent variations, periods of occurrence or evolution within the temporal scope of models' components. Such a dynamic modelling can be applied to both technosphere systems (for LCI) and ecosphere systems (for LCIA).
Evolution	Changes of process, structure or state models' components (e.g. technology replacement, pollutant concentration in a compartment of the environment).
Inherent variations	Variations of flows in the models' components (e.g. cycles of solar energy production, growth rates of vegetation, seasonal functional traits, biogeochemical and biophysical dynamics). The discontinuities of flow rates are also part of such changes.
Moisture content (MC)	Moisture content, also called water content, is the amount of water that can be measured in the biomass. It is normally expressed as a percentage of water per unit of volume.
Period of occurrence	The moment when a model's component is starting, modified or finishing over time. (e.g. lifespan of a building, beginning of waste management, start of a life cycle).
Prospective modelling	A prospective LCA addresses future life cycle impacts using different modelling strategies (e.g. scenario-based, technology development curves and agent- or activity-based models). The evolution of systems is thus defined and/or simulated using a list of explicit assumptions regarding the future. Prospective modelling can be applied to both the technosphere and ecosphere and is a subset of the dynamic of systems, which only concerns future forecasts.
Radiative forcing	The difference between solar irradiance (sunlight) absorbed by the Earth and energy radiated back to space
Rotation period (R)	The growth period required to generate the biomass derived from a stand of timber. The calculation of this period is specific to each stand and to the economic and sustainability goals of the harvester.
Storage period (S)	The time in years when the carbon (S) stays as form of glucose in the biomass, often assumed equal to the service life of the product.
Temporal considerations	Any aspects (i.e. information) described in relation to the time dimension or dynamic of systems in the LCA framework. This is the overarching term relating to all other terms of the glossary.
Temporal differentiation	The action of distributing the information on a time scale related to the models' components. For example, elementary flows could be described per day or year. Different processes representing yearly average are another example.
Temporal resolution	Describes the time granulometry when temporal differentiation is carried out. For instance, a monthly or daily resolution can be used to describe the flows in technosphere models. The same term can be used to describe a time step for period-specific CFs.
Temporal representativeness	Qualitative or quantitative assessment of data, processes or LCIA methods in relation to how appropriate their information fits with their temporal scope.
Temporal scope	Defines any type of period that is considered in a LCA study (e.g. temporal considerations along a life cycle, service life of a product, data collection period).
Temporalization	Attribution of temporal properties to the models' components. (e.g. definition of temporal scopes)
Time horizon (TH)	Relative temporal scope over which environmental impacts are summed up to provide LCA results.

4. Scientific literature review

A considerable point of contention within LCA is the assessment of biogenic carbon (Levasseur et al. 2013; Breton et al. 2018). Biogenic carbon dioxide, i.e. CO_2 emissions from the degradation or combustion of biomass, often is not considered in LCA (Liu et al., 2017). It 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 considered as carbon sequestration (Brandão et al. 2013). The main reason why its inclusion is neglected in carbon footprint assessment in building is linked to the estimation with standard "static" LCA of the time dependency of the cycles (emission-uptake) and their consequence on GWP. Moreover, buildings and building materials are affected of a lack of information about the real service life, and treatments of materials at the end of life after a long service life is typically an unknown data difficult to be predicted at the time of installation.

However, several studies stretched the importance of taking biogenic carbon into account. Bio-based products contain roughly 50% carbon in dry mass, creating an opportunity to store carbon in buildings constructed with biogenic materials (e.g., timber, hemp, straw, etc.). Both energy and material use of wood can contribute to mitigating climate change when replacing carbon intensive materials. Using wood in products with long service lives can additionally contribute to increasing the amount and time of carbon (C) stored in the anthroposphere. Cascading the use of wood e the multiple material utilizations of wood resources prior to their conversion into energy (Sirkin and Houten, 1994) has been pointed out as a strategy to improve resource efficiency and contribute to the circular economy by extending the service life of the wood resource (Carus and Dammer, 2018). The environmental assessment of such multi-output cascade systems is challenging due to the multiple products and recycling steps involved, and the distribution of emissions, particularly of biogenic CO2, over long-time spans. It is therefore reasonable that the carbon footprint assessment of biogenic materials is conducted in a transparent and comparable manner to avoid misleading information, especially when long rotation species are used as construction material and long service life is expected for products (Lippke et al., 2011).

The majority of LCA scholars and practitioners in the early 2000's used the "carbon neutral approach" when calculating biogenic carbon (Vogtländer et al., 2014). This is due to the release of carbon from a biogenic product at the end of its life being neutralized by the uptake of carbon dioxide by its replacement via photosynthesis during the forest growth. However, to assess the impact of temporary carbon storage, some LCA methods include carbon sequestration as an option, namely the British Publicly Available Specification PAS 2050 and the European Commission's International Reference Life Cycle Data System (ILCD) Handbook. Similarly, SIA 2032 standard do not include biogenic CO_2. In these standards, it is possible to give credit to temporary storage by discounting delayed emissions. This method has been criticized by Vogtlander et al (2014) who conclude that this leads to an overestimation of the benefits as a focus that is restricted to the production stages would consider only the uptake of biogenic carbon and disregard emissions, e.g., from landfilling or combustion at the product's end of life. In traditional LCAs used for buildings, the two most common approaches for assessing biogenic carbon removals and emissions are the 0/0 and -1/+1 approaches. 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. According to this approach, as timing of emission-removal is not included in the calculation and all GHG inputs are shifted at time zero, the carbon neutrality assumption leads automatically to a climate-neutrality. Consequently, there is no consideration of biogenic CO_2 uptake (0) and release (0). The approach is illustrated in Figure 2 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 2, biogenic CO2 is not considered in any module. Only the release of biogenic methane (CH4) is modelled in module C, due to its higher impact on GW compared with biogenic CO2.

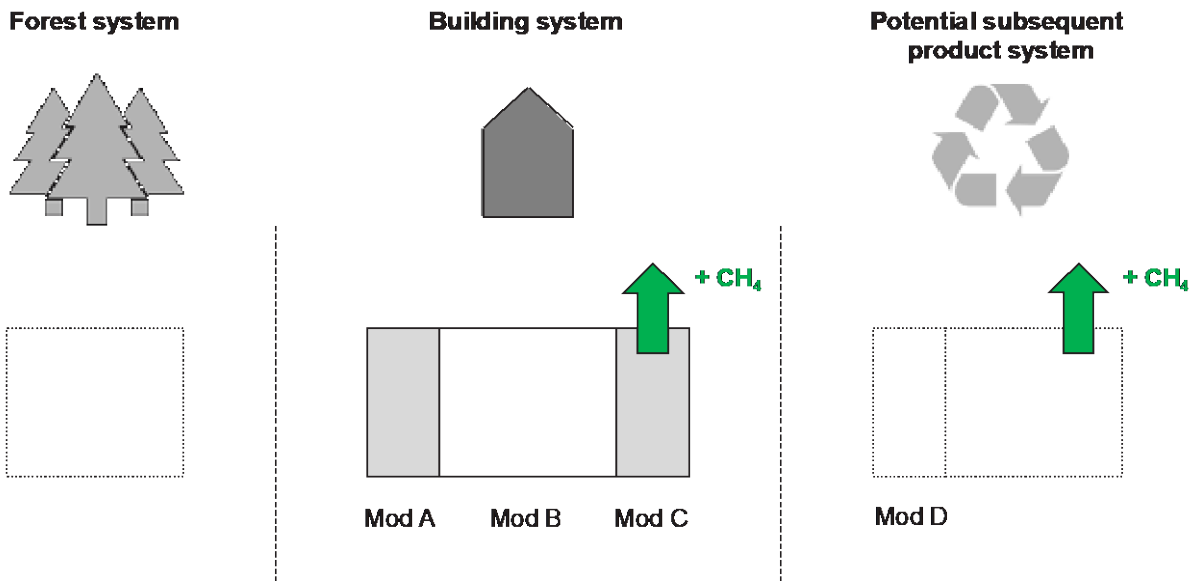


Figure 2. 0/0 approach for biogenic carbon. Dotted lines indicate the product systems that fall outside the system boundaries (Hoxha et al., 2020).

The second approach, which is referred to as the '–1/+1' method, consists of tracking all biogenic carbon flows over the building life-cycle. In this approach both biogenic CO_2 uptake (–1) and emission (+1) are considered, as well as the transfers of biogenic carbon between the different systems, as illustrated in Figure 3. 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.

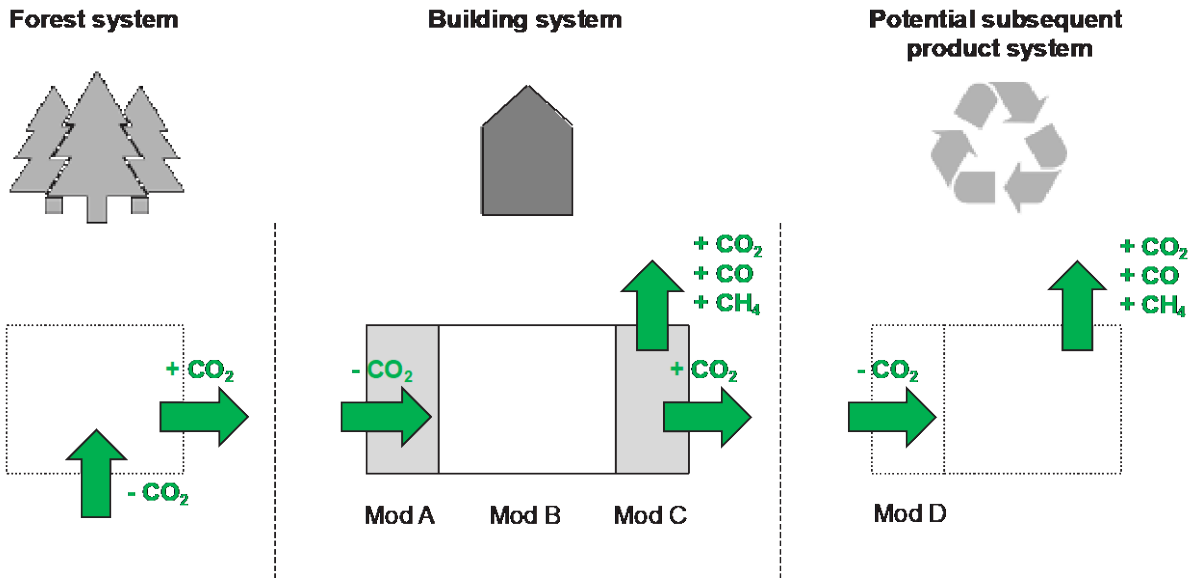


Figure 3. –1/+1 approach. Dotted lines indicate the product systems that fall outside the system boundaries (Hoxha et al., 2020)..

An important aspect in this approach is that the biogenic carbon balance should be zero for all product systems. Compared to 0/0 approach, the main advantage of the –1/+1 approach is to provide an overview of all biogenic carbon flows, but still the main limitation of not considering the time influence on GWP persists. Moreover, there is a risk of biased and misleading results when only the impact of the product and construction 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 to 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 GHG impact of bio-based products. Studies such as Pittau et al. (2018) demonstrate that not all bio-based products can be considered as climate neutral, even if 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). 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 4); 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 5) (Peñaloza 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.

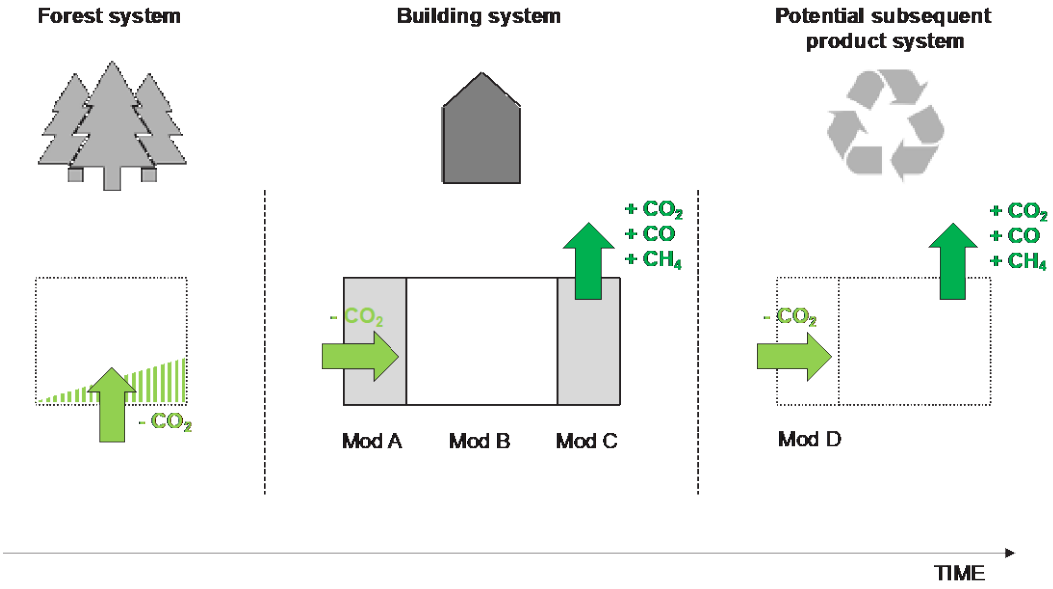


Figure 4. Dynamic approach – Temporal carbon storage in forests during the life of the building is considered based on the tree rotation period (Hoxha et al., 2020).

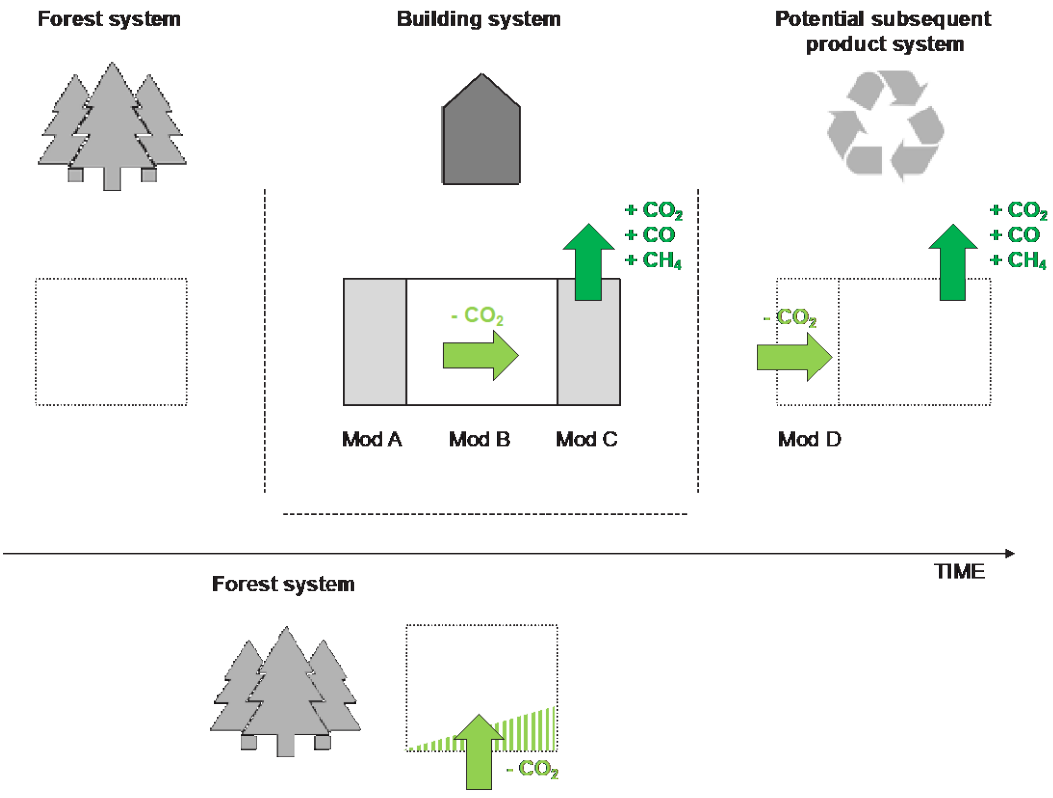


Figure 5. The dynamic approach, considering that trees regrow after harvesting. The dotted lines indicate the product systems which fall outside the building system boundaries (Hoxha et al., 2020).

When biogenic materials are used in construction, emissions and sequestration of biogenic CO_2 usually occur at very different points in time, but, in most LCA studies the related climate change effect is not taken into account: biogenic CO_2 is either not considered or biogenic CO_2 emissions are assumed to balance out CO_2 uptake during biomass growth. To circumvent this issue, a number of dynamic approaches to account for these temporal effects have emerged, focusing on bioenergy at first (e.g. O'Hare et al., 2009; Kendall et al., 2009; Levasseur et al., 2010; Cherubini et al., 2011), and encompassing bio-based materials later (Guest et al., 2013; Levasseur et al., 2013). The issue of biogenic C accounting has also been raised in several standards, such as ISO 14067:2018 (ISO, 2018), Greenhouse Gas (GHG) Protocol (WRI and WBCSD, 2011), International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010), and Publicly Available Specifications (PAS) 2050 (BSI, 2011), which either prescribe a method or leave the approach to the user. While several approaches have been reported in literature (Daystar et al., 2017; De Rosa et al., 2018; Levasseur et al., 2013), there is still a lack of consensus regarding which methodologies for dynamic accounting of C flows to employ in carbon footprinting and LCA studies.

