Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Carbon footprint assessment of a wood multi-residential building considering biogenic carbon

Claudiane Ouellet-Plamondon
claudiane.ouellet-plamondon@etsmtl.ca

École de technologie supérieure

Livia Ramseier
Treeze Ltd

Maria Balouktsi
Karlsruhe Institute of Technology

Laetitia Delem
Belgian Building Research Institute

Greg Foliente
The University of Melbourne

Nicolas Francart
KTH - Royal Institute of Technology

Antonio Garcia
Universidad de Sevilla

Endrit Hoxha
Graz University of Technology

Thomas Lützkendorf
Karlsruhe Institute of Technology

Freja Nygaard Rasmussen
Aalborg Universitet København

Bruno Peuportier
MINES ParisTech

Jared Butler
BRANZ

Harpa Birgisdottir
Aalborg Universitet København

David Dowdell
BRANZ

Manish Dixit
Texas A&M University

Vanessa Gomes
University of Campinas
Maristela Gomes da Silva
Federal University of Espirito Santo
Juan Carlos Gómez
Universidad de Sevilla
Marianne Kjendseth Wiik
SINTEF
Carmen Llatas
Universidad de Sevilla
Ricardo Mateus
University of Minho
Lizzie M. Pulgrossi
University of Campinas
Martin Röck
KU Leuven
Marcella Ruschi Mendes Saade
Graz University of Technology
Alexander Passer
Graz University of Technology
Daniel Satola
Norwegian University of Science and Technology
Seongwon Seo
The University of Melbourne
Bernardette Soust Verdaguer
Graz University of Technology
Jakub Veselka
University Centre for Energy Efficient Buildings
Martin Volf
University Centre for Energy Efficient Buildings
Xiaojin Zhang
Paul Scherrer Institute
Rolf Frischknecht
Treeze Ltd

Research Article

Keywords: Biogenic carbon, Life cycle assessment, Building, Construction, Wood products

Posted Date: November 15th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2273783/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Version of Record: A version of this preprint was published at Journal of Cleaner Production on June 1st, 2023. See the published version at https://doi.org/10.1016/j.jclepro.2023.136834.

Carbon footprint assessment of a wood multi-residential building considering biogenic carbon

Claudiane M. Ouellet-Plamondon[1], Livia Ramseier[2], Maria Balouktsi[3], Laetitia Delem[4], Greg Foliente[5], Nicolas Francart[6], Antonio Garcia[7], Endrit Hoxha[8], Thomas Lützkendorf[3], Freja Nygaard Rasmussen[9], Bruno Peuportier[10], Jared Butler[11], Harpa Birgisdottir[9], David Dowdell[11], Manish Dixit[12], Vanessa Gomes[13], Maristela Gomes da Silva[14], Juan Carlos Gómez[7], Marianne Kjendseth Wiik[15], Carmen Llatas[7], Ricardo Mateus[16], Lizzie M. Pulgrossi[13], Martin Röck[8,17], Marcella Ruschi Mendes Saade[8], Alexander Passer[8], Daniel Satola[18], Seongwon Seo[5], Bernardette Soust Verdaguer[7,8], Jakub Veselka[19], Martin Volf[19], Xiaojin Zhang[20,21], Rolf Frischknecht[2]

[1] École de technologie supérieure, Montreal, Canada
[2] Treeze Ltd, CH- 8610 Uster, Switzerland
[3] Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
[4] Belgian Building Research Institute, 1000 Bruxelles, Belgium
[5] The University of Melbourne, Parkville VIC 3010, Australia
[6] KTH - Royal Institute of Technology, 114 28 Stockholm, Sweden
[7] Universidad de Sevilla, 41004 Sevilla, Spain
[8] Graz University of Technology, 8010 Graz, Austria
[9] Aalborg Universitet København, Aalborg Universitet København
[10] MINES ParisTech, PSL Research University, CES, 75272 Paris, France
[11] BRANZ, Judgeford 5381, New Zealand
[12] Texas A&M University, College Station, TX 77843, United States
[13] University of Campinas, 13083-852, Campinas, Brazil
[14] Federal University of Espirito Santo, 29075-910, Vitoria, Brazil
[15] SINTEF, NO-7465 Trondheim, Norway
[16] University of Minho, 4710-057 Braga, Portugal
[17] KU Leuven, 3001 Leuven, Belgium
[18] Norwegian University of Science and Technology, 7491 Trondheim, Norway
[19] University Centre for Energy Efficient Buildings, Czech Technical University in Prague, 273 43, Bustehrad, Czechia
[20] Technology Assessment Group, Laboratory for Energy Systems Analysis, Paul Scherrer Institute, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland
[21] ETH Zürich, Institute of Construction and Infrastructure Management (IBI), Chair of Sustainable Construction, Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland

Abstract

Wood and other bio-based building materials are often perceived as a good choice from a climate mitigation perspective. This article compares the life cycle assessment of the same multi-residential building from the perspective of 16 countries participating in the international project Annex 72 of the International Energy Agency to determine the effects of different datasets and methods of accounting for biogenic carbon in wood construction. Three assessment methods are herein considered: two recognized in the standards (the so-called 0/0 method and –1/+1 method) and a variation of the latter (–1/+1* method) used in Australia, Canada, France, and New Zealand. The 0/0 method considers neither fixation in the production stage nor releases of biogenic carbon at the end of a wood product's life. In contrast, the –1/+1 method accounts for the fixation of biogenic carbon in the production stage and its release in the end-of-life stage, irrespective of the disposal scenario (recycling, incineration or landfill). The -1/+1 method assumes that landfills offer only a temporary sequestration of carbon. In the –1/+1* variation, landfills and recycling are considered a partly permanent sequestration of biogenic carbon and thus fewer emissions are accounted for in the end-of-life stage. We examine the variability of the calculated life cycle-based greenhouse gas emissions calculated for a case study building by each participating country, within the same assessment method and across the methods. The results vary substantially. The main reasons for deviations are whether or not landfills and recycling are considered a partly permanent sequestration of biogenic carbon and a mismatch in the biogenic carbon balance. Our findings support the need for further research and to develop practical guidelines to harmonize life cycle assessment methods of buildings with bio-based materials.