Dynamic LCA (DLCA) approaches are able to include the impact of timing. Levasseur et al. (2010) proposed a method based on time-dependent characterization factors. Cherubini et al. (2011) developed specific characterization 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.

Accounting for the timing of carbon uptakes and greenhouse gas emissions is particularly relevant for the assessment of wooden materials, because it allows considering temporarily storing carbon and delaying GHG emissions (Levasseur et al., 2013). To address the concerns related to time, Levasseur et al. proposed Dynamic Global Warming Potential characterization factors, which provide a more accurate picture, particularly for the temporary storage of carbon and delayed emissions, as it includes the rotation periods (see Figure 3). Indeed, as Fouquet et al. (Fouquet et al., 2015) concluded using the dynamic Global Warming Impact (GWI) concept to examine three different construction types (timber frame, concrete blockwork and cast concrete), although timber was the least impacting choice, it was not climate neutral. This was due to the impact of the different end of life scenarios, particularly when bio-based products are landfilled.

In the same order of idea, Cherubini and colleagues developed the GWP_{bio} index for different time horizons and biomass rotation periods to account for the fact that biogenic CO_2 has an impact before its sequestration by growing biomass growth, especially for long rotation species (Cherubini et al., 2011). In fact, it has been demonstrated that different rotation periods strongly influence the capacity to remove carbon from the atmosphere by storage in buildings. In particular, fast-growing materials, e.g. straw, hemp, flax, etc., have a higher potential as negative carbon technologies when used as thermal insulation in buildings, as shown in Figure 6, because the carbon embedded in the bio-based product is fully regenerated in less than one-year in the crops (Pittau et al., 2018).

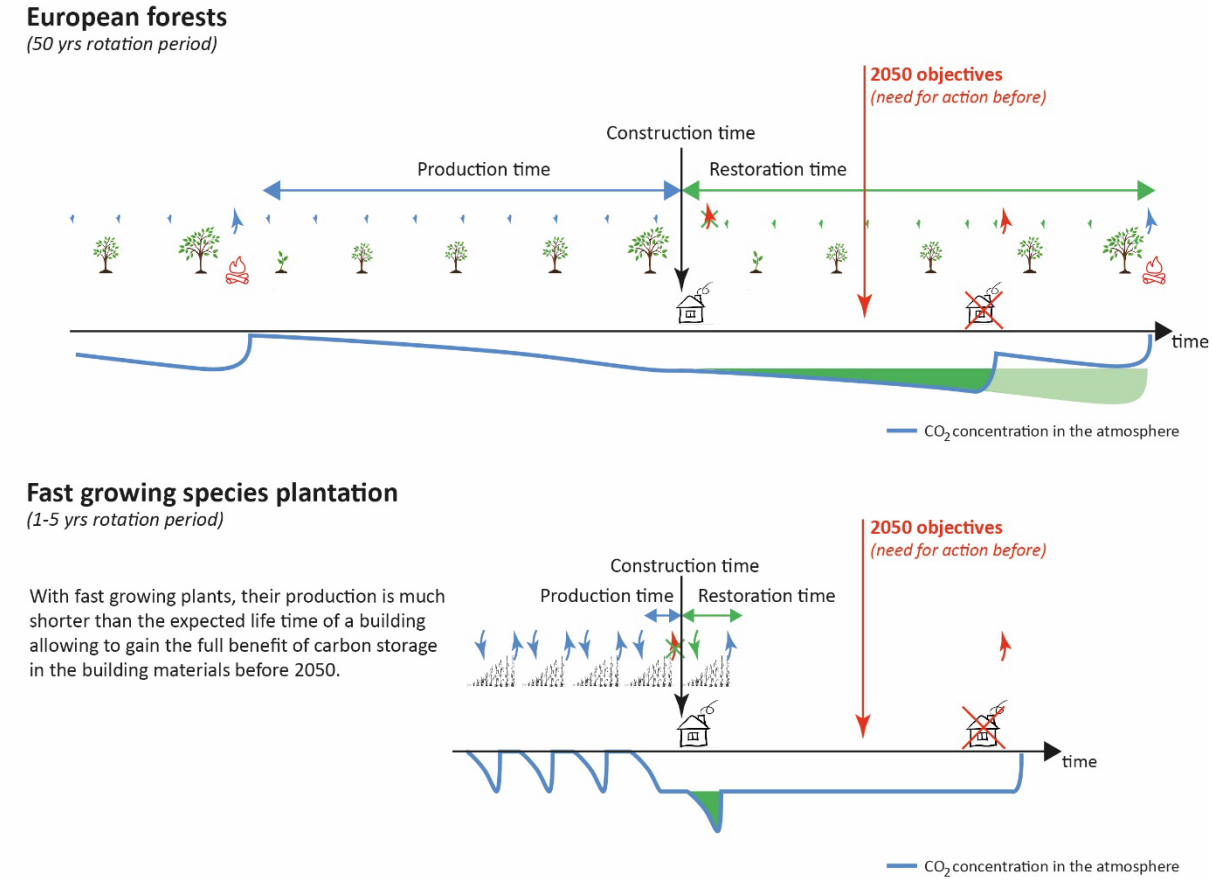


Figure 6. Carbon cycle of long-rotation species and fast growing species when used in construction (Gauzin-Müller et al., 2019).

The longer the rotation period, the longer the mean stay of CO_2 in the atmosphere and therefore the higher the biogenic GWP. Guest et al (Guest et al., 2013) extended the GWP_{bio} method proposed by Cherubini et al. to assess the impact of carbon storage in wooden products. Based on the research, it was found that climate neutrality in 100 years is obtained for a storage time of about half of the rotation period. Considering the limited time we have ahead to complete the transition, a fast transformation of the building stock with fast growing bio-based materials is the most effective option to store carbon in the built environment and foster the uptake in the land (Pittau et al., 2019).

As discussed above, due to the methodological limits in LCA standards, carbon storage and end-of-life of bio-based products are not included in most of LCA databases and validated Standards. In Switzerland, for instance, both Ecoinvent and KBOB eco-BAU are largely used by practitioners as dataset for assessing the carbon footprint of buildings, but none of them reports data about biogenic carbon and, from a building designer prospective, a comprehensive estimation of the carbon storage and delayed emissions potential is not possible so far. This generates certainly a limitation in the promotion of bio-based materials in construction. In the next section, a methodology needs urgently to be integrated in the standards.

5. Methodology for biogenic carbon accounting

5.1 Temporal limitation in carbon footprint calculation

Traditional LCA is a static approach, based on the aggregation of past, present and future GHG emissions at time zero, without a time factor being applied on CF (Fenner et al., 2018). When specifically examining products containing biogenic materials, this can be problematic. Studies such as Pittau et al. (Pittau et al., 2018), demonstrate that not all biogenic products are equal. Timber specifically has a longer rotation period due to forest growth periods, meaning it should not be considered carbon neutral in 100 years time horizon, whereas other biogenic materials such as hemp actually have negative GWP values, as it is carbon negative over a 100-year. Focusing on production, biogenic materials, and in particular timber, contributes to a significant share of emissions from biogenic carbon during extraction and manufacturing (module A1-3). This is related to the large share of wood residues (forest residues during logging and production residues during sawing) that are largely used as biofuel, both to supply energy to the main process inside the same system or allocated to other systems when sold as biofuel (wood chips, pellets, etc.). As shown in Figure 7, this biogenic CO_2 can be assumed as emitted at time of production (time 0) and goes directly into the air. In this case, when the biomass is used as fuel, there is no carbon storage associated to that mass and the CF can be assumed as the same as fossil CO_2 (CF=1 for CO_2 emissions at time 0).

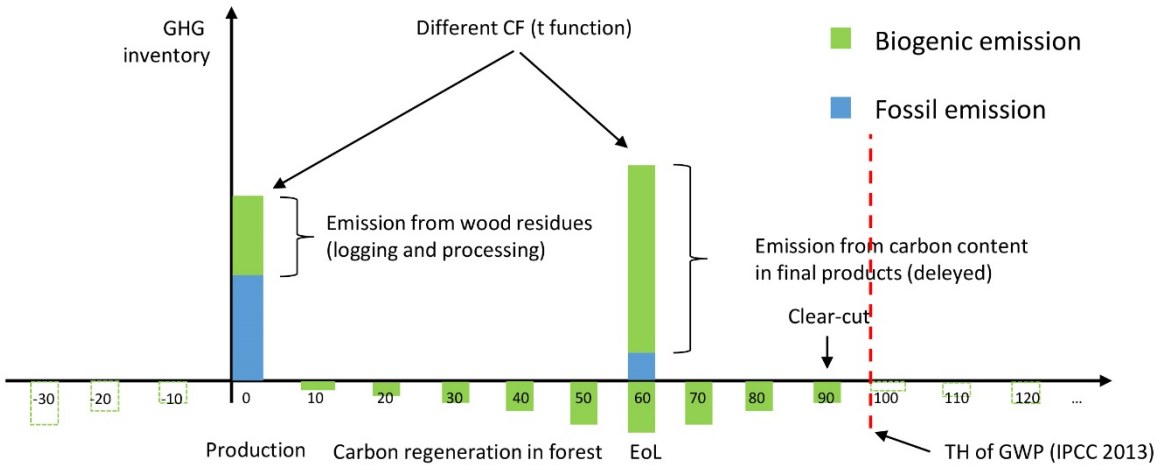


Figure 7. Time allocation of GHG emissions/uptakes during the life cycle of a wood building.

Contrarily, the biogenic emissions at the end of life, if the incineration is assumed as disposal scenario for biogenic construction products, is dominant as equal to the CO_2 stored during the service life. Effect of delay in time has a positive consequence on GW as the CF, which is time dependent, is reduced. In parallel, if the biomass is supplied from sustainable forests (i.e. the trees are re-planted in the forest after the clear-cut and the same amount of biomass is restored after a rotation period), the CO_2 is restored in the land through plants regrowth, with an annual speed of carbon removal which depends on the maturation of the plant. In fact, trees during maturation increase their annual capacity to sequester the CO_2 up to a pick, normally reached by coniferous species after 50-60 years (Masera et

al., 2003). After the pick, the annual carbon sequestration rate starts to decrease as the growth capacity is reduced in old trees. Often, the kinetics of carbon uptake in forest systems is simplified in DLCA by considering a constant carbon sequestration rate from the early-stage of the growth to the final clear-cut (Negishi et al., 2018). As discussed in Figure 4 and Figure 5, the carbon regeneration from forest growth can be accounted for before the construction or after construction. As demonstrated by Peñaloza et al (Peñaloza et al., 2016) the two different approaches lead to radical differences in GWP results.

The inclusion or exclusion of the contribution of the residues (forest extraction + production) plays a fundamental role in the total GHG balance. As shown in Figure 8, to process 1 m^3 of solid wood spruce (final product), an input of around 1.5 m^3 of wood logs is needed. The equivalent biogenic CO_2 stocked in 0.5 m^3 of processed residues is 427 $kgCO_2$ and dominate the GHG emissions if the residual biomass is used for internal processes as biofuel (e.g. energy supply for drying process). In that case, the total amount of biogenic carbon that needs to be restored in the forest is therefore equivalent to the sum of the carbon stored in the final product, and installed in the building, plus the carbon stored in the residues and emitted at time 0.

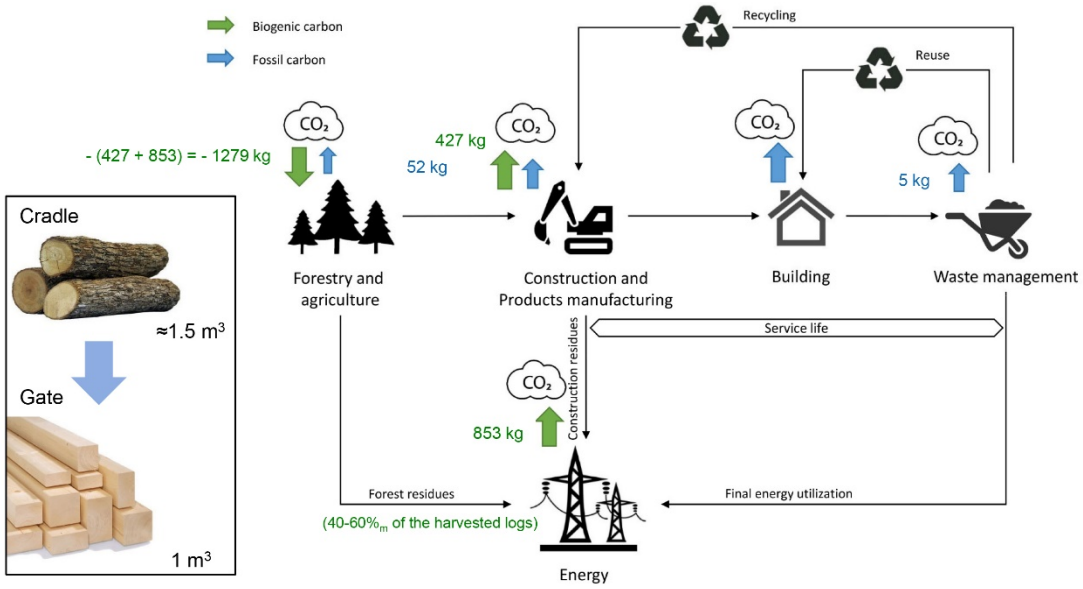


Figure 8. Emissions (fossil and biogenic) and uptake along the life cycle for 1 m^3 of solid wood spruce, kiln-dried, planed, CH (process from ecoinvent 3, allocation cut-off by classification).

In this report, the contribution on GWP from biogenic residues is neglected and only biogenic carbon stored in final products is included in the accounting method.

5.2 Carbon content and CO_2 storage in bio-based products

When biogenic materials are used in construction, in addition to their possible structural capabilities, aesthetic qualities and creative design potential, possesses the valuable natural property of carbon storage. By the process of photosynthesis, growing trees absorb atmospheric carbon dioxide which is then, together with the release of some of the oxygen back into the atmosphere, incorporated, within the cambium, into the vegetal cells. When the biomass is harvested for industrial use, other than for fuel, the sequestered carbon dioxide is locked, as carbon and oxygen, into the manufactured product for as long as it remains in service. The lifetime of bio-based products can vary from a matter of days or weeks (e.g. newspapers) to many decades and even centuries when properly designed and incorporated into buildings.

The biomass, depending on the species and nature of the fibers, is comprised of, in varying amounts, cellulose, hemi-cellulose, lignin and extractives. In case of wood and forest products, 50% of the dry mass is carbon, while the rest is oxygen (44%) and hydrogen (4) and other elements (2%). The amount of water in plants, present as free moisture and bound moisture, also varies widely. In most cases the amount of water in bio-based products is reduced to a level commensurate with the end-use. The residual water in the product after this reduction, naturally achieved or after an oven-drying process, is called moisture content (MC).

The sequestration calculation is based on the atomic weights of carbon (12) and oxygen (16). CO_2 is proportionally 1 part carbon to 2.67 parts oxygen. Thus, the mass ratio between 1 mole of CO_2 and 1 mole of C corresponds to 3.67 kg/kg. The carbon content (CC) of biogenic fibers depends on the chemical composition of the species. Forest products, when fully dry, has a CC which is roughly 0.5, while other bio-based materials (e.g. straw, hemp, cork, etc.) stays with a range values 0.25-0.65.

The CO_2 sequestered in 1 m^3 of bio-based product (S_{CO2}) can be expressed as the following Equation 1:

$$S_{CO_2} = \rho_0 \times CC \times 3.67 \qquad (1)$$

The derivation of the density of dry biomass (ρ_0), expressed in kg/m^3, depends on the moisture content (MC) and can be expressed according to the following two equations, namely Equation 2 with MC ≤ 25% and Equation 3 with MC > 25%:

$$\rho_0 = \rho_{MC\leq 25} \cdot \frac{100+0.45 \cdot MC}{100+MC} \qquad (2)$$

$$\rho_0 = \rho_{MC>25} \cdot \frac{111.25}{100+MC} \qquad (3)$$

where:

- ρ_0 is the biomass density at 0% moisture content [kg/m^3]
- $\rho_{MC\leq 25}$ is the biomass density at moisture content ≤25% [kg/m^3]

- $\rho_{MC>25}$ is the biomass density at moisture content >25% [kg/m^3]
- MC is the moisture content in the biomass [%]

In the absence of moisture content information, solid and laminated forest products for interior applications can be assumed to have MC=20%; solid flooring MC=15%, bio-based panels and insulation MC=10%.

5.3 Time-dependent characterization factors for biogenic carbon accounting

Traditional LCA approaches (static modelling) require the GWP for the 0/0 approach to be calculated as the sum of all CO_2, CO, N_2O emissions and the sum of all fossil and biogenic CH_4 emissions, multiplied by their respective GWP factor, based on Equation 4:

$$GWP_{0/0} = \sum_t g_{CO2,fossil}(t) * GWP_{CO2} + \sum_t \left(g_{CH4,fossil}(t) + g_{CH4,biogenic}(t)\right) * GWP_{CH4} + \sum_t \left(g_{CO,fossil}(t) + g_{CO,biogenic}(t)\right) * GWP_{CO} + \sum_t g_{N2O,fossil}(t) * GWP_{N2O} \quad (4)$$

The GWP for the -1/+1 approach, on the other hand, is calculated as the sum of all fossil and biogenic CO_2, CO, N_2O emissions minus removals and the sum of all fossil and biogenic CH_4 emissions, multiplied by their respective GWP factor, based on Equation 5:

$$GW_{-1/+1} = \sum_t \left(g_{CO2,fossil}(t) + g_{CO2,biogenic}(t)\right) * GWP_{CO2} + \sum_t \left(g_{CH4,fossil}(t) + g_{CH4,biogenic}(t)\right) * GWP_{CH4} + \sum_t \left(g_{CO,fossil} + g_{CO,biogenic}\right)(t) * GWP_{CO} + \sum_t \left(g_{N2O,fossil}(t) + g_{N2O,biogenic}(t)\right) * GWP_{N2O} \quad (5)$$

where:

- $g_{CO2,fossil}(t)$ = emissions of fossil CO_2 at time t
- $g_{CO2,biogenic}(t)$ = removals of biogenic CO_2 at time t
- $g_{CH4,fossil}(t)$= emissions of fossil CH_4 at time t
- $g_{CH4,biogenic}(t)$= 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
- $g_{N2O,fossil}(t)$= emissions of fossil N_2O at time t
- $g_{N2O,biogenic}(t)$= emissions of biogenic N_2O at time t
- GWP_{CO2} = GWP factor of CO_2
- GWP_{CH4} = GWP factor of CH_4
- GWP_{CO} = GWP factor of CO
- GWP_{N2O} = GWP factor of N_2O

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

For the dynamic approach, the dynamic LCA model developed by Levasseur et al. (2010) is adopted, with a specific focus to CO_2, N_2O, CH_4 and CO, as these are the greatest contributors to global

warming impact (GWI). The effect on the energy equilibrium in the atmosphere of a pulse emission of a generic GHG can be described by the impulse response function (IRF) used by Forster and Ramaswamy (2007). In case of CO_2 emission, the decay in time after the initial unitary impulse at t=0 can be calculated by the following Equation 3, based on the revised version of the Bern Carbon cycle model (Joos et al., 2001) assuming a background CO_2 concentration of 378 ppm.

$$C_{CO2}(t) = a_0 + \sum_{i=1}^{3} a_i \cdot e^{\frac{-t}{\tau_i}} \qquad (6)$$

where:

- $C_{CO2}(t)$ 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: $\tau_1 = 172.9$ years; $\tau_2 = 18.5$ years; $\tau_3 = 1.186$. years

For the calculation of the IRF of CH_4 and N_2O, the first order exponential decay function is used as described by the following Equation 7:

$$C(t)_{CH_4,N_2O} = e^{\frac{-t}{\tau}} \qquad (7)$$

τ = 12 years (Pittau et al., 2018) and τ = 114 years (Shine et al., 2007) are assumed for CH_4 and N_2O, respectively. CO rapidly oxidizes when released in the atmosphere. Consequently, all carbon monoxide emissions are considered entirely converted into CO_2 during the first year after the emission.

The following radiative efficiencies (RE) are considered for the three GHG, as reported in table 2.1 by Hartmann et al. (2013):

- $RE_{CO2} = 1.37 \times 10^{-5}$ $Wm^{-2}\,ppb^{-1}$
- $RE_{CH4} = 3.63 \times 10^{-4}$ $Wm^{-2}\,ppb^{-1}$
- $RE_{N2O} = 3.03 \times 10^{-3}$ $Wm^{-2}\,ppb^{-1}$

Then, using the conversion factor of 2.12 PgC ppm^{-1} from Ciais et al. (2013), and the GHGs molar masses, it is possible to transform concentration into mass through the factors 7.77 Gt ppm^{-1} for CO_2 and N_2O and 2.83 Gt ppm^{-1} for CH_4, obtaining for each gas the following instantaneous radiative forcing per unit mass change in the atmosphere (a):

- $a_{CO2} = 1.76 \times 10^{-15}$ $Wm^{-2}\,kg^{-1}$
- $a_{CH4} = 1.28 \times 10^{-13}$ $Wm^{-2}\,kg^{-1}$
- $a_{N2O} = 3.90 \times 10^{-13}$ $Wm^{-2}\,kg^{-1}$

The formulation conceived by Levasseur et al. (2010) is based on the combination of a flexible instantaneous dynamic characterization factor (DCF_{inst}), which takes into account the decay of a GHG emission in time, with a dynamic inventory result (DIR), which considers the evolution of GHG emission

and/or removals in time. The DCF_{inst} of each GHG can be calculated as function of the time (t) according to the following Equation (8):

$$DCF_{inst,GHG}(t - t_j) = \int_{t_j}^{t} a_{GHG} \cdot C_{GHG}(t)dt \qquad (8)$$

where:

- a_{GHG} are the specific radiative forcing per unit mass, calculated according to Hartmann et al. 2013..

The instantaneous global warming impact ($GWI_{inst,GHG}(t - t_j)$ can be calculated according to the following Equation 9:

$$GWI_{inst,GHG}(t - t_j) = \sum_{GHG} \sum_{t} g_{GHG}(t) \cdot DCF_{inst,GHG}(t - t_j) \qquad (9)$$

And the cumulative global warming impact under a given horizon (t) is calculated with Equation 10:

$$GWI_{cum}(t) = \sum_{j=0}^{t} GWI_{inst,GHG}(t - t_j) \qquad (10)$$

Finally, the dynamic global warming (dynGWP) 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 1kg CO_2 pulse emission over the same time (Equation 11):

$$dynGWP(t) = \frac{GWI_{cum}(t)}{AGWP_{CO_2}(t)} = \frac{\sum_{j=0}^{t} GWI_{inst,GHG}(t-t_j)}{\int_{j=0}^{t} A_{CO_2} C_{CO2}(t)dt} \qquad (11)$$

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; (2) after harvest during the building service life and beyond, accounted for in module B1.

5.4 A semi-static approach: GWP_{bio} method

Guest et al. pointed out that current LCA practice often implicitly assumes climate neutrality of bio-based products, based on their carbon-neutrality. They propose a holistic model to assess the global warming potential (GWP) from the release of stored biogenic carbon in the anthroposphere (Guest, Cherubini, & Stromman, 2012). The GWP of CO_2 emissions from stored carbon is dependent on the duration of the storage, the rotation period of the biogenic material and the chosen time horizon (see Figure 9). The GWP_{bio} index method is a quantification of the contribution of biogenic CO_2 emissions, which can be measured and added to the fossil GWP measured with standard IPCC method if the considered TH is the same. A negative GWP_{bio} indicates that the positive effects of long-term storage outweigh the emissions released at the end of life of the biogenic material (at the end of the storage

period), which may lead to a negative GWP. The longer the storage period and the shorter the rotation period, the bigger the positive climate effect is.

In most LCA studies on building and construction, a time horizon of 100 years is generally assumed for the calculation of the GWP. There is a large discrepancy between fast growing, more unconventional plant-fibre materials, and wood. Straw is typically harvested annually, and fiber hemp is even ready to harvest after 70 to 90 days after seeding (Growing Hemp, 2016). First-year reed can be used for insulation plates or as chaff in clay construction. There are specific dimension requirements for reeds as roofing material in Europe. However, it requires over-year reed (Stenman, 2008). In tropical regions, bamboo should be harvested only after complete maturation, when the lignification process is completed to ensure the desired mechanical strength for construction-use. Guadua bamboo reaches maturity between four and seven years, after which it slowly degrades (Schröder, 2012). The optimal forest rotation is a complex optimization problem, as its dependent on many factors, such as the management technique, the specific tree species, as well as many other economic and ecological factors (Helmedag, 2008). Gibbons et al. suggest that the typical harvesting rotation in natural forests, managed for wood production, lies between 50 and 120 years (Gibbons, McElhinny, & Lindenmayer, 2010). In the following Figure 9, a DLCA was performed for four different time-dependent CO_2 pulse configurations.

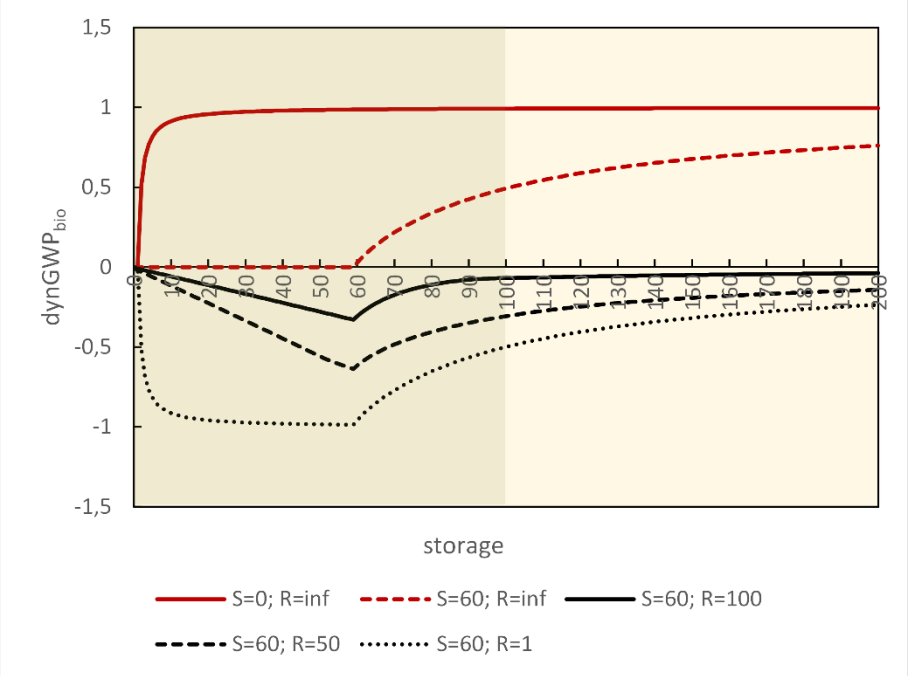


Figure 9. Dynamic GWP (in kgCO2-eq) of 1kg CO2 emission after 60 years of storage (S) according to different rotation (R) periods.

The continuous red line represents the dynamic GWP value for a pulse of 1 kg CO_2 at time 0 when no uptake is considered over time. Similarly, the red dashed line represent the same pulse emission but delayed year 60. As reported in the figure, with DLCA a time dependent characterization factor is

considered, which can be different than 1 for CO_2 when the pulse is emitted along the time frame (see Eq. 8). Consequently, the GWP value at year 100 do not correspond to 1 $kgCO_2$-eq, as in the case of emission at time 0, but a reduction of nearly 50% is measured. This can describe the effect of storing biogenic CO_2 in a long lifespan product and the consequent release in the air through incineration with no uptake assumed after construction (no biomass regeneration in the land after harvesting).

When the uptake from plants re-growing is assumed after time 0, the GWP measured at a TH of 100 years is dependent both on the storage (S), assumed equal to 60 years in every case, and to the speed of the regrowth, also called rotation period (R). It is evident that if the regrowth of the biomass is included after harvesting, this generates a positive effect on the climate (cooling effect) due to the removal of the carbon form the ar. Fast growing biobased materials, such as straw, hemp, flax, etc., often used in construction as insulating products, can re-absorb the whole volume of carbon stored in the product in less than one year as most of the cultivations have a seasonal growth which can include even two rotations per year. Similarly, if the regrowth is coupled with a short storage, the effect on the climate at 100 years can be negative, with positive GWP values observed. The results of this DLCA analysis are summarized in the following Figure 10, where a matrix is created on the base of the two influencing factors - S and R - on the GWP. The table collects the GWP indexes, also called GWP_{bio} indexes, which express the GWP values of storing 1 kg CO_2 in a product, under the assumption that the carbon is regenerated in the forest/plantation/crop after the construction (sustainable land management).

	Storage period									
Rotation	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
1	-0.07	-0.15	-0.23	-0.32	-0.4	-0.5	-0.6	-0.71	-0.84	-0.99
10	-0.04	-0.12	-0.2	-0.28	-0.37	-0.46	-0.57	-0.68	-0.8	-0.96
20	0	-0.08	-0.16	-0.24	-0.33	-0.42	-0.53	-0.64	-0.76	-0.92
30	0.04	-0.04	-0.12	-0.2	-0.29	-0.38	-0.48	-0.6	-0.72	-0.88
40	0.09	0.01	-0.08	-0.16	-0.25	-0.34	-0.44	-0.55	-0.68	-0.84
50	0.13	0.05	-0.03	-0.12	-0.21	-0.3	-0.4	-0.51	-0.64	-0.8
60	0.17	0.09	0.01	-0.07	-0.16	-0.26	-0.36	-0.47	-0.59	-0.75
70	0.22	0.14	0.06	-0.03	-0.12	-0.21	-0.31	-0.42	-0.55	-0.71
80	0.26	0.18	0.1	0.02	-0.07	-0.17	-0.27	-0.38	-0.5	-0.66
90	0.31	0.23	0.15	0.06	-0.03	-0.12	-0.22	-0.33	-0.46	-0.62
100	0.37	0.29	0.21	0.12	0.032	-0.06	-0.16	-0.27	-0.4	-0.56

Figure 10. Summary table of GWP_{bio} index at 100 years for 1 kg CO_2 stored. Effect from delayed emission after a given storage period are considered as well as the carbon regeneration during rotation assumed to start at the same time of the storage.

Through this table, a semi-static approach can be adopted in ordinary attributional LCA for biogenic construction products. In fact, carbon storage in products can be estimated according to the carbon content, as discussed in chapter 5.2. Nowadays, ordinary LCA databases do not contain a specific section on CO_2 storage, but this lack is expected to be covered soon as a Standard calculation is under publication in new version of EN 15804. Values from the table can be assumed by building practitioners on the base of the estimated product service life and biomass rotation. Then, the calculated index can

be used in LCA calculations to obtain a net-GWP value as the sum of the two contribution, fossil + biogenic, as described by Equation 12:

$$GWP_{net} = GWP_{fossil} + GWP_{bio} \qquad (12)$$

where:

- GWP_{fossil} is the contribution to climate change of fossil GHG
- GWP_{bio} is the contribution to climate change of biogenic CO_2

It is important to note that Eq. 12 can be applied only in case the temporal scope for the calculation of the two factors is consistent.

As shown in Figure 11, the biogenic CO_2 can significantly influence the GWP balance. In the figure two forest products with the same FU (1 kg) are compared: b) solid wood spruce and b) OSB. When the service life of the two materials is considered equal, a similar carbon storage is measured. ith negative GWP value measured only for product a

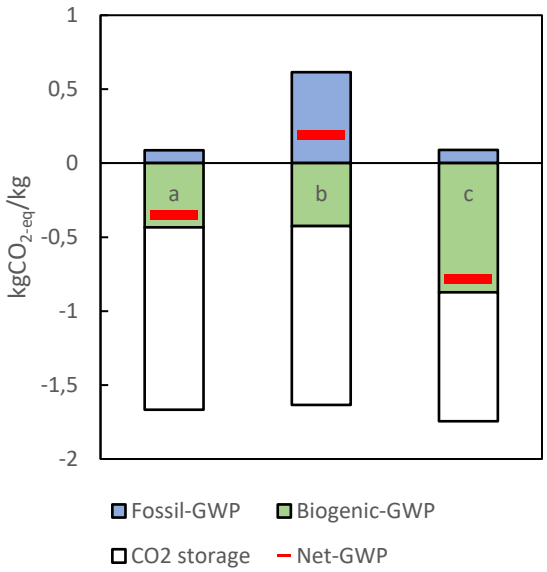


Figure 11. Example of Net-GWP calculation (KBOB process). a) 1 kg Solid wood spruce / fir / larch, air-blown, planed, production CH; b) 1 kg OSB board, PF-bound, humid area; c) Straw bale insulation. Moisture content: 20%. S=60 years; R=60 years.

5.5 Permanent carbon storage in soil and products

The carbon cycle of forest products and biogenic products in general, can be considered as a closed loop since the biogenic carbon embedded in the biomass is sooner or later emitted in the air and soil as a consequence of natural degradation or incineration. The resulting biomass from building demolition can be re-processed according to the wood cascade logic to generate new materials (e.g., laminated strand lumber (LSL) from plywood or solid wood, or fibreboards from veneer strips, etc.), which contribute to extend the carbon storage through a second life of the recycled product (Garcia

et al., 2020). Contrarily to wood harvested for biofuel, forest products used as construction products often require chemical treatment to withstand weathering and degradation, which make incineration process hazard to exposure of humans and ecosystems to toxic compounds (Werner and Richter, 2007). Nevertheless, municipal incineration is considered more beneficial than landfill due to the energy recovery from biomass combustion and the equivalent avoided emissions from fossil fuels (Gustavsson et al., 2017).