Keywords: biogenic carbon, life cycle assessment, building, construction, wood products.

1- Introduction

The search for solutions to reduce resource use and the impact of human activities on the local and global environment reached the international scale. Since the operation of buildings accounts for approximately 30% and the manufacture of construction products for approximately 10% of global greenhouse gas (GHG) emissions (UN Environment and International Energy Agency, 2017), the great potential for reducing the impacts in the construction sector becomes clear. At the moment, whether and to what extent the increased use of bio-based products in constructing new buildings and the refurbishing existing ones can contribute to resource conservation and environmental relief is increasingly discussed (Ramage et al., 2017). Furthermore, methods and data for objectively assessing wood and other bio-based building materials/construction products, as well as buildings with a predominant use of bio-based products are necessary (Andersen et al., 2021; Takano et al., 2015). This results in a need to check the status of methodological discussions concerning biogenic carbon in building life cycle assessment (LCA). Biogenic carbon is defined as the carbon that is extracted from the atmosphere during biomass growth and is released back to the atmosphere later due to combustion of the biomass and decomposition (Stamford, 2020). Furthermore, the consequences of method- and data-related issues for the environmental performance assessment of wood buildings must be discussed, to develop consensus-based and scientifically recognized assessment procedures in the context of sustainability.

1.1 Context and background

The world is in a climate emergency (World Green Building Council, 2019). The latest intergovernmental report released by the IPCC (AR6) states that with the current level of government commitment, the planet is on course for a disastrous 3°C temperature rise (IPCC, 2021). For sustainable development of the future, it was agreed at COP21 in Paris that global warming should be limited to well below 2 and preferably to below 1.5°C. To limit the increase in global temperatures by 1.5°C, mankind must drastically reduce carbon emissions until the net-zero status is reached by 2050 latest (IPCC, 2018).

The design, construction and operation of buildings and other constructed assets have a major impact on the environmental with the reduction of GHG emissions across the life cycle of buildings being especially relevant for effectively mitigating climate change (Röck et al., 2020). Many governments are aware of the extent of the environmental impacts caused by the construction and use of buildings, but also acknowledge that the construction and use of buildings are an indispensable basis for economic and social development. To cope with their responsibility in creating the basis and prerequisites for more sustainable national building stocks (Röck et al., 2021), national sustainability strategies have been developed and implemented (Government of Canada, 2019; Ministry of the Interior and Housing, 2021; The Federal Government, 2016), legislative initiatives (Government of Spain, 2021; Ministry of the Interior and Housing, 2021; Swedish National Board of Housing Building and Planning, 2020), funding programs (Association for the Conservation of Energy, 2013), and exemplary public buildings have been proposed, implemented, and built (World Green Building Council, 2021). In the interests of present and future generations, such activities serve to protect the climate, preserve ecosystems and conserve natural resources. Most of them have long focused on the building operational energy, by reducing energy demand and increasing the renewable energy share.

More recently, the impacts embodied in the manufacturing of building products, as well as the maintenance, deconstruction and recycling of buildings had gained attention not only in the academic literature (Birgisdottir et al., 2017), but also in the political circles (ISO, 2017b; Kuittinen and Häkkinen, 2020; Ministère de la transition écologique, 2021; Ministry of Business Innovation & Employment, 2020 ; Swedish National Board of Housing Building and Planning, 2020). As the emissions due to energy consumption decrease, construction products become greater contributors to the building environmental impacts.

Recently, the focus has been placed on the role of bio-based construction materials and products, and especially wood, as a contribution to climate change mitigation (Himes and Busby, 2020). With the development of mass timber technology and expertise in recent decades, which made possible to build mid- and high-rise buildings with wood, many view wood materials as a substitute for the traditional construction materials, such as steel and concrete used in building frames (Chen et al., 2020; Green and Karsh, 2012; Harte, 2017). Therefore, increased use of wood and bio-based materials is often seen as an important contribution to resource conservation and climate protection. Furthermore, these building materials and construction methods can store carbon, i.e. they can serve as temporary carbon reservoirs offering time to develop effective technologies to capture and permanently sequester biogenic carbon contained in buildings (Churkina et al., 2020).

1.2 Wooden products and buildings as part of political strategies and actions

When analyzing political actions concerning the use of bio-based materials, trends can be observed. Public authorities at varied levels (local, regional or national) directly promote the use of bio-based materials through, for example, local requirements prescribing or promoting the use of bio-based insulation in existing buildings e.g. in Belgium (Crucke and Bue, 2019; Region de Bruxelles-Capitale, 2011), or wood materials for specific projects or areas (Francart et al., 2019), regulatory incentives (e.g. Swiss Forest Act and Swiss CO_2 Act (Schweizerische Eidgenossenschaft, 2020; Schweizerischen Eidgenossenschaft, 2017), funding programs (City of Munich, 2013), and/or advancement of technical specifications and structural standards to ease the wood uptake (Natural Ressources Canada, 2020; Wood Sector Alliance for the New European Bauhaus, 2021). This situation encourages more policy initiatives, research and demonstration projects focusing on wood or bio-based construction. The latest trend is the discussion or realization of multi-storey buildings with a primary load-bearing timber frame.

Such actions are particularly prevalent in countries where forestry plays an important economic role (Food and Agriculture Organization (FAO), 2020).

However, a sole reliance on wood and bio-based material encouragement policies and related prescriptive requirements can be problematic for both designers who may feel constrained to use such products in sub-optimal designs and non-bio-based product manufacturers who may perceive unfair procurement practices (Francart et al., 2019; Goodland, 2016). Therefore, some governments feel obliged to adopt a technology-open and material-neutral approach when developing funding programs or legal requirements. With a performance-based approach, the focus is on the required performance and not the specified solution (Foliente, 2000) but its implementation requires an accepted assessment method to verify that the proposed solution, product, design and/or construction method meet the performance criteria. For this purpose, the application of environmental LCA has already established itself in international standardization to provide the basis for assessing the environmental performance of individual buildings (ISO, 2010). Furthermore, LCA has already entered practice and is starting to be used in procurement, certification (e.g. DGNB and BNB, SNBS, Minergie-eco, SIA 2040) and regulation (recent examples from e.g. Sweden, France and Denmark (Ministry of the Interior and Housing, 2021; Swedish Parliament, 2021)).

Bio-based materials compete with other building materials and construction methods. Therefore, to secure market share and avoid future climate regulatory risks, concrete, steel as well as brick and tile industries are currently developing strategies to reduce the GHG emissions caused during the production stage, to reduce resource consumption by expanding recycling and the use of secondary materials, and to improve durability (Bataille, 2020; Cerame Unie, 2012; Eurofer, 2019; Habert et al., 2020; HERA, 2017). The discussion on and quantification of the effects of using wood-based materials thus takes on a social dimension and necessitates the provision of scientific advice to policy. Therefore, it becomes crucial to understand, interpret, correctly apply, or advance according to current scientific knowledge the basic possibilities of dealing with wood and/or bio-based products and buildings in the context of LCA.

Bio-based materials like wood, straw, hemp wool and other (insulation) materials are light, heat insulators, but do not store as much energy as heavy masonry (Hens, 2016). Therefore, they contribute little to the whole building thermal inertia. This results in a lower storage capacity of solar gains which in turn may increase heating needs during the use stage of buildings in certain climate zones (Kuczyński and Staszczuk, 2020; Mantesi et al., 2015). Thermal mass also has implications for thermal comfort and cooling needs. However, the influence of building materials on the indoor climate and operational energy demand is outside the scope of this article.

1.3 Research questions

In the international project Annex 72 of the Energy and Building Communities program of the International Energy Agency (IEA), we investigate harmonization issues in the methods of calculation and assessment of primary energy consumption, GHG emissions and other environmental impacts caused along the life cycle of buildings. In particular, the treatment of GHG emissions of bio-based products indicates a lack of consistency and transparency worldwide. This leads to the following questions

- What assumptions and methods are used in LCA of buildings with wood and bio-based materials in different countries?
- What causes the variability within the same overall assessment and between the methods for the selected case?
- What are the implications of the biogenic carbon accounting method on the carbon footprint of building components and buildings?
- What are the similarities and differences when comparing the approaches applied in different countries?

This study aims to analyze and understand the differences in methodological approaches across countries when applied to the same multi-residential wood building (construction method, material inventory, operational energy demand, etc.) and address the above questions to better understand the differences in the national methods. The study is based on the national LCA approach of the participating countries. For countries not having a national standard, the national approach means the most common or frequent practice in that specific country currently, in terms of both method and database used. On purpose, the databases are those used in the practice. The authors are aware that it will bring differences and the intention is to understand the sources of variation in the results in these circumstances. This extends the work of the European thematic network PRESCO (Practical recommendations for sustainable construction), where seven building LCA tools were applied to a wooden frame house (Peuportier et al., 2004). The exercise presented here aims to reach countries members and nonmembers of the European union. The following section presents the two primary approaches used by participating countries to consider and model biogenic carbon. The analysis highlights the differences when the same methodology is applied and across the different methodologies. The results reflect how practitioners would take their decision on. The implications of the LCA methodological choices on the outcome are discussed. This comparative LCA helps to reduce the risks of misinterpretation, guide material selection decisions based on LCA and identify key areas for harmonization of methods.

2- System of perspectives and state of the art in the methodology of wood assessment

Three different approaches are distinguished within the LCA literature on the calculation of biogenic carbon and fossil greenhouse gases (GHG) (Hoxha et al., 2020), based on how temporal biogenic carbon fixation and its release to the atmosphere are considered (Figure 1). First, the 0/0 method considers neither fixation nor releases of biogenic carbon. Secondly, in contrast, the –1/+1 method, recommended by EN 15804+A2 (European Committee for Standardization (CEN), 2019), accounts for the fixation of biogenic carbon in the production stage and its release in the end-of-life (EN 15804+A2). Variants of the -1/+1 approach apply a -1/+1* in the case of recycling or landfill at the end of life (meaning that the fixation of biogenic carbon is considered, but no or not all biogenic carbon is modelled as an emission at the end of life). In France a 0/+1 approach is used if no tree is regrowing (i.e. the forest is transformed to agricultural or built-up land) or if the wood stems from native forests (EN 15802+A2) and the wood is incinerated at the end of life (meaning that no fixation of biogenic carbon is considered, but emissions do happen at the end of life). Thirdly, the so called "dynamic" approach accounts for biogenic carbon fixation during the growth of trees and its releases at the end-of-life based on annual balances (Levasseur et al., 2013). The method applies a fixed temporal system boundary (100 years after construction) to derive time-dependent global warming potentials. However discounting future emissions may induce impact shifting, particularly by reducing the benefit of energy-saving measures, and it may be considered unfair to future generations so that climate scientists discourage it (Brunner, 2022) and it is adopted in only a few laws, standards or design tools (France and Norway). The dynamics of the countries is also very variable and there is not yet harmonization on the methods. The dynamic approach has not been used by any of the countries participating in the exercise, so it is not further discussed here.