As shown in Figure 12, after multiple-reuse or recycling process, biowaste from building disposal can be treated in municipal incineration for energy recovery or can be treated through a pyrolysis process for the production of the biochair.

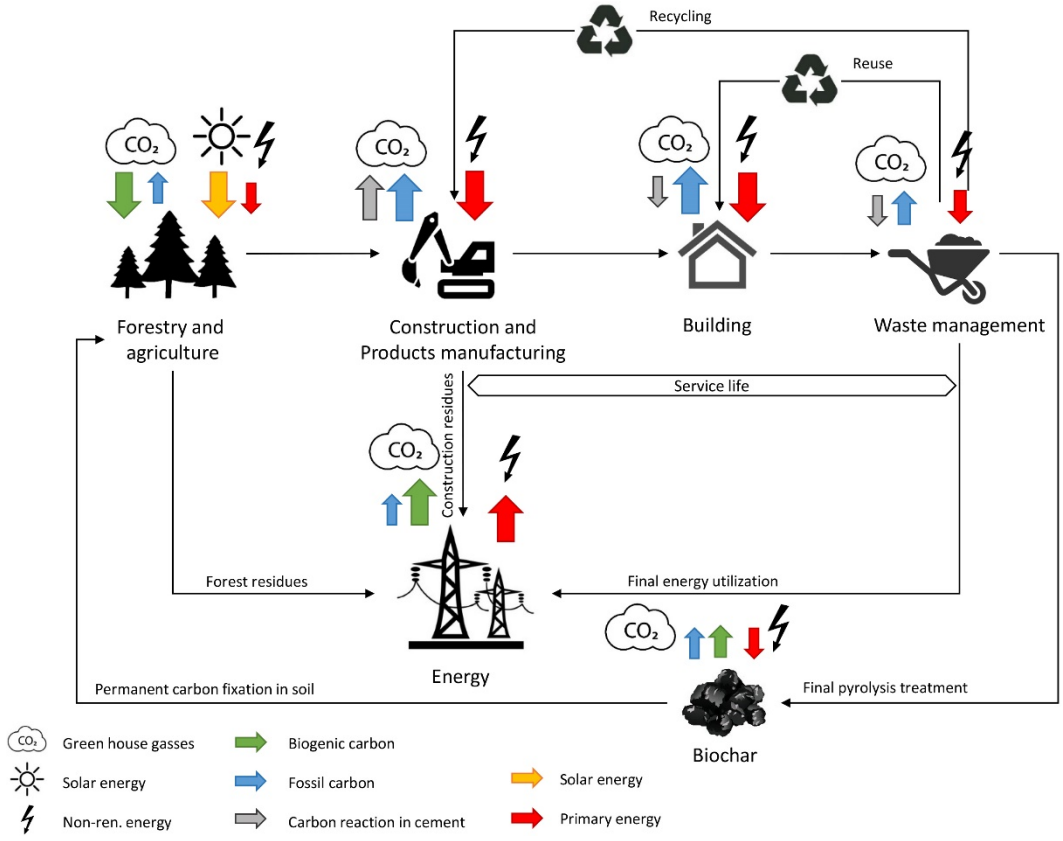


Figure 12. Carbon and energy cycles of cross-sectoral activities linked to biobased building.

The pyrolysis is a process based on the thermal decomposition of materials at elevated temperatures in an inert atmosphere, which involves a change of the chemical composition.

In general, pyrolysis of biogenic substances produces volatile products and leaves a solid residue enriched in carbon, the biochar. Pyrolysis is considered as the first step in the processes of gasification or combustion due to the low temperature needed to run the process generally between 450-650 °C. The resulting solid product, the biochar, is a charcoal produced in the absence of oxygen and is used in agriculture as a soil ameliorant for carbon enriching. In fact, its high porosity increases the retention of water and nutrients, which remain available to plants for longer. It also improves soil structure and

mechanical properties. Many studies have already demonstrated the positive impact of biochar application on agricultural yields by decreasing water and fertilizer requirements (Laird et al., 2010; Palansooriya et al., 2019). The biochar can be obtained from the pyrolysis of different types of vegetal biomass. A particular interest is the production from agricultural residues/biowastes: pruning, corn or wheat stubble, rice husks, almond hulls, dry leaves, etc. As shown in Figure 13, the pyrolysis allows to obtain a gas (syngas) with a calorific value that can be used in production processes that require heat (e.g., drying or electricity production), and solid matter (biochar). The pyrolysis process can have several purposes and can be classified according to its operational parameters, such as maximum temperature reached and residence time. The residence time varies from a few seconds to several days depending on the desired product, syngas or biochar.

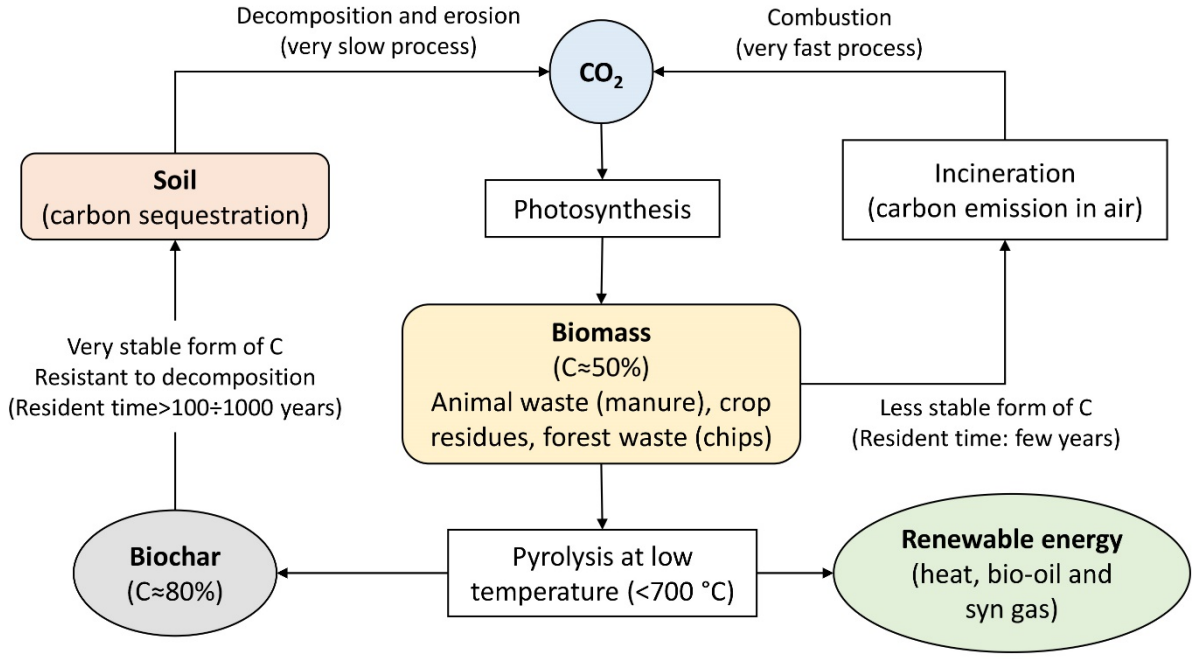


Figure 13. Schematic diagram of pyrolysis process for biochar formation vs standard biomass incineration.

The organic matter contained in the biochar is a stable form of carbon that can be stored in the soil for thousands of years (Yousaf et al., 2017). For this reason, biochar is being investigated as a valuable strategy for carbon removal as it may be a means to mitigate global warming and climate change (Williamson, 2016; Woolf et al., 2010). In general, any form of organic matter introduced into soils is quickly degraded resulting in emissions of carbon dioxide. Contrarily, biochar appears to have great stability and resistance to chemical and biological decomposition, and is therefore considered an important carbon sink, able to sequester large quantities of CO_2 if applied to soils. Biochar owes its chemical, physical and microbiological stability to its chemical composition, which is poorly degradable. In fact, this charcoal consists of a complex aromatic polycyclic structure, highly conjugated to form crystalline structures. This makes it recalcitrant to both physical and chemical degradation. Given its poor degradabilitỳ, once placed in the ground, the biochar provides a carbon store for hundreds or even thousands of years, reducing emissions into the atmosphere.

The pyrolysis process greatly affects the characteristics and properties of biochar and, consequently, its potential value in terms of agronomic performance or carbon sequestration. Both the process and the process parameters (mainly the final temperature reached and the residence time) are particularly important in determining the nature of the product. As the pyrolysis temperature increases, the yield in terms of solid product (biochar) decreases. Moreover, this will consist of a greater proportion of inorganic mineral substance. During pyrolysis, in fact, organic matter loses hydrogen, oxygen and nitrogen resulting richer in minerals. For example, in char produced using chicken litter as feedstock, the ash content increases from 40% to 60% at temperatures between 300°C and 600°C. Usually, as the pyrolysis temperature increases, the pH also increases and the surface area of the biochar increases.

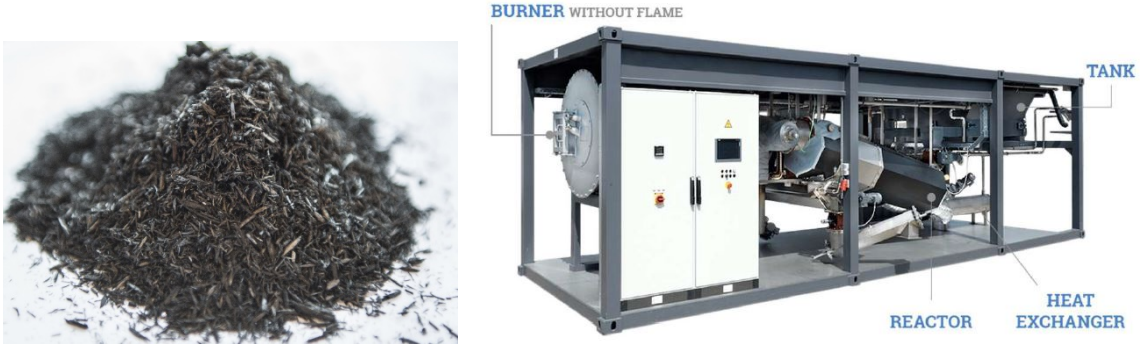


Figure 14. on the left: biochar, obtained from a biomass through a slow pyrolysis process; on the right: a full scale system for biosolid waste treatment with energy recovery.

In the following Figure 15 the process of wood incineration is compared with the production of biochar via pyrolysis.

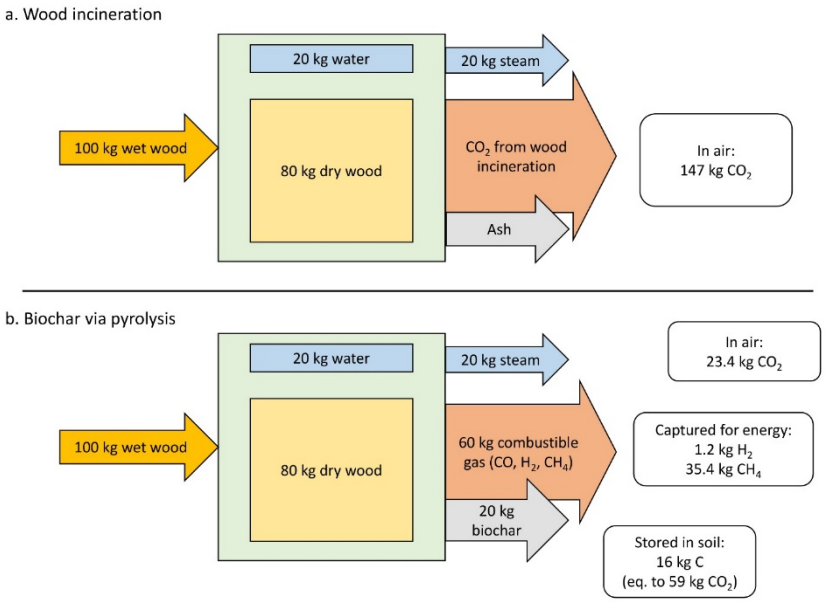


Figure 15. Example of formation of airborne compounds through a. wood incineration and b. biochar production from 100 kg of wet wood.

A standard incineration in a municipal plant of 100 kg of wet wood with 20% of humidity content and 50% carbon content allow to emit 147 $kgCO_{2\text{-}eq}$ in the air. This value is drastically reduced if the same amount of wood is used to produce biochair through a slow pyrolysis process at 600 °C. In this case, 59 kg CO_2 remains fixed in the resulting 20 kg of char as carbon. The rest of carbon react with oxygen and hydrogen to generate carbon monoxide and bio-methane, which can be used within the hydrogen (the second syngas produced from the process) for self-feeding the process or used as biofuel for external processes.

Assuming that the same amount of wet wood (100 kg) can be regenerated in the forest after a rotation period of 60 years, and that the wood is stored in a building as construction product for 60 years, the two discussed processes for end-of-life treatment (incineration vs pyrolysis) can be compared with a dynamic LCA. As shown in Figure 16, the standard incineration process contributes to remove from forest regrowth 26% of the stored carbon in the product, equivalent to roughly -40 $kgCO_{2\text{-}eq}$ at 100 years.

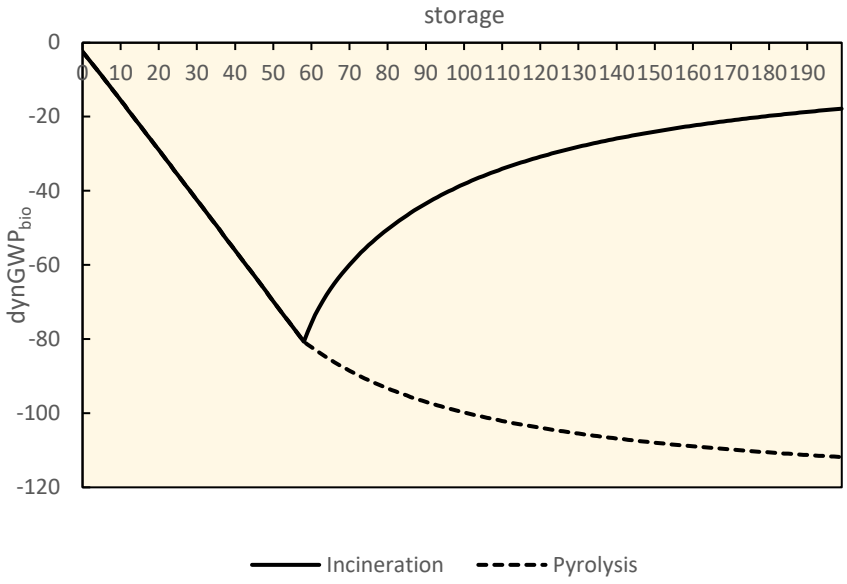


Figure 16. Dynamic GWP results, in $kgCO_{2\text{-}eq}$, from equivalent biogenic CO_2 emissions of treating 100 kg of wood according to three different post-use process: incineration, pyrolysis and mineralization. Assumptions: S=60 years; R=60 years.

On the other hand, if a pyrolysis process is adopted at the end of life of the wooden product after 60 years of service life, its contribution grows to 68%, equivalent to roughly -100 $kgCO_{2\text{-}eq}$ due to the reduced amount of carbon emitted in the air at year 60 and the high concentration of carbon remained in the resulting biochar (80% of the mass).

6. Methodology for CO_2 uptake accounting in concrete

Concrete represents the most demanding material worldwide nowadays. During the last century there has been an exponential growth in the use of cement in the construction sector and this growth is expected to continue over the next decades, since the volume of concrete used in construction is that large that no other material can replace it (Habert et al., 2020). In developed countries, there has been a slight slowdown in the construction of new structures and an increase in renewing the existing ones, while in developing countries the increase will continue to be exponential in the next 30 years. This important use brings greater attention to the role of cement from an environmental point of view, which plays and will play an important part in achieving the environmental goals set worldwide, such as the reduction of GHG emissions to stay below 2°C. Indeed, this material today represents 8% of the total fossil CO_2 emissions. Since cement, as mentioned above, is difficult to be fully replaced, especially in the short term, it is necessary to understand how GHG emissions can be minimized during its use. Compared to alternative construction materials, e.g. steel, aluminum, bricks, etc., cement does not show an high carbon footprint, as its carbon emissions are lower then others when measured per mass or volumetric unit. However, its demand is so intense that its large use risks to limit the decarbonization of the sector. Therefore, to achieve a sustainable path it should become nearly zero carbon by 2050. Unfortunately, a fast decarbonization would require a great amount of investments to transform the infrastructure, unless a radical change in the vision would affect the whole cement value change (Habert et al., 2020).