Currently, biogenic carbon is accounted according to three methods by national assessment: the 0/0 method, the -1/+1, and the -1/+1* (Figure 1, Table 1). Explanation of the modules in the life cycle assessment of buildings can be found in standards (European Committee for Standardization (CEN), 2019). The -1 means that the carbon is extracted from the atmosphere and enters the system. The +1 means that the carbon leaves the system. An overview of available standardized product-level guidance and the type of approach recommended is provided in Table 2. ISO/TC 59 SC 17 and ISO 21930 (ISO, 2017a) provide an international basis for developing EPD, while CEN TC 350 standards and EN 15804+A2 (European Committee for Standardization (CEN), 2019), in particular, apply to Europe.

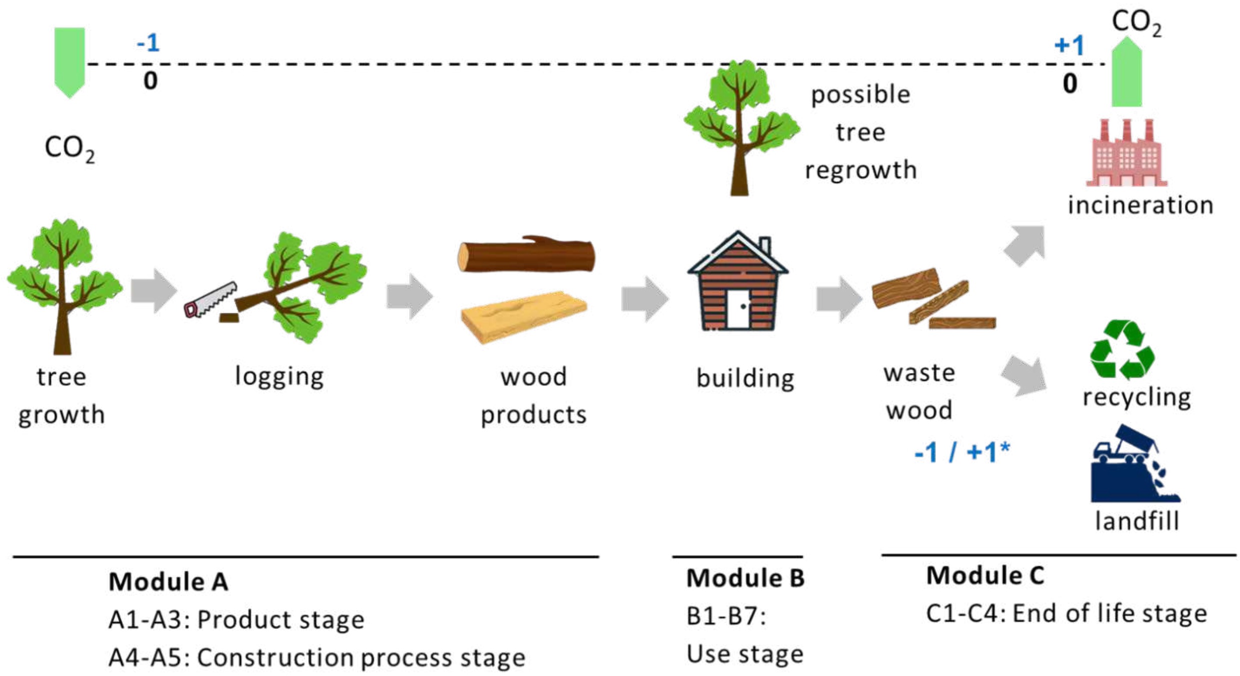


Figure 1: Methods applied on modelling biogenic carbon in the LCA bio-based products. Carbon fixation is assumed to happen either before the construction stage or carbon fixation during the use stage of the building life cycle.

Table 1: Summary of the biogenic CO_2 accounting approaches considered in this article

Method	**Forest system**	**Building system**		
		Module A	Module B	Module C
0/0	-	-	-	-
-1/+1	Carbon fixation	Carbon fixation (-1)	-	Carbon emission (+1)
-1/+1*	Carbon fixation	Carbon fixation (-1)	-	Carbon emission (+1) Carbon landfilled (variable indicated by the star) [1])

[1]: 0.11 (Canada); 0.001 (New Zealand); 0.08-0.09 according to wood type (France); 0.1 (Australia)

Table 2: Standard methods to account biogenic carbon

Standardized guidance for product-level data	Approach
PEFCR (European Commission, 2017)[1], SIA 2032 (SIA, 2020)	0/0
PAS 2050 (BSI, 2011), EN 15804+A2 ;2019 (CEN, 2019), ISO 14067 (ISO, 2018) and ISO 21930 (ISO, 2017a)	-1/+1

[1]: for cradle to grave assessments of final products with a life time of less than 100 years

According to the current version of EN 15804:2012+A2:2019 (European Committee for Standardization (CEN), 2019), which came into effect in 2019, bio-based products shall address the full life cycle (i.e. at least the modules A1-A3, C1-C4, and, strictly kept separate, module D), as required for all construction products. This standard offers particularly relevant guidance concerning GHG emission-related calculation for developing EPDs of bio-based products

- Global Warming Potential (GWP), broken down into (1) GWP - total, (2) GWP - fossil, (3) GWP – biogenic, (4) GWP - LULUC (land use and land use changes);
- The biogenic carbon content expressed as kg C (as additional information).

Figure 2 illustrates the difference between using the 0/0 method and the –1/+1 method (showing the three components of GWP separately) for the GHG emissions associated with a wood product using the example of 1 m^3 of untreated, dried sawn softwood. For the –1/+1methodology, the carbon content of the wood is calculated according to EN 16449:2014 (European Committee for Standardization (CEN), 2014), assuming a moisture content of 10%. At the end-of-life, the scenario is 75% recycling, 25% incineration, 0% landfill, which is the current Belgian situation where landfill is prohibited. The results show that the choice for the -1/+1 or 0/0 approach should, in theory, only influence the relative contribution of the individual life cycle stages to the total GHG emissions, but not the total itself (sum of modules A to C). Indeed, with the –1/+1 approach a negative contribution to $GWP_{biogenic}$ is recorded for the product stage (A1-A3), but this removal of CO_2 from the atmosphere is counterbalanced by equal emissions of biogenic CO_2 back to the natural environment at the end-of-life, resulting in a net-zero biogenic CO_2 balance over the product's life cycle.

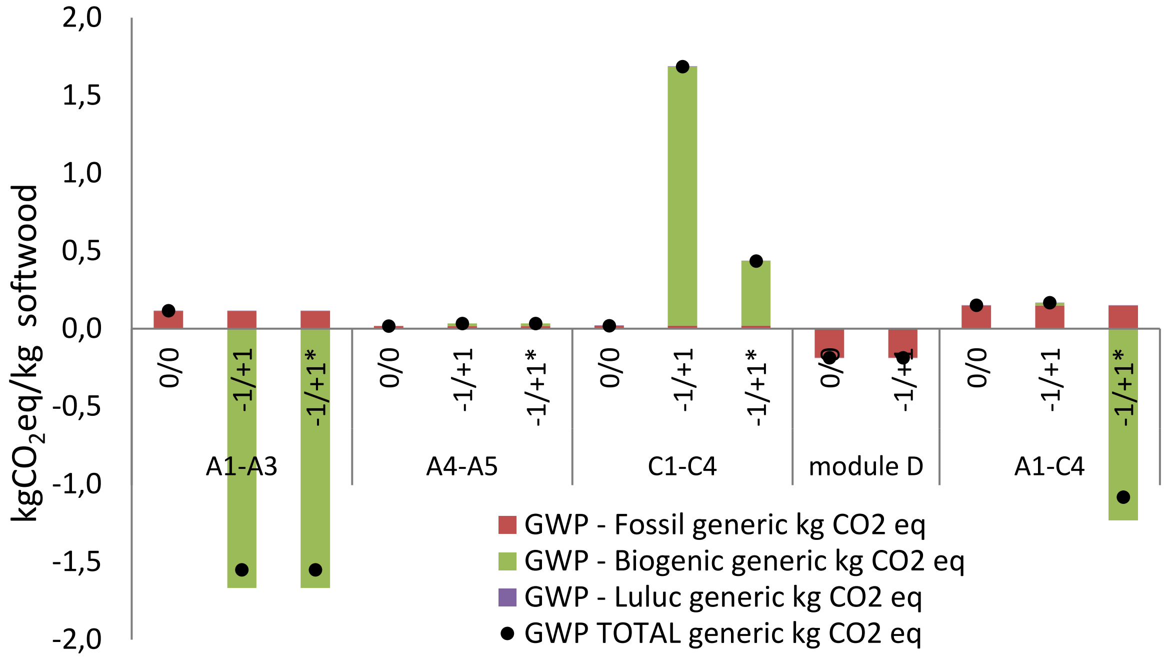


Figure 2: Life cycle GWP of 1 m^3 planed, dried (MC=10%) softwood beam (density (wet) =465 kg/m^3, carbon content 0.494 kg/kg dry wood) according to the life cycle stages using the 0/0, -1/+1 and the -1/+1*methodologies.

The above is only valid when the –1/+1 approach is based on a coherent inventory of biogenic carbon flows. In practice, one may observe both net positive and net negative balances of GWP biogenic carbon because the wood product characteristics (water content, density, carbon content) and the often-generic waste wood characteristics do not match and call for individual adjustments. Moreover, as an inherent material property, biogenic carbon content shall be allocated between co-products based on physical relationships, but it is not always done this way. Therefore, applying the –1/+1 approach on product level using generic data or cradle-to-grave EPD's usually requires a separate calculation of $GWP_{biogenic}$, based on the specific biogenic carbon content of the product, to ensure a net-zero biogenic carbon balance over the life cycle (Rasmussen et al., 2021). The -1/+1* approach may lead to very different GWP total results than the 0/0 and -1/+1 approach as it does not lead to a net zero biogenic carbon balance when the end-of-life scenario includes landfilling and/or recycling.

Finally, the contribution of the timber to GWP_{luluc} is, in this case, negligible as the timber is assumed to be from sustainably managed forests. According to EN 15804+A2 rules, the contribution to GWP_{luluc} would be substantial for wood logged from native forests as in that case no biogenic CO_2 uptake would be reported in A1-A3, and emissions from release/export of stored carbon at the end-of-life (EOL) would be reported (under GWP_{luluc} instead of $GWP_{biogenic}$).

3- Case study description and national methodologies

The object of assessment, the PAL6 multi-residential building, was constructed in 2016 in Quebec City, Canada, in the humid continental climate zone (Dfb) in the Köppen-Geiger climate classification system (Figure 3, Figure S1). The building has 59.4 m in length, 18.3 m in width, and 18.2 m in (above ground) height, comprising 6 floors of 1090 m^2 and 59 social housing units. Its lightweight wood structure is made of (in mass) 52% concrete 25 MPa, 27% wood beams (38 mm x 89 mm (locally known as 2 x 4 inches in nominal dimensions) or 38 mm x 140 mm (locally known as 2 x 6 inches)), 7.6% fire-resistant gypsum panels and 4.6% regular gypsum panels. In total, around 1500 metric tons of wood were used, with a volumetric breakdown into 1896 m^3 softwood beams, 116 m^3 softwood plywood, 102 m^3 oriented strand board panel, 32 m^3 wood fiber board, and 0.1 m^3 laminated wood flooring. The wood used came from new grown certified forest with no land use change after logging. Detailed specifications are given in Table 3.