In order to evaluate the contribution that a structure creates to climate disturbance, several studies have been carried out and there several methods have been developed. In ordinary LCA, very often, only positive emissions from cement production are considered, neglecting the positive contribution of CO_2 sequestration through chemical reaction processes, the so-called carbonation, during structure service life. The process of carbonation is a chemical reaction that occurs primarily between readily available calcium silicate hydrate (C-S-H) and portlandite (CH) with atmospheric CO_2. During their lifetime, concrete and cement mortar can sequester, in marginal but not negligible parts, a share of CO_2, resulting in a positive influence on carbon mitigation. This exclusion of carbonation in conventional LCA of a structure is due to the complexity of carbon kinetics models and uncertainties quantification of the main influencing parameters. A negative effect of carbonation is that the CO_2 gas reacting inside the cement reduces the PH inside the pores, which can destabilize the passivation layer that it is formed on the surface of the steel. Consequently, it is correct to try to increase CO_2 sequestration, but with the necessary precautions and without affecting the steel and its reinforcing function.

The goal of this section is to present a simple but robust method, based on the semi-static concept discussed for the GWP_{bio} index presented in section 5.4 to calculate, or rather predict, the carbon dioxide absorption of different concrete mixtures, to implement the carbon sequestration in concrete structures in ordinary LCA projects. The novel GWP_{cem} factors developed indicate how much CO_2 is possible to sequester via carbonation in 1 m^2 of exposed concrete surface within a specific time horizon. The results offer engineers and architects the possibility to select certain types of concrete in the design phase on the base of the capacity to uptake the carbon dioxide during its service life. However, as carbonation is a time dependent function, a static LCA is no longer suitable for this

calculation. Therefore, a dynamic LCA approach is proposed to improve the accuracy of LCA by entering the time profile of emissions, more precisely the sequestration of CO_2 in concrete over the years.

In this dynamic model, the GWP due to the absorption of different types of concrete is calculated, by varying the type of cement, the amount of cement per unit mass of concrete, the type of cement, the amount of SCM and the CO_2 exposure classification in combination with different types of storage periods, from 10 to 100 years. As the estimating of the GWP depends on the TH chosen, the results are shown using 100 years as TH.

6.1 Analytic dynamic model for carbonation kinetic

The developed model for carbonation kinetic simulation is simple but robust, based on the variation of the five main influencing parameters: i) cement type; ii) amount of supplementary cementitious materials (SCMs); iii) amount of cement per cubic meter of concrete; iv) exposure classifications; v) compressive strength. When the uptake of CO_2 is calculated for different types of concrete, finally the global warming impact is determined with the DLCA. As mentioned, calculating carbonation is extremely difficult, because it varies by a large number of factors, many of which are difficult to fit into mathematical calculations. The developed model is based on the formulation proposed by the department of civil, environmental, and architectural engineering, materials science and engineering program of the University of Colorado Boulder presented in the paper "*A mathematical model for predicting the carbon sequestrations potential of ordinary Portland cement (OPC) concrete*" (Souto-Martinez et al., 2017). In fact, through few formulas the method can take into account many parameters and factors that affect carbonation depth and CO_2 sequestration. It considers the main factors determined for the design of a structure, such as the type of cement, the amount of SCMs in the mixture and the amount of cement in the concrete, which are easily incorporated into the formulas. Moreover, the theoretical results obtained reflect very well the empirical ones. Other more complex models might be used (Ta et al., 2016; Xi et al., 2016; Zajac et al., 2020) but the high level of uncertainties might limit the application in practice. On the other hand, the *EN16757* Standard offers a very simple model that can be applied to reality. In fact, the uptake of CO_2 with a few formulas can be calculated, as the carbonation depth and the degree of carbonation are already tabulated for different exposure conditions, different concrete strengths, and different contents of cement supplements. However, this method is dependent on these tables and therefore limited for certain values and exposures classes. A closer look at the differences in the final CO_2 sequestration could be a starting point for a future works.

6.2 Calculation of the carbon sequestration potential

The complete analytic method developed for this work is described in this section. All included formulations and variables are presented below and since the CO_2 sequestration depends on several factors, some simplifications have been assumed to make the model more flexible for our scope. A backwards path is followed, from the final formulation the individual factors are extracted, which in turn are defined and calculated.

Total mass of sequestered CO_2

The total mass CO_2, C_s (kg of CO_2) potentially sequestred can be calculated as following Eq. 13:

$$C_s = \phi \cdot C_m \cdot [V_C \cdot m] \qquad [13]$$

Where:

- ϕ is the degree of carbonation (%)
- C_m is the carbon sequestration potential of hydrated cement paste (kg of CO_2)
- V_c is the total carbonated volume (m^3)
- m is the total mass of cement per unit volume of concrete (kg of cement/ m^3 of concrete) obtained from the concrete batch mixture proportions. In the following chapters, each component is described and analyzed.

Degree of carbonation

The degree of carbonation is the first variable that is taken as fixed. From experiments by previous researchers (Thiery et al., 2013; Van Balen, 2005; Villain and Thiery, 2006) and data from Eurocode, different values of carbonation degrees have been obtained, ranging from 0.4 to 0.85. To have a more correct analysis, the degree of carbonation should be calculated for each situation, but it would make the computational model way too complex to be implemented into practice. For this reason, a degree of carbonation of 70%, as an average value between the two extremes, has been chosen. Larger values would have led to a higher sequestration of CO_2, while a smaller percentage would have led to estimates in a more conservative way.

Total carbonated volume

To calculate the total carbonated volume, is necessary to know the total surface area of exposed concrete members, *SA,* and the total carbonation depth*, x*. The total volume is calculated multiplying the exposed area with the carbonation depth, as described in Eq. 14:

$$V_c = SA \cdot x \qquad [14]$$

To implement the model a surface area of 1 m^2 has been assumed as FU. Important to mention, the exposed concrete considers surfaced without coatings or paints that could obstruct the diffuse penetration of CO_2.

Carbonation depth

The prediction of the carbonation depth is complex because depends on several parameters, such as the moisture, temperature, CO_2 concentration, time, humidity, and exposure to water. An accurately prediction is difficult to obtain, but an empirical model for predicting the carbonation depth, *x* (mm), has been developed according the following Eq. 15:

$$x = \sqrt{\left(\frac{2 \cdot c \cdot t}{R}\right)} \cdot \left[\sqrt{k_0 \cdot k_1 \cdot k_2} \cdot \left(\frac{1}{t}\right)^n\right] \qquad [15]$$

Where:

- c is the environmental CO_2 concentration (kg/m^3)
- t is exposure time in years
- k_o is equal to 3
- k_2 is equal to 1 for standard curing and R is the carbonation resistance coefficient (kg year/m^5).

To simplify and make the model applicable to any reality, it is assumed, that the environmental CO_2 concentration, *c*, is equal to the global average atmospheric carbon dioxide and the average of the 2018 is taken. In 2018, the global average atmospheric carbon dioxide was 407.4 parts per million and this means an equivalent of 0,789 mg/m^3 CO_2 (Note: 1 kg/m^3 CO_2 is equal to 516 ppb). The resistance coefficient is calculated differently for Types I-II and for Types III-V according to the following Eq. 16 and Eq. 17:

$$Types\ I-II: R = 0.0016 \cdot f_c^{3.106} \quad [16]$$

$$Types\ III-V: R = 0.0018 \cdot f_c^{2.862} \quad [17]$$

Where:

- f_c stands for the compressive strength of concrete (MPa). For the final calculation, the most common values are used, namely 30, 40, and 50 MPa.

Carbonation depth also depends on environmental exposure, which is included in the formula by the factors k_1 and *n*. The parameters values, shown in Figure 18, are dependent on the exposure classification based on the SIA classification as illustrated in Figure 17. Playing an important role on CO_2 absorption, the carbonation depth was calculated for each environmental class.

Class	Environment	Examples
XC1	Dry or permanently humid	Reinforced concrete inside buildings or structures, except areas of high humidity; Reinforced concrete permanently under non-aggressive water.
XC2	Humid, rarely dry	Reinforced concrete under non-aggressive soil; Reinforced concrete subjected to long periods of contact with non-aggressive water.
XC3	Moderately humid	Outer surfaces of reinforced concrete sheltered from wind-driven rain; Reinforced concrete inside structures with moderate to high air humidity.
XC4	Cyclically humid and dry	Reinforced concrete exposed to wetting/drying cycles; Outer surfaces of reinforced concrete exposed to rain or outside the scope of XC2.

Figure 17. Carbonation environmental exposure classifications.

Parameter	XC1	XC2	XC3	XC4
k_1	1.0	0.20	0.77	0.41
n	0	0.183	0.02	0.085

Figure 18. Parameters values for k_1 and n based on exposure classification.

Carbon sequestration potential of hydrated cement paste

The theoretical amount of sequestrable CO_2, via the formation of calcium carbonate in the hydrated cement paste, per kg of carbonated cement paste (kg CO_2 /kg cement) in the concrete can be calculated according to the following Eq. 18:

$$C_m = \alpha - \beta \cdot y \quad [18]$$

Where:

- α accounts for the variation in cement type
- β accounts for the type and amount of the supplementary cementitious type (SCMs) and y is the percent replacement (by mass of cement) by SCMs.

The relative magnitudes of the parameter α are quantitative measures of the amount of readily available CH that is produced by the hydration reactions. The values are obtained by the following Eq. 19:

$$\alpha = \phi_h MW_{CH}\left(\frac{3}{2}\cdot\frac{B_{C_3S}}{MW_{C_3S}} + \frac{1}{2}\cdot\frac{B_{C_2S}}{MW_{C_2S}} - \frac{2}{1}\cdot\frac{B_{C_4AF}}{MW_{C_4AF}}\right) \quad [19]$$

Where:

- ϕ_h is the hydration of cement minerals (%)
- B_{C_3S}, B_{C_2S} and B_{C_4AF} are the bogue composition (%) of C_3S, C_2S and C_4AF, respectively
- MW_{C_3S}, MW_{C_2S} and MW_{C_4AF} are the molecular weights of C_3S (228.314 g/mol), C_2S (172.237 g/mol), C_4AF (485.955 g/mol), and CH (74.09 g/mol). Stoichiometric ratios of CH consumed or produced by C_3S, C_2S and C_4AF in the hydration reactions are the multipliers (3/2), (1/2) and (2) respectively. The hydration of cement minerals is fixed at 0.595.

The carbon sequestration potential varies also by the type and amount of SCMs. The variation is considered in the formula by the coefficient β, which depends on the weight percent of silicon dioxide in the SCM. If the silica content in the SCM is known, the factor β can be calculated according to the following Eq. 20:

$$\beta = 1.1 \cdot \sigma \quad [20]$$

Where:

- σ is the weight percent (%) of SiO_2 (silicon dioxide) in the supplementary cementitious material in decimal form.

If the content of SiO_2 is not known or it cannot be obtained via chemical analysis, average silica contents for common types of SCM are shown in Table 4. The scalar of 1.1 is obtained by dividing the molar ratio of calcium hydroxide to silica (3/2) by the molecular weight of silicon dioxide (60.083 g/mol) and multiplied by the molecular weight of CO_2 (44.01 g/mol).

In the world today, cement types I and II are mainly used. In recent years there has also been an increase in the use of cement type III. In this work, cements type I and II with different percentage of replacement by SCM are analyzed. Cement type III is also studied, but only with a replacement of 35%, since with a bigger replacement the uptake rate tends to 0. In Figure 19, the average mineral composition of used cement types is listed. The cement chemistry notation is used to present the minerals.

Cement Type	Average mineral (Bogue) composition (%)				
	C_3S	C_2S	C_3A	C_4AF	Other
I	54	18	10	8	10
II	55	19	6	11	9
III	55	17	9	8	11

Figure 19. Average mineral composition of cement types.

Average silica contents for used types of SCM and coefficients obtained with the previous formulas are shown in the following Figure 20.

Cement Type	SCM	Average σ % SiO_2	β	α*
I	Fly Ash	50	0.55	0.165
II	Fly Ash	25	0.27	0.163
III	Slag	35	0.38	0.166

*assumption of 60% hydration of cement minerals ($\phi_h = 0.6$)

Figure 20. Coefficients per cement type and SCM used.

For more clarity, Figure 21 contains all the parameters chosen for the carbon sequestration calculation.

Category	Symbol	Unit	Quantity
Degree of carbonation	Φ	%	70
Exposed surface	SA	m2	1
Environmental CO2 concentration	c	mg/m3	0,789
Exposure time	t	years	1 to 100
standard curing	k_o	-	3
standard curing	k_2	-	1
compressive strength of concrete	f_c	MPa	30-40-50
Environmental exposure class	k_1	-	XC1: 1.0 XC2: 0.20 XC3: 0.77 XC4: 0.41
	n	-	XC1: 0 XC2: 0.183 XC3: 0.02 XC4: 0.085
Hydration of cement minerals	Φ_h	%	0,595
Cement type	α	-	CEM I: 0.165 CEM II: 0.163
Supplementary type	β	-	CEM I: 0.55 CEM II: 0.27
Percentage of SCMs	y	%	0-35

Figure 21. List of parameters chosen for the carbon sequestration calculation model.

Once the absorption in kg of CO_2 has been calculated, the positive impact it has on the climate can be determined. As previously mentioned, with a static LCA approach it is not possible to assess the impact of the temporal uptake of CO_2, since carbonation occurs over the course of years and cannot be considered as a single sum. To consider this temporal distribution of CO_2 sequestration, the DLCA approach is used, assuming 100 years as TH.

6.3 GWP_{cem} indexes calculation

The GWP_{cem} indexes obtained by the proposed method are shown in this section and grouped by different environmental classes (XC1, XC2, XC3 and XC4), by varying the types of cement, the amount of it in concrete and the volume of SCMs. Results are shown in Figure 22-25. The exposed concrete structures are assumed to stay in the building for 60 years before demolition. To get a more general overview, the GWPs after 60 years of storage for each environmental class are grouped in a unique graph, as shown in the following Figures 22-25.

Environmental class	Type of cement	SCM %	KgCem/m^3concrete	f_c (MPa)	GWP 100 years
XC1	CEM 1	0	200	30	-1,31
				40	-0,84
				50	-0,59
			300	30	-1,97
				40	-1,26
				50	-0,89
			400	30	-2,62
				40	-1,68
				50	-1,19
	CEM 2A	6	200	30	-1,17
				40	-0,75
				50	-0,53
			300	30	-1,76
				40	-1,12
				50	-0,79
			400	30	-2,34
				40	-1,50
				50	-1,06
		15	200	30	-0,97
				40	-0,62
				50	-0,44
			300	30	-1,46
				40	-0,93
				50	-0,66
			400	30	-1,95
				40	-1,25
				50	-0,88
	CEM 2B	25	200	30	-0,75
				40	-0,48
				50	-0,34
			300	30	-1,13
				40	-0,72
				50	-0,51
			400	30	-1,51
				40	-0,97
				50	-0,68
		35	200	30	-0,54
				40	-0,34
				50	-0,24
			300	30	-0,80
				40	-0,51
				50	-0,36
			400	30	-1,07
				40	-0,69
				50	-0,48

Figure 22. GWP_{cem} indexes for environmental class category XC1.

Environmental class	Type of cement	SCM %	KgCem/m^3concrete	f_c (MPa)	GWP 100 years
XC2	CEM 1	0	200	30	-0,29
				40	-0,19
				50	-0,13
			300	30	-0,44
				40	-0,28
				50	-0,20
			400	30	-0,58
				40	-0,37
				50	-0,26
	CEM 2A	6	200	30	-0,26
				40	-0,17
				50	-0,12
			300	30	-0,39
				40	-0,25
				50	-0,18
			400	30	-0,52
				40	-0,33
				50	-0,24
		15	200	30	-0,22
				40	-0,14
				50	-0,10
			300	30	-0,33
				40	-0,21
				50	-0,15
			400	30	-0,43
				40	-0,28
				50	-0,20
	CEM 2B	25	200	30	-0,17
				40	-0,11
				50	-0,08
			300	30	-0,25
				40	-0,16
				50	-0,11
			400	30	-0,34
				40	-0,22
				50	-0,15
		35	200	30	-0,12
				40	-0,08
				50	-0,05
			300	30	-0,18
				40	-0,11
				50	-0,08
			400	30	-0,24
				40	-0,15
				50	-0,10

Figure 23. GWP_{cem} indexes for environmental class category XC2.

Environmental class	Type of cement	SCM %	KgCem/m^3concrete	f_c (MPa)	GWP 100 years
XC3	CEM 1	0	200	30	-1,07
				40	-0,68
				50	-0,48
			300	30	-1,60
				40	-1,02
				50	-0,72
			400	30	-2,13
				40	-1,36
				50	-0,96
	CEM 2A	6	200	30	-0,95
				40	-0,61
				50	-0,43
			300	30	-1,43
				40	-0,91
				50	-0,65
			400	30	-1,90
				40	-1,22
				50	-0,86
		15	200	30	-0,79
				40	-0,51
				50	-0,36
			300	30	-1,19
				40	-0,76
				50	-0,54
			400	30	-1,58
				40	-1,01
				50	-0,72
	CEM 2B	25	200	30	-0,61
				40	-0,39
				50	-0,28
			300	30	-0,92
				40	-0,59
				50	-0,42
			400	30	-1,23
				40	-0,78
				50	-0,56
		35	200	30	-0,44
				40	-0,28
				50	-0,20
			300	30	-0,65
				40	-0,42
				50	-0,30
			400	30	-0,87
				40	-0,56
				50	-0,39

Figure 24. GWP_{cem} indexes for environmental class category XC3.