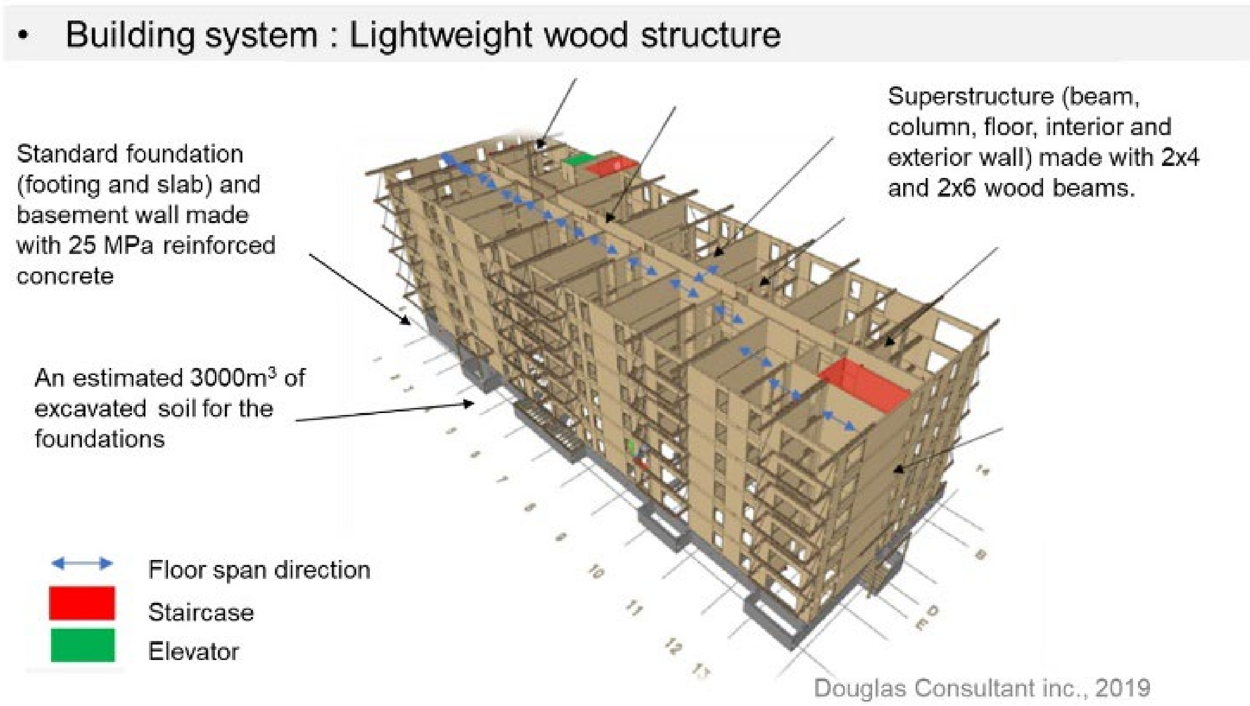


Figure 3: PAL6 multi-residential building made of a light wood frame structure

Table 3: Specification of the building PAL6

Description	Dimension of PAL6	Unit	Materialisation of PAL6
Excavation	3053	m^3	0.1m to 2.1m of backfill, 0.3m to 3.3m of sandy silt, 13.4m to 19.6m of sand and 8.4m or more of clay. Highly seismic soil
Refilling	1032	m^3	//
Foundation	1121	m^2	Concrete - 30 MPa (GU, with air), reinforcing steel (5/8", 6/8", 7/8", 8/8" and 9/8"), drawbar and shrinkage compensator
Slabs	1121	m^2	Concrete - 25 MPa (GU, without air entrained) and reinforcing steel
Roofs	1108	m^2	Base coat elastomeric bitumen membrane, gypsum panel 16 mm and type X (16-25 mm), polyisocyanurate insulation (100 mm)/ rock wool, self-adhesive vapour barrier, softwood plywood and top coat elastomeric bitumen membrane.
Pillars (pile head)	289	pieces	Concrete - 25 MPa (GU, without air entrained) and reinforcing steel
Outer walls basement	982	m^2	Concrete - 30 MPa (GU, with air) and reinforcing steel
Flooring basement	269,6	m^2	Concrete - 25 MPa (GU, without air entrained) and reinforcing steel
Stairs flooring basement	292	m^2	Concrete - 25 MPa (GU, without air entrained) and reinforcing steel
Outer walls first and upper floors	1409	m^2	Ext Wall M-2: aluminium mesh panel/aluminum cladding, gypsum panel 16-25 mm type X, metal stud, OSB panel covered with self-adhesive membrane, polyethylene vapour barrier, wood beam (2x4, 2x6)
	1082	m^2	Ext Wall M-5: gypsum panel 16-25 mm type X, hot galvanized steel plate, lightweight concrete panel, metal stud, OSB panel covered with self-adhesive membrane, perforated solar panels - 10% steel and 90% polycarbonate glazing, polyethylene vapour barrier, prefabricated lightweight concrete panel, rock wool, wood beam (2x4, 2x6)
	101	m^2	Ext Wall M-7: aluminum cladding, metal stud, self-adhesive membrane, softwood plywood
	789	m^2	Floor P-2: extruded polystyrene rigid insulation and polyethylene vapour barrier
	5417	m^2	Floor P-4: acoustic membrane, acoustic panel, gypsum panel 16-25 mm type X, polyethylene membrane, rock wool, softwood plywood, sound insulators and metal furrings soundproof drywall ceiling

	297	m^2	Floor P-5: Acoustic panel, gypsum panel 16-25 mm type X, rock wool and softwood plywood
Windows	415	m^2	PVC - U Double-glazed window
Inner separating walls	6143	m^2	Non-structural interior partition wall: gypsum panel 16 mm, metal stud, softwood plywood, and wood beam (2x4 or 2x6)
	731	m^2	Non-structural exterior partition wall: aluminium mesh panel, concrete block 190 mm, gypsum panel 16-25 mm type X, metal stud, rock wool, wood beam (2x4 or 2x6), wood fibre board
Inner bearing walls	771	m^2	Structural common partition wall: gypsum panel 16-25 mm type X, oriented strand board panel, rock wool, wood beam (2x4 or 2x6), wood fibre board
	843	m^2	Structural interior partition wall: gypsum panel 16-25 mm type X, oriented strand board panel, rock wool, wood beam (2x4 or 2x6)
	2339	m^2	Structural exterior partition wall: gypsum panel 16-25 mm type X, oriented strand board panel, rock wool, wood beam (2x4 or 2x6), wood fibre board
Inner / Outer doors	123	m^2	Exterior door and exterior sliding patio door
Flooring	4477	m^2	Ceramic flooring and laminated wood flooring
Ceiling covering	8362	m^2	Acoustic tile and gypsum panel 16 mm

This study aims at comparing the carbon footprint accounting methods from 16 countries. Details on the field of application of each method are shown in Table S1 in the supplementary information. The object of assessment, the PAL6, is the same for all applied national methods. However, each national team applied the reference study period (RSP), life cycle modules covered (according to the modular life cycle model from CEN TC 350 standards), modelling rules, the geographical scope of inventory data as well as the LCA database according to its specific national method.

The first two are presented in Table 4. RSP together with the expected service life of replaced elements (given in Table S2 in the supporting information) define the number of replacements to be accounted for under module B4. The latter is often identified as the most influencing parameter on use-stage embodied GHG emissions, as the higher the number of replacements, the larger the relative contribution of B4 is (Goulouti et al., 2020). Except for France and New Zealand, the RSPs used by different countries do not largely variate. New Zealand did the analysis with a RSP of 90 years based on (Johnstone, 1994), but it was recently changed to 50 years (Ministry of Business Innovation Employment, 2022). The building material's quantities and technical quality are predefined in the inventory and element composition, thus consistent across the different applied methods. All teams presented the results according to the same structure of building components. Austria and Norway could not assign the impacts of all modules to building components. Those impacts are summarized in "others". For Austria, these are the impacts occurring in life cycle stage A5 and for Norway the impacts in the life cycle stages A4-A5, B2-B5 and C1-C4. The stages B6/B7 were not included in the analysis and not discussed. The inclusion/exclusion of module D is here shown only for information; it is not part of the following analysis.

Table 4: Reference study period (RSP) and life cycle modules (according to CEN TC 350 standards) covered in the country's assessment (Stages B6, B7, and D were not analyzed)

Country	Code	RSP	Life cycle modules covered														
			Product stage			Use stage							EoL stage				Additional
			A1-3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Australia	AU	50	x	x	x		x		x		x			x	x	x	
Austria	AT	50	x	x	x				x		x			x	x	x	
Belgium	BE	60	x	x	x				x		x		x	x	x	x	
Brazil	BR	50	x	x	x				x		x		x	x	x	x	
Canada	CA	60	x	x	x				x		x		x	x	x	x	
Czechia	CZ	50	x						x		x						
Denmark	DK	50	x						x		x				x	x	
France	FR	100	x	x	x				x		x	x		x	x	x	x[1]
Germany	DE	50	x				x		x						x	x	x
New Zealand	NZ	90	x	x	x		x		x		x	x	x	x	x	x	x
Norway	NO	60	x						x		x						
Portugal	PT	50	x						x	x							
Spain	ES	50	x						x								
Sweden	SE	50	x	x	x		x		x		x						
Switzerland	CH	60	x						x		x		x	x	x	x	
USA	US	50	x	x	x		x		x				x	x	x	x	x

[1] For France, D is reported separately in the Annex 72 spreadsheet but subtracted from C in the tool as it is used in France.

Table 5 shows the methodological approach for accounting biogenic carbon, the software, the database, and the source of biogenic carbon of each national expert teams. Each national assessment applied the database most used in the respective national context on purpose, which brings variability in the results. This has also been shown in other similar exercises (Frischknecht et al., 2019; Frischknecht et al., 2020). While some countries have national databases (e.g. Ökobau.dat) and EPDs in place, most countries use different versions of Ecoinvent adapted to the national tools and context. Spain for example chose to keep the continuity of environmental data over time, instead of a new version of the database and they found the version of the database does not affect significantly their results. The method to account for biogenic CO_2 was either 0/0 or -1/+1, or a variation of the latter. Belgium and Switzerland will change to -1/+1, but the change is not yet made. The methods applied in Brazil,Canada, and New Zealand allow to quantify the biogenic GWP integrated in the LCA tool, while in all other countries GWP biogenic is integrated into the GWP total values. The LCA approach was attributional with a process based LCA database approach in all cases. The scope covers the construction, use-stage embodied GHG emissions, not the operational emissions, and end of life of the PAL6 residential building in a national-specific methodological setting. The software SimaPro was the most often used software for the calculation and many countries had their own tool.

Table 5: Method for biogenic carbon, software and database used, as well as the possibility of showing GWP biogenic values (separately from GWP total values.

Country code	LCA method			Software	Database	Carbon content source	Is GWP biogenic separately given?
	0/0	-1/+1	-1/+1*				
AU			x*	SimaPro 9.0.0.41	AusLCI database (2016)	AusLCI database in SimaPro and EPDs Australasia	Yes
AT	x			SimaPro 9.1.0.8	Ecoinvent v3.5	n/a	No
BE	x			SimaPro 8.5.0	Ecoinvent v3.6	n/a	No
BR	x			SimaPro 9.0	Ecoinvent v3.4, 3.5, 3.6	n/a	No
CA			x*	Simapro 9.1.0.8	Ecoinvent v3.4	Ecoinvent	Yes
CZ	x			Excel-based tool/calculation	Ecoinvent v3.3	n/a	No