Environmental class	Type of cement	SCM %	KgCem/m^3concrete	f_c (MPa)	GWP 100 years
XC4	CEM 1	0	200	30	-0,61
				40	-0,39
				50	-0,27
			300	30	-0,91
				40	-0,58
				50	-0,41
			400	30	-1,21
				40	-0,78
				50	-0,55
	CEM 2A	6	200	30	-0,54
				40	-0,35
				50	-0,25
			300	30	-0,81
				40	-0,52
				50	-0,37
			400	30	-1,08
				40	-0,69
				50	-0,49
		15	200	30	-0,45
				40	-0,29
				50	-0,20
			300	30	-0,68
				40	-0,43
				50	-0,31
			400	30	-0,90
				40	-0,58
				50	-0,41
	CEM 2B	25	200	30	-0,35
				40	-0,22
				50	-0,16
			300	30	-0,52
				40	-0,34
				50	-0,24
			400	30	-0,70
				40	-0,45
				50	-0,32
		35	200	30	-0,25
				40	-0,16
				50	-0,11
			300	30	-0,37
				40	-0,24
				50	-0,17
			400	30	-0,50
				40	-0,32
				50	-0,22

Figure 25. GWP_{cem} indexes for environmental class category XC4.

The use of the above tables is a very practical instrument to assess the carbonation of concrete during design phase, since once defined the place where it is located, internally or externally, with much or little humidity and so on, he can easily have an idea about which type of cement concrete is better to use to maximise the uptake. The values obtained are dependent on the selected variables, but also TH chosen and many other parameters may be influencing. The effects of the main parameters are analysed one by one on the following pages.

Influence of environmental exposure

Carbonation is dominated by the exposure class, the total CO_2 sequestered varies sharply for the type of structure analyzed, whether it is calculated internally or externally from the building and especially if exposed or not to water and exposed to low or high humidity. If the analyzed concrete is inside a building, class XC1 is generally used, while if it is outside class XC4. As shown in Figure 26, after 100 years there is an increase of about 3.3 kg of CO_2 per square meter. This is due to the concentration of CO_2 in different environments and the exposure of concrete to water and humidity and therefore the level of saturation of the pores of the mixture. The more saturated the pores are, the less CO_2 can penetrate into the concrete and thus be stored. On average, indoor environments have a higher concentration (about 500ppm) than outdoor environments and therefore a greater quantity is available to be captured. The worst case is for elements submerged in soil or water (XC2), where the concentrations of carbon dioxide are low, and the pores of the mixture are saturated with water. For class XC3 (elements encased and protected from ambient conditions), the behavior is similar to exposure classification XC1, but with less marked impact. Being protected from water, the mixture can capture more CO_2 than class XC4 elements, since the pores of the mix are not saturated with water and the entry of CO_2 into the pores is facilitated. However, for the same reason, they have a lower GWP than class XC1. In fact, the XC3 class, in addition to including external protected elements, also includes internal structures with high humidity and therefore manage to absorb less CO_2.

Environmenal class	Uptake of CO_2 (kg of CO_2)			GWP		
	30 MPa	40 MPa	50 MPa	30 MPa	40 MPa	50 MPa
XC1	-4.04	-2.58	-1.83	-2.88	-1.84	-1.30
XC2	-0.78	-0.50	-0.35	-0.62	-0.40	-0.28
XC3	-3.23	-2.07	-1.46	-2.33	-1.49	-1.05
XC4	-1.75	-1.12	-0.79	-1.31	-0.84	-0.59

Figure 26. Uptake of CO_2 and the corresponding Global warming potential (GWP) after 100 years for different environmental classes and different concrete strength for a fixed cement content in concrete (400 kg/m^3) and cement type CEM I.

As previously mentioned, between the environmental class XC1 and XC3 the quantity of CO_2 stored is minimal, if compared to the others. An element in a dry or permanently humid environment absorbs 125% more CO_2 than an element in environmental class XC3 after 100 years. Compared to classes XC2 and XC4, an element in class XC1 absorb 517% and 230% more CO_2, respectively. Also, for GWP_{cem} the impact that an protected surface can have is much greater than an exposed one. The GWP after 100 years is -2.88 for class XC1, while for class XC2 it is only -0.62. In calculating the environmental impact of a building, it is therefore necessary to calculate the CO_2 sequestration separately for concrete used

externally and internally, otherwise the results could be too pessimistic or optimistic. However, this result is not comforting, as many structures such as dams and bridges, where the use of concrete is massive and the exposed surfaces are very large, are exposed to wetting/drying cycles or rain and therefore the potential CO_2 uptake is limited. Even for foundations, where large quantities of concrete are used, the same problem occurs.

Influence of concrete compressive strength

Contrarily to what one might expect, an increase in strength class does not correspond to an increase in the amount of CO_2 sequestered. An increment of compressive strength leads to a higher content of cement but also a lower porosity. Thus, also a higher carbonation resistance factor R and an increase of this factor in the Equations 16-17 implies a decrease of the carbonation depth. The higher resistance in sequestering CO_2 is attributed to the mixture of the high-strength concrete, namely a denser mixture and a lower water/cement rate and less gas in general. CO_2 sequestration is influenced more by the porosity and density of concrete mixture than the amount of cement in a higher-class resistance. In the following Figure 27 approximate proportions of standard concrete mixtures for different strength classes are shown.

	Cement	W/C	Water	Sand	Aggregates	Total	f_c (28d)
Class	kg	--	kg	kg	kg	kg	MPa
Low grade	258	0.7	181	722	1192	2353	25
Standard	310	0.6	186	700	1156	2352	40
Good quality	350	0.5	175	699	1153	2377	50

Figure 27. Approximate proportions of standard concrete formulations for different strength classes.

In fact, by choosing the same cement content but different strength classes, i.e. different porosity and density, the uptake of CO_2 and therefore the GWP_{cem} decrease considerably. The amount of CO_2 captured decreases by more than half, from 4kg for a low-grade class (30 MPa) to less than 2kg for a good quality concrete (50 MPa).

Therefore, in order to have a greater sequestration of CO_2 and a larger environmental benefit from a structure, it is essential to use, where possible, a lower density concrete and therefore a lower resistance mixture to gases and water.

Influence of cement content in concrete

It is probably the most intuitive effect of all those analyzed. Increasing the amount of cement in the concrete also increases the available reagent amount of calcium silicate hydrate (C-S-H), which increases the sequestration potential. An example is shown in Figure 28. The amount of CO_2 captured is significantly higher for greater amount of cement in concrete and therefore the GWP is also higher. However, an increase in cement also leads to a higher GHG emissions during production, which has not been considered in this work. The right balance should be found by including both factors.

Cement content in concrete (kg/m^3)	Uptake of CO_2 (kg of CO_2)			GWP		
	30 MPa	40 MPa	50 MPa	30 MPa	40 MPa	50 MPa
400	-4.04	-2.58	-1.83	-2.88	-1.84	-1.30
300	-3.03	-1.94	-1.37	-2.16	-1.38	-0.98
200	-2.02	-1.29	-0.91	-1.44	-0.92	-0.65

Figure 28. Uptake of CO_2 and the corresponding Global warming potential (GWP) after 100 years for different cement content in concrete and different concrete strength for environmental class XC1 and cement type CEM I.

As it can be seen, the increase is considerable and is proportional to the amount of cement used. In fact, from Equation 18, the amount of CO_2 sequestered depends directly on the amount of cement in the concrete. Thus, going from 200 kg of cement in 1 m^3 of concrete to 400, the amount of CO_2 captured is twice as much. Therefore, carbonation and CO_2 sequestration are very sensitive to this variable and its consideration in the choice during the design phase should always be included for this reason.

Influence of cement type and percentage of SCMs

The influence of the cement type and supplementary cementitious materials percentage is very similar to the behavior of the previous factor analyzed, i.e. the cement content in concrete. In fact, increasing the percentage of SCM decreases the amount of cement and less portlandite is available for carbonation. Therefore, as can be seen in Figure 29, the GWP decreases with increasing SCMs. In fact, the GWP after 100 years of storage has a 60% decrease for a type CEM I without SCMs to CEM IIB with 35% SCMs, i.e. from 2.88 to 1.18.

Cement type and SCMs(%)	CEM I 0%	CEM IIA 6%	CEM IIA 15%	CEM IIB 25%	CEM IIB 35%
Uptake of CO_2 (kg of CO_2)	-4.04	-3.60	-3.00	-2.32	-1.65
GWP	-2.88	-2.57	-2.14	-1.66	-1.18

Figure 29. Uptake of CO_2 and the corresponding Global warming potential (GWP) after 100 years for different cement type and different supplementary cementitious materials for a fixed environmental class (XC1), cement content in concrete (400 kg/m^3) and concrete strength (30 MPa).

The GWP after 100 years of storage has a 60% decrease for a type 1 cement without SCM to a type II cement with 35% SCMs, i.e. from 2.88 to 1.18. However, the same is true for the cement content in concrete, i.e. increasing the SCMs decreases the cement used and therefore the emissions due to its production decrease. An in-depth study should be carried out to find the right balance between emissions due to cement production and emissions captured by carbonation. In this model, a cement with 40% more SCMs does not have enough portlandite to react and therefore it cannot store CO_2. For cement of type III, with α equal to 0.166, β equal to 0.38 and with a percentage of 40% of SCMs, the

carbon sequestration potential, calculated according to Equation 18, tends to zero and by increasing the percentage, negative numbers are obtained. For this reason, GWPs have been calculated only for CEM I and II. The cement type has no influence on the final result, since the parameter that considers the two types of cement (α) varies from 0.165 for CEM I to 0.163 for CEM II and therefore not enough to influence the result.

Influence of exposed surface of concrete and geometry design

An important factor that has been taken as fixed here is the exposed surface of the concrete. All the results refer to 1 m^2 of surface area, so by increasing the surface area you can achieve significant amounts of CO_2 sequestered. An important improvement for structures is to increase the surface area of exposed parts by looking for new construction solutions and increasing the surface-volume ratio. In fact, increasing the surface area for the same volume of concreate also increases the CO_2 sequestration. For example, using a square column instead of a round one can increase the surface area in contact with air (see Figure 30). Considered individually it is a slight increase, but if repeated several times and trying to maximize the area on all elements of a structure, especially on large surfaces such as walls and floors, the difference in the GWP can change considerably. By transforming a round column into a cross-shaped one, design and engineering permitting, the surface in contact with air is doubled maintaining the same volume. In the future, it is necessary to consider this aspect in the design phase, such as, for example, building walls with small engravings in order to increase the surface area and at the same time not to compromise the engineering aspect and it is also important, where possible, not to use paints or coatings that obstruct the sequestration of CO_2.

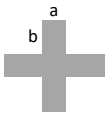
Geometry	Dimensions (m)	Cross sectional area (m^2)	Length (m)	Total surface area (m^2)	Volume
	d=0.8	0.49	2.5	6.28	1.225
	l=0.7	0.49	2.5	7	1.225
	a=0.2 b=0.56	0.49	2.5	12	1.225

Figure 30. Effect of geometry on the exposed surface area with a fixed volume.

This work is not covered, but it is important to mention the relevance of the management system at the end of the concrete life. In fact, the carbonation and sequestration of CO_2 continues even after the end of the life of a structure and, if the cement is not saturated, it can still sequester large quantities of CO_2. This sequestration is dependent on the use of the cement after its demolition, time and shape of the particles. After the demolition phase, large elements with little exposed surface area are fragmented into small particles increasing the total surface area and therefore the efficiency of the sequestration and the absorption ratio increases. Therefore, with fast demolition and quick storage of the broken fragments can increase the sequestration and also important is the way to crush the

elements, forming different shapes and sizes to have a less compact material and allow air to circulate in it.

One problem that may arise is that the structure analyzed is not thick enough compared to carbonation depth, especially new types of structures, whose thickness has decreased considerably. However, in the most favorable case for carbonation (CEM I, 400kgcem/m^{3}concrete, 30 MPa, XC1), the carbonation depth reaches a depth of 6.5cm after 60 years.

Influence of sequestration time

As shown in the following Figures 31-32, the first years of storage in concrete play a fundamental role.

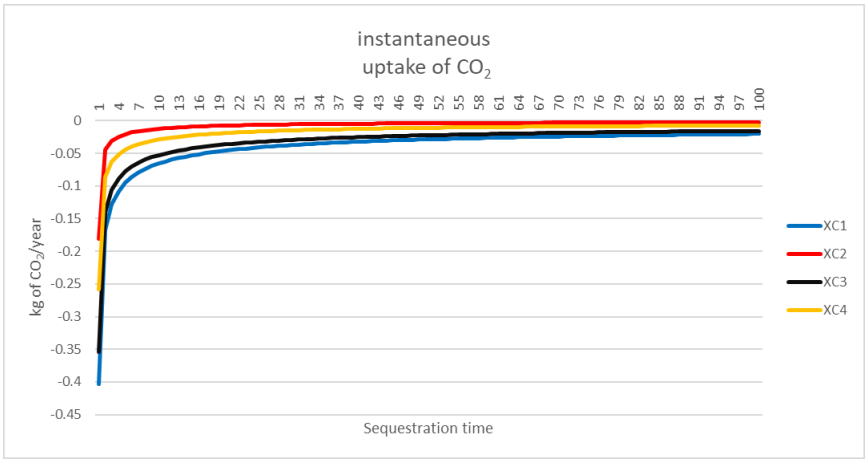


Figure 31 instantaneous sequestration of CO2 considering the first year for CEM I for different environmental classes and for a fix class strength (30 MPa) and cement content in concrete (400 kg/m^3).

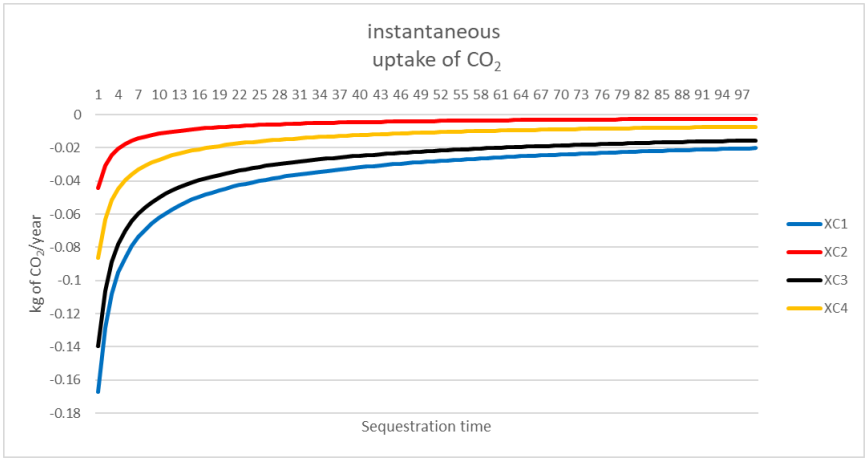


Figure 32 instantaneous sequestration of CO_2 without the first year for CEM I for different environmental classes and for a fix class strength (30 MPa) and cement content in concrete (400 kg/m^3).

Figure 31 shows the instantaneous sequestration of each year up to 100, including the first year of storage. However, the first year, as the result obtained, is much larger than the ones after and therefore probably overstated by the formulation. After 30 years more than half of the total CO_2 uptake is already sequestered (considering the total after 100-year storage period), so for buildings, whose use is estimated at 60 years, concrete is three-quarters saturated at the end-of-life of them. In the first years the sequestration is faster and the difference between year by year is larger, until it becomes practically the same after 50 years. Consequently, the GWP_{cem} index also tends to flatten after a storage period of 60 years.

Influence of the fixed parameters

The first fixed parameter that has a great influence on the result is the degree of carbonation. In fact, the total mass of CO_2 sequestered is directly related to the percentage of carbonation, as outlined in Equation 13. As discussed in section 6.2, the chosen degree is fixed to facilitate calculations and to obtain simple and practical graphs and is a mean value between the different percentages obtained from various experiments. However, choosing a carbonation degree of 0.5 instead of 1, would halve the amount of CO_2 absorbed and thus significantly affects the GWP_{cem} value of the structure. Therefore, to obtain even more precise results, it would be necessary to vary the value for each circumstance, as well as the other factor taken as fixed but varying for each structure, that is the concentration of CO_2 in the environment. Even in this case, taking more values would have led to too many results and therefore to poorly applicable tool.

Influence of the time horizon

In determining the GWP_{cem} factor due to sequestration of CO2 in cement concrete, the time horizon is an important factor. Variable TH are used in dynamic LCA approach to account for the residence time of CO_2 emission, which can change the result very significantly and affect the decisions of those who invest in mitigation options. The choice of 100 years corresponds approximately to the time of a living generation and is a good compromise between a higher and a lower TH. With a higher TH, such as 500 years, no importance is attached to time and no encouragement is given to immediate rather than future change and it is inconsistent with fast actions in climate change. In fact, it discourages investors to act now rather than in the next decades. Furthermore, if the time horizon is too long, the return to investors in mitigation project such this will be insufficient to motivate them to enter this field at all. Therefore, the political choice of the time horizon is a key as it may or may not make the CO_2 storage or even the building itself acceptable and reasonable in relation to the prefixed targets.

7. Wood implementation in Zurich City

Cities and settlements play a strategic role in implementing virtuous strategies for climate change mitigation, but their overall role in global solution pathways remains unclear (Creutzig et al., 2016). Most of construction materials requested in the next decades to build new constructions and infrastructure as well as renovate the existing stock is required in urban centres, both in developing economies and Global South (Göswein et al., 2018; Müller et al., 2013; Stephan and Athanassiadis, 2017). City of Zurich, as many municipalities in Switzerland and the in EU Community, is planning a sustainable pathway in order to fully move toward a carbon neutrality by 2050 (Admin.ch, 2020; swissinfo.ch, 2019). Increasing the use of wood, and biobased materials in general, in construction has been demonstrated to be a valuable strategy to fight climate change and achieve a carbon neutral society by many researchers (Churkina et al., 2020; Pittau et al., 2019; Verena et al., 2021). However,

the negative consequences of incrementing intensive monoculture forestry (e.g. loss of biodiversity, inducing water scarcity, reduction of carbon efficiency of the land, etc.) have not been fully explored and many concerns have been arisen by other scholars (Brockerhoff et al., 2008; Haberl et al., 2014; Hart and Pomponi, 2020).

The objective of this section is to evaluate the contribution on carbon mitigation from wood implementation as construction material in City of Zurich. The MFA model developed by bfu (Savi and Klingler, 2020) has been assumed for calculating the GHG flows and relative GWP from input data (i.e. inflow/outflow of mineral materials, timber, metals, etc.). The calculation includes within its system boundaries the material inflow for new building and outflow from building demolition in the period between 2013 and 2050. All additional materials required for building transformation and upgrade (e.g. energy retrofit, building extensions, façade/roof renovations, etc.) is excluded from the model. Three different scenarios have been identified: scenario 0 (base) which assumes a business-as-usual condition with a constant share of wood in construction in future; scenario 1 (wood promotion) where an increased demand of timber for construction is assumed in the next decades; scenario 2 (only wood), which assumes the full replacement of ordinary constructions with timber buildings from 2021.

7.1 Static -1/+1 method for the estimation of GWP and CO_2 potential uptake by 2050

The first method adopted to evaluate the potential of the CO_2 uptake in biogenic product and concrete elements is the static -1/+1 approach. Seven categories have been identified: two which describe the flow of CO_2 in biogenic products from manufacturing (in) and end of life from disposed wood (out), two related to the biogenic CO_2 uptake in forest regrowth and carbonation in concrete, two which represent the non-biogenic GWP for building materials production (in) and waste treatment of demolished buildings (out), and finally the total, representative of the sum of the previous six contributions.

The biogenic CO_2 uptake (CO2 bio_uptake) has been assumed on the base of the density of each biogenic material used in the stock and CO2 stored calculated according to Eq. 1 and reported in the above Figure 33.

		Ref.	Density [kg/m^3]	CO_2 stored	Biogenic CO_2 emission
Brennbare Materialien	Korkplatte	kg	120	-1,8	0,60
	Weichfaserplatte	m^3	148	-93,5	51,45
Holz	3-Schicht Massivholzplatte, PVAc-gebunden	m^3	470	-820,2	165,24
	Brettschichtholz, MF-gebunden, Feuchtbereich	m^3	470	-817,3	261,42
	Massivholz Fichte / Tanne / Lärche, luftgetrocknet, rau	m^3	485	-817,1	0,89
	OSB Platte, PF-gebunden, Feuchtbereich	m^3	605	-882,3	294,74
	Spanplatte, UF-gebunden, Trockenbereich	m^3	640	-1183,7	109,98
	Sperrholz/Multiplex, PF-gebunden, Feuchtbereich	m^3	500	-1157,1	858,70

Figure 33. List of biogenic materials (insulation and wood) and relative volumetric mass, carbon storage and biogenic emissions expressed per functional unit (Ref.).

The temporal assumption considers that all biogenic CO_2 stored in the building is sequestered by the regrowing trees overtime, as detailed illustrated in Section 5.2. The reference rotation period of coniferous trees has been assumed 70 years for this study with a constant annual removal. This value reflects the average growing time of forests in central Europe (Lippke et al., 2011). The assessment of carbonation in concrete structure (CO2 cem_uptake) has been performed on the base of secondary data provided in Tab. 7.1 of the report "LCA of climate friendly construction materials" (Alig et al., 2020). An average value representative of the CO_2 annually removed by concrete elements over their service life has been estimated equal to $8.75x10^{-2}$ $kgCO_2/t$ of concrete added in the stock. This extremely low value results influenced by the large volume installed in foundations, which capability to carbonate the available C-S-H and CH results up to 5-folds lower than above the ground structures (i.e., pillars, roof, external concrete walls, etc.). Moreover, only carbon removal from inflow concrete materials has been included in the model. The additional potential CO_2 removal from demolished concrete (outflow) has been neglected.

The annual GWP intensity and uptake is shown in the following Figure 34.

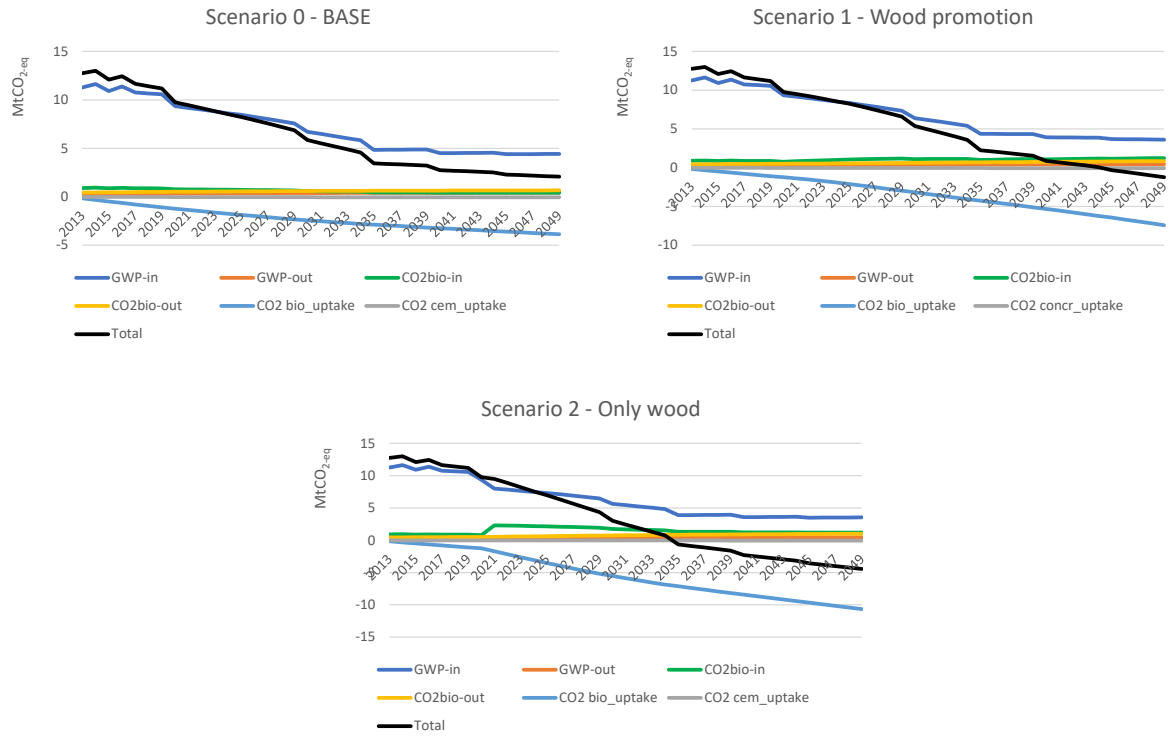


Figure 34. Annual emission and uptake. "GWP-in" is the annual contribution on climate change from material inflow in new construction; "GWP-out" is the annual contribution on climate change from material outflow generate by building demolition; "CO2bio-in" is the annual emission of biogenic CO2 from wood materials in new construction; "CO2bio-out" is the annual emission of biogenic CO2 from incineration of disposed wood from demolished buildings; "CO2 bio_uptake" is the annual uptake of CO2 from carbon storage in new buildings; "CO2 cem_uptake" is the annual CO2 which is sequestered in new concrete structure via carbonation; "Total" is the total annual GWP resulting from the sum of each contribution.

In the base scenario a significant GWP reduction is measured in year 2020-2035, with a nearly constant contribution in the period 2035-2050 due to population stabilization. Similarly, the biogenic CO_2 emitted from wood processing is reduced, even if its contribution results minimal in this scenario due to a small share of wood added annually in the stock. The net annual GWP results always positive even in 2050 since the sum of the annual CO_2 removal via carbonation and forest uptake is not sufficient to compensate the positive emissions from material processing and end-of-life of buildings. Contrarily, in scenario 1 the increasing amount of timber in new constructions generates a negative net-annual change from 2045. In scenario 2, a great technology breakthrough is assumed at year 2021, with a complete shift to timber constructions. In this case, even if most of the saved fossil emissions from material manufacturing is replaced by biogenic emissions for timber element, which moves from 0.76÷0.84 $MtCO_2/a$ in 2050 for base scenario to 1.00÷2.32 $MtCO_2/a$ for scenario 2, the increasing influence of biogenic uptake as a consequence of carbon storage in timber elements, generates a negative net-annual GWP from 2035.

The cumulative GWP and uptake is presented in the following Figure 35.

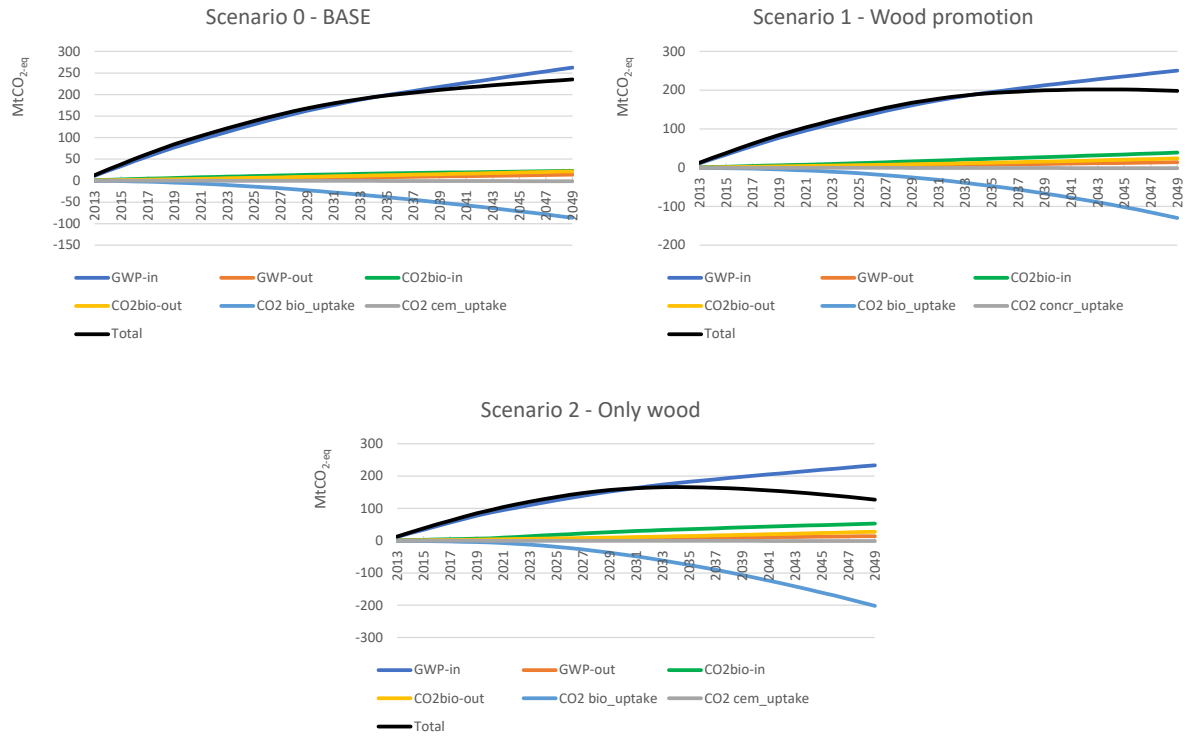


Figure 35. Cumulative emission and uptake. "GWP-in" is the cumulative contribution on climate change from material inflow in new construction; "GWP-out" is the cumulative contribution on climate change from material outflow generate by building demolition; "CO2bio-in" is the cumulative emission of biogenic CO2 from wood materials in new construction; "CO2bio-out" is the cumulative emission of biogenic CO2 from incineration of disposed wood from demolished buildings; "CO2 bio_uptake" is the cumulative uptake of CO2 from carbon storage in new buildings; "CO2 cem_uptake" is the cumulative CO2 which is sequestered in new concrete structure via carbonation; "Total" is the total cumulative GWP resulting from the sum of each contribution.

In the base scenario, the CO_2 removal in growing forest and concrete structures contributes to minimally reduce the GWP, with a GWP decreasing of 27% from nominal value in 2050. In scenario 1, the pick of net cumulative emissions is expected in 2044, equal to 202 $MtCO_{2\text{-eq}}$, with a marginal reduction in the following six years. Finally, in scenario 2 the massive increase of timber construction share contributes to attenuate the pick, limited in this scenario to 166 $MtCO_{2\text{-eq}}$, and shifted to 2034, with a final net-GWP in 2050 equal to 127 $MtCO_{2\text{-eq}}$ which correspond to 54% reduction compared to base scenario.

7.2 Dynamic GWP estimation

The impact on the climate as a consequence of GHG emissions and CO_2 uptake within the time boundaries has been estimated according to the dynamic LCA method presented in Section 5.3. A time dependent function for carbonation kinetics has been obtained as a reverse function from Eq. 14 and Eq. 15, assuming a cumulative CO_2 removal via carbonation equal to 5.25 $kgCO_2/t$ of installed concrete as estimated from Alig et al. (Alig et al., 2020).

The time-dependent cumulative global warming impact is shown in the following Figure 36.

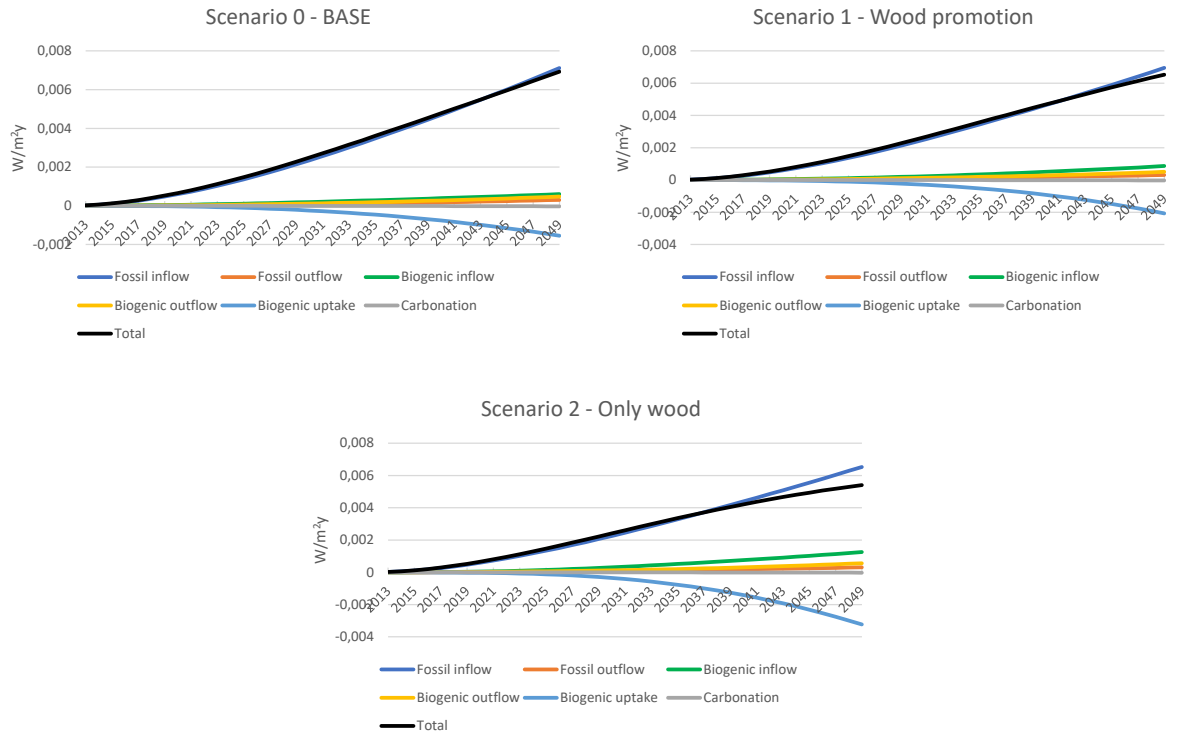


Figure 36. Cumulative Global Warming Impact (GWIcum), calculated according to the dynamic LCA method. "Fossil inflow" is the contribution on radiative forcing from GHG emissions generated by material inflow in new construction; "Fossil outflow" is the contribution on radiative forcing from GHG emissions generated by material outflow from building demolition; "Biogenic inflow" is the contribution on radiative forcing generated by biogenic CO2 emissions from wood materials in new construction; "CO2bio-out" is the contribution on radiative forcing generated by biogenic CO2 emissions from incineration of disposed wood from demolished buildings; "Biogenic uptake" is the contribution on radiative forcing generated by the uptake of CO2 from carbon storage in new buildings; "Carbonation" is

the contribution on radiative forcing generated by the CO_2 sequestered in new concrete structure via carbonation; "Total" is the total cumulative Global Warming Impact resulting from the sum of each contribution.

In base scenario, the contribution of storing carbon in building and carbonation of concrete on mitigating the climate change in 2050 is marginal, with an influence of 18% on the total. In scenario 1, the increased share of wood in construction influences sensibly the result, with a reduction of 24% of the radiative forcing on the total in 2050 and 25% compared to base scenario. Finally, in scenario 2 the cumulative radiative forcing result nearly stable in 2050, with a significative reduction of roughly 40% compared to base scenario. The equivalent dynamic GWP (dynGWP) is shown in the following Figure 37. While the base scenario presents an increasing pressure on the climate change, with a minimal mitigation basically governed by the decreasing demand of construction materials in 2035-2050, both scenario 1 and in particular scenario 2, present a stabilization of the GWP values around 2050. It means that the combination of reduced material input within the increasing pressure on the forest industry are able to stabilize the climate with a mitigation which may lead to carbon neutrality by 2050. In case of scenario 2, the CO_2 budget to spend for the transition in construction is equal to 157 $MtCO_{2\text{-eq}}$, while for scenario 2 the budget may be limited to 130 $MtCO_{2\text{-eq}}$, with a reduction of 17% which may be spent to decarbonate other strategic sectors.

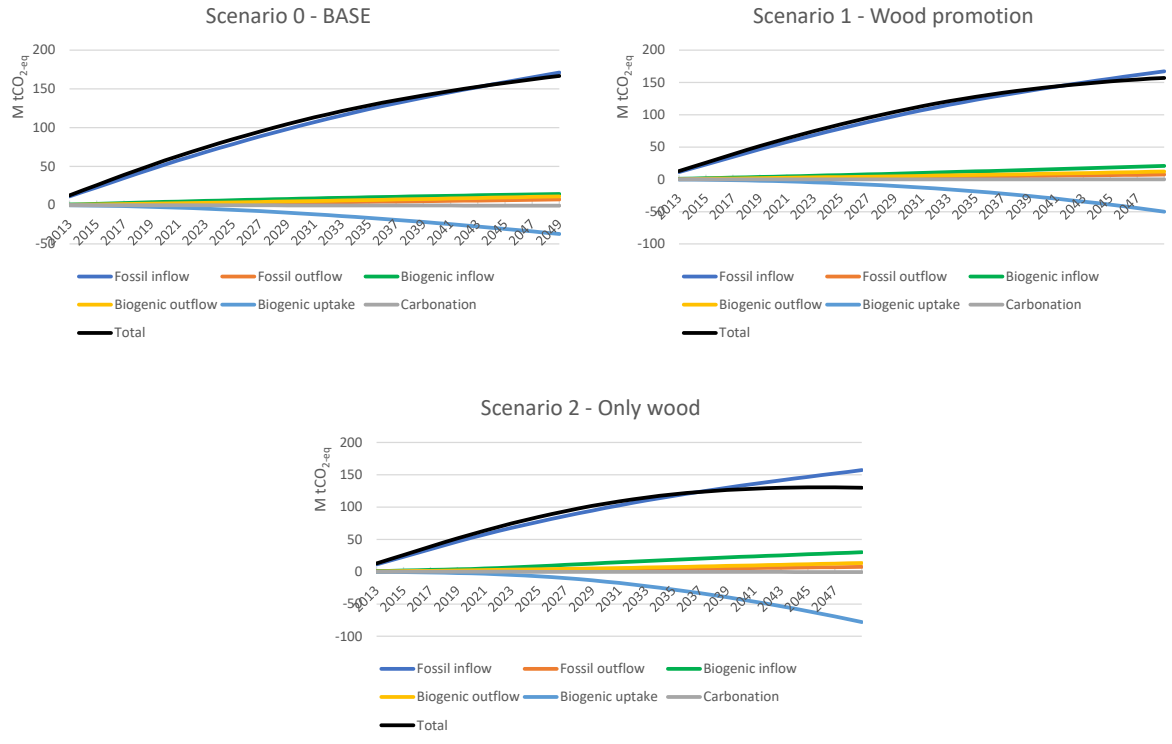
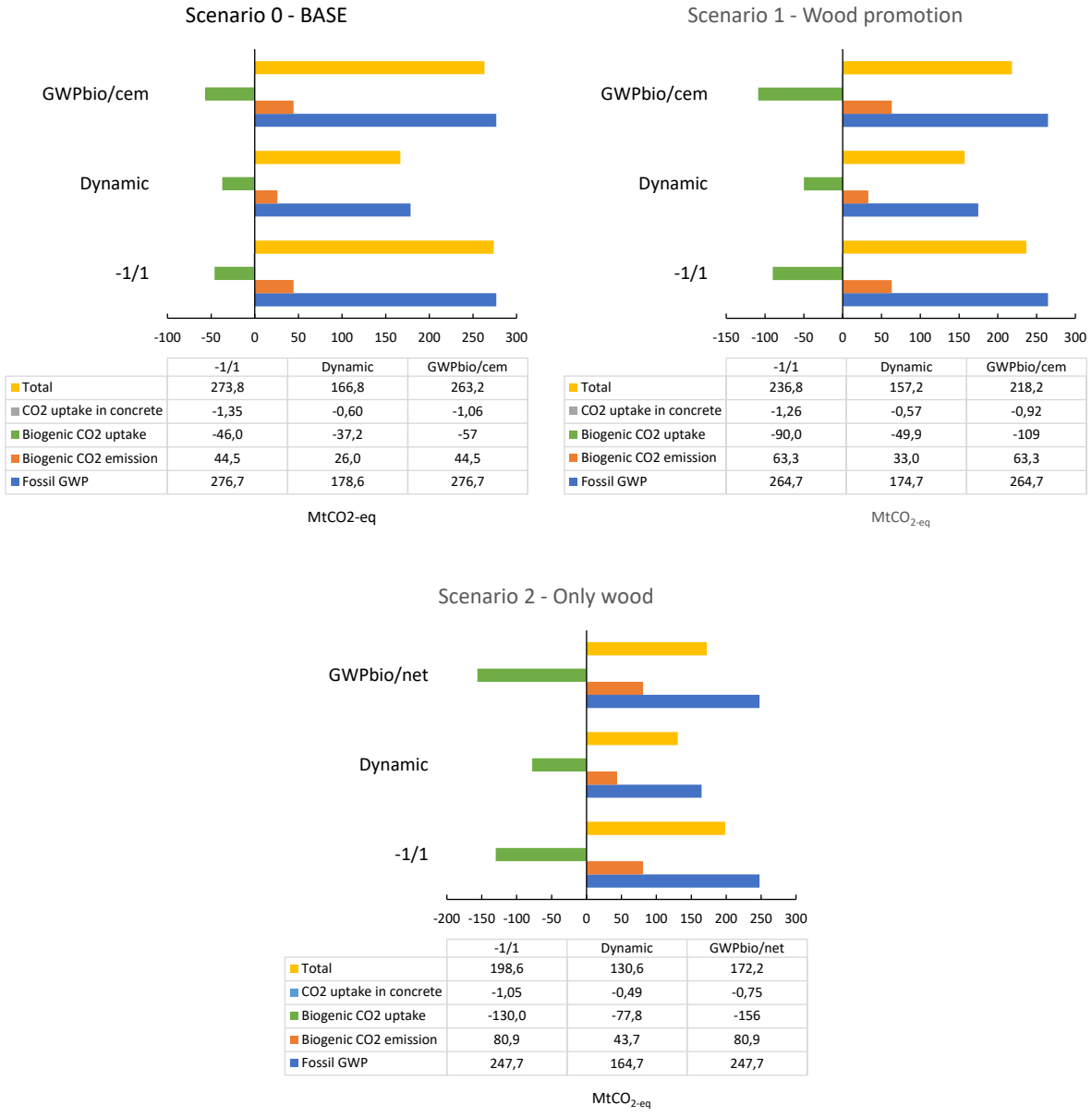


Figure 37. Dynamic Global Warming Potential (dynGWP). "Fossil inflow" is the dynamic contribution on climate change from material inflow in new construction; "Fossil outflow" is the dynamic contribution on climate change from material outflow generate by building demolition; "Biogenic inflow" is the dynamic contribution on climate change from biogenic CO_2 emissions generated by wood materials in new construction; "Biogenic outflow" is the dynamic contribution on climate change from biogenic CO_2 emissions generated by incineration of disposed wood from demolished buildings; "Biogenic uptake" is

the dynamic contribution on climate change from CO_2 uptake due to carbon storage in new buildings;
"Carbonation" is the cumulative CO_2 which is sequestered in new concrete structure via carbonation;
"Total" is the total cumulative GWP resulting from the sum of each contribution.

7.3 Sensitivity of the calculation methods for biogenic carbon and concrete carbonation

The comparison of the GWP in 2050 achieved according to the three calculation methods (i.e. -1/+1, dynamic LCA and semi-static approach, through the adoption of GWP_{bio} and GWP_{cem} indexes) is presented in the following Figure 38.



	-1/1	Dynamic	GWPbio/cem
Total	273,8	166,8	263,2
CO2 uptake in concrete	-1,35	-0,60	-1,06
Biogenic CO2 uptake	-46,0	-37,2	-57
Biogenic CO2 emission	44,5	26,0	44,5
Fossil GWP	276,7	178,6	276,7

	-1/1	Dynamic	GWPbio/cem
Total	236,8	157,2	218,2
CO2 uptake in concrete	-1,26	-0,57	-0,92
Biogenic CO2 uptake	-90,0	-49,9	-109
Biogenic CO2 emission	63,3	33,0	63,3
Fossil GWP	264,7	174,7	264,7

	-1/1	Dynamic	GWPbio/net
Total	198,6	130,6	172,2
CO2 uptake in concrete	-1,05	-0,49	-0,75
Biogenic CO2 uptake	-130,0	-77,8	-156
Biogenic CO2 emission	80,9	43,7	80,9
Fossil GWP	247,7	164,7	247,7

Figure 38. Comparison of resulting GWP in 2050 according to the three selected calculation methods: i) static LCA -1/+1; ii) dynamic LCA; semi-static GWP-bio method.

The results achieved through the simplified semi-static method resulted very close to those obtained with a static -1/+1 approach, with a deviation between 4% min and 13% max. On the contrary, a large deviation of the results is observed for dynamic LCA, with a difference which varies between 34% min and 39% max compared to standard static approach. In every scenario the CO_2 uptake from concrete carbonation results with a magnitude 10^2 lower than the biogenic uptake in wooden elements, which limits the capacity of carbon removal in concrete structures. As already discussed, most of the concrete is supposed to be used for foundation and basement, with a limited capacity to expose large part of structural surface to the air. Consequently, an increasing demand of timber would benefit of a lower demand of concrete, with a consequent large reduction of fossil GHG, which results the main driver to consider for building decarbonation when ordinary concrete mixtures are used.

8. Conclusions

The objective of this report is to identify, test and discuss robust methods to measure the mid and long-terms disturbance on the climate when wood-based and concrete materials are adopted for building construction. Three alternative methods for biogenic carbon accounting were identified from literature and discussed, namely: static (-1/+1) method, temporal-depending (dynLCA) method, and semi-static (GWP_{bio}) method. On one side, the application of the standard -1/+1 method resulted limited since the positive effect of delaying the biogenic CO_2 emissions at end of life cannot be observed due to a non-time dependent characterization factor adopted for a finite time horizon, generally assumed equal to 100 years. Consequently, the adoption of a single indicator able to reflect the climate disturbance of a human action (i.e., building with timber) is not possible since the carbon neutrality is assumed for wood when supplied from sustainable forestry. Therefore, according to the static carbon footprint approach, only the non-biogenic contribution can be accounted for the GWP 100y calculation, while the CO_2 temporally stored in the building over its service life period can be only accounted for as separate value. This issue creates serious limitations in the interpretation whether storing biogenic carbon in building is a sustainable strategy or not, since there is no chance of measuring the long terms effect and the consequent risk of charging the next generations of a large emission share from timber building end of life. Nevertheless, its application on the building stock has been demonstrated to return robust results for a mid-period of occurrence (2013-2050). In a long-term scenario, which includes the end of life of timber buildings built during the transition period, the static -1/+1 method still might be theoretically adopted to measure the disturbance on the climate and the CO_2 stored in the city, but only under the condition that demolished buildings are replaced with timber building again. On the other side, the dynLCA method permits to quantify the disturbance to the climate due to a time-dependent pulse emission. The method is robust and well supported from data and scientific evidence in literature. Unfortunately, its implementation in standards and LCA everyday practice results limited due to the complexity of the calculation, which requires LCA practitioners able to disaggregate yearly input flow per each GHG (e.g., inflow/outflow of CO_2, CH_4, N_2O, etc.) as well as with advanced knowledge in systems dynamic and dynamic modelling skills. Moreover, some temporal aspects which influence the results are still controversial, especially the time allocation of biogenic carbon uptake by forest growth. In this report, the uptake has been assumed to be accounted for in the period after the construction, which is provided by regrowing trees planted in sustainable forests as a replacement of the biomass harvested for construction. Also, the rotation period of forests is dependent of economic and management factors, which is typically an unknown factor that increases the level of uncertainties in the system. Finally, the semi-static method detailly presented in this report

resulted simple to be applied to the building stock and able to return a representative result influenced by temporal factors (storage period and rotation period). While large differences can be observed in literature at building scale when comparing dynamic or semi-static approach with a static approach, no significative deviation have been observed at building stock assessment for City of Zurich in a mid-term period (2013-2050). While carbon storage has been demonstrated to provide a significative contribution in the climate change mitigation, the uptake form carbonated concrete structure seems to be irrelevant in the carbon-neutrality discussion. The results are certainly influenced by low resolution input data used to set up the carbonation model and a more realistic overview about the potential of carbon removal in concrete would benefit of further investigation through more advanced models, to predict with higher resolution the contribution from the large amount of demanding concrete still expected in next years.

9. Recommendations and further work

Even if temporal factors and considerations have been demonstrated to play a fundamental role in the GWP assessment of building when biogenic carbon is included in the system, a static approach -1/+1 can provide robust results in a mid-term prospective which can support environmental policies to move to Zero-carbon city. A fast implementation of timber in construction would reduce the contribution of fossil emission due to a lower volume of concrete used for buildings and, even considering the increasing share of biogenic CO_2 emission for timber processing, the balance stays favorable for a carbon mitigation. The more wood we can introduce in the stock during the transition period the better for the society, which would benefit of investing a lower carbon budget to make the annual net-emissions equal to zero by 2050. Concerns remain about the resiliency of forests due to climate change, which may become much more vulnerable to wildfires than in the past and, consequently, their contribution to keep the carbon cycle neutral might be compromised. Strong policies and actions are required to ensure the forest protection and reduce the risk of open carbon cycles in the next years. In a long-term prospective, the risk of uncontrolled biogenic emissions from building end of life must be avoided though the adoption of an efficient wood cascade strategy, able to to extend the carbon stored in the Technosphere for a period beyond a building service life. As last step of the cascade, wood pyrolyzation has been demonstrated to be more beneficial than ordinary municipal incineration and able to reduce by nearly 70% the GWP of end-of-life. Therefore, boosting investments on bio-digestion power plants are strongly encouraged since a large carbon content can be permanently stored in soils. Additionally, since a rapid complete shift to timber construction seems to be unconvincing if not supported by massive incentives, the implementation of low carbon concrete should be a priority as well to reduce the carbon emission from cement production and make the transition safer. Finally, a large share of the stock is expected to be renovated in the next 30 years and the risk of large use of carbon intensive materials (EPS, XPS, mineral fibers, etc.) for insulation production might seriously affect the carbon budget for construction. A large promotion of biobased insulation for building renovation and retrofit (e.g., expanded cork, woodfibers, flax fibers, hempcrete, etc.) is strongly recommended to benefit of an additional carbon sink in the stock and ensure a safe transition to a carbon-neutral society.

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Stadt Zürich
Amt für Hochbauten
Lindenhofstrasse 21
Postfach, 8021 Zürich
T+ 41 44 412 11 11
stadt-zuerich.ch/hochbau

M-System-Nr.