DK		x		LCAbyg 3.2	Ökobaudat v2016	EN 16449:2014	No
FR			x*,**	EQUER	Ecoinvent v3.4	Ecoinvent	No
DE		x		LEGEP 2018	Ökobaudat v2018	EN 16449:2014	No
PT	x			SimaPro 8.4.0	LCIA database for Portuguese Building Elements and Materials	EN 16449:2014	No
ES	x			Excel-based tool/calculation	Ecoinvent v2.0	n/a	No
SE	x			Byggsektorns Miljöberäkningsverktyg (BM), (Swedish Building Sector Environmental Calculation Tool)	Database embedded in Swedish Building Sector Environmental Calculation Tool (BM)	n/a	No
NZ			x*	LCAQuick 3.4.2	EPDs + Ecoinvent v3.1	EPDs Australasia	GWP total (biogenic carbon can be derived)
NO		x		ZEB tool	Norwegian EPDs + Ecoinvent 3.1	EN 16449:2014	Yes
CH	x			Excel-based tool/calculation	KBOB LCA data DQRv2:2016	n/a	No
USA	x			Athena IE v5.4	GaBi v9.2	n/a	No

* Wood sent to recycling and landfill gets a value ">0" but <<1".
** Differentiation between certified (-1) and non-certified (0) forests

In the European standard EN 15804:2012+A2:2019, the +1 shall also apply on recycling and landfill of wood. However, in Canada, France, New Zealand and Australia wood sent to landfill gets a factor close to zero. Wood that exits the system boundary e.g. for reuse, recycling gets a

“+1” in NZ, and then the potential benefit of its reuse, recycling is calculated in module D. In the French EQUER method (Table 6), negative biogenic CO_2 emissions are accounted for in the production stage if a new tree is growing which is the case for wood from certified forests. But if the wood stems from non-certified forests, the same amount of carbon is stored in the building as if it were stored in the forest. Therefore, no carbon fixation is considered (“0” instead of “-1”). At the end of life, the quantity of biogenic CO_2 is emitted if the wood is incinerated, but not if the wood is landfilled or recycled (see Table 6). See electronic materials for more details on the approaches.

Table 6: Biogenic carbon accounting according to the French Equer method

End of life -> Production	Incineration	Landfill, recycling or reuse
Sustainable forest management (a new tree is growing)	-1 / +1	-1 / >0
Other case (non-certified forest)	0 / +1	0 / >0

Table 7 shows the share of wood recycled, incinerated and landfilled in the end-of-life scenarios of the countries participating to the case study as well as whether or not biogenic carbon in wood landfilled is considered (partly) permanently sequestered. This information is important for the module C end of life assessment. Landfilling of wood is not allowed in certain countries due to the reactive nature of organic materials, leading to leachate and methane which require additional treatment . In Canada, the given proportion of wood recycled and landfilled is based on the practice and not the legal requirement (Audet, 2020). The transformation of landfilled wood into methane is not assessed in every country, for precaution, many countries prefer forbidding to landfill organic materials including wood. Australia, New Zealand, and USA have experimental data to support the landfilling of wood (Wang et al., 2011; Ximenes et al., 2019).

Table 7: Shares of solid wood recycled, incinerated, landfilled in the countries' assessments for module C assessment (n/a means not available because end-of-life is not considered in the national methods)

	Wood recycled %	Wood incinerated %	Wood landfilled %	Permanent sequestration in landfill assumed Yes/No
AU	40	5	55	Yes
AT	75	25		No
BE	75	25		No
BR		100		No
CA	60		40	Yes
CZ	n/a	n/a	n/a	n/a
DK		100		No
FR		100		Yes (see Table 1)
DE		100		No
ES	10	80	10	Yes
NO		100		No
PT	n/a	n/a	n/a	n/a
NZ	15	10	75	Yes
SE		100		No
CH	50	50		No
US	n/a	n/a	n/a	n/a

4- Results and Discussion

4.1 Assessment on life cycle stages of the superstructure

The choice of the approach (0/0, -1/+1, -1/+1*) has a greater impact on the variability of the results of the wooden superstructure, especially at the module A and C stages, than the choice of the database and software. Results of greenhouse gas emissions calculated with both 0/0, -1/+1, and -1/+1* approach for the superstructure according to life cycle stages are presented in Figure 4. The greenhouse gas emissions calculated with a 0/0 approach are, an average of 1.77

$kgCO_2eq/m^2a$ with variation between 1.41 $kgCO_2eq/m^2a$ for Portugal to 2.44 $kgCO_2eq/m^2a$ for Czech Republic. The average of greenhouse gas emissions calculated with -1/+1 equals to 3.75 kg CO_2eq/m^2a with a variation between 2.23 $kgCO_2eq/m^2a$ for Denmark to 6.43 $kgCO_2eq/m^2a$ for Spain. With the -1/+1* method, the greenhouse gas emissions averaged 1.05 $kgCO_2eq/m^2a$ with a variation from -0.41 $kgCO_2eq/m^2a$ for New Zealand to 3.11 $kgCO_2eq/m^2a$ for Australia.

A more in-depth analysis of the greenhouse gas emissions of building life cycle stages highlights large differences in the results of the modules A1-A3 and C1-C4. Comparisons of the greenhouse gas emissions for the stages A1-A3 and C1 to C4 highlight the main difference between the three approaches. The emissions calculated for A1-A3 with the -1/+1 and -1/+1* approaches are (partly) offset by emissions in the modules C1-C4. It deserves to be highlighted that the quantities of biogenic carbon uptake and release may differ due to non-matching biogenic carbon mass balances. For France and New Zealand, the longer service life of 100 years and 90 years, respectively, has the effect of making the results for these countries in Figure 4, expressed per m^2a, smaller, in comparison with most countries that use a 50 year or 60 years' service life.

The assessment of the superstructure made of light frame wood construction highlights the influence of the end-of-life scenarios of the wood products and the choice of the methodology for the biogenic carbon accounting on the GHG emission results. The assessments of countries with a -1/+1* and a landfilling scenario approach report less GHG than those applying the 0/0 and -1/+1 method. New Zealand also shows a net fixation of carbon in the superstructure (Figure 4) because a large share of the wood is landfilled and because it assumes permanent carbon sequestration. Table 5 shows that 75% of wood is landfilled in New Zealand, 55% in Australia and 40% in Canada. The interpretation of landfills as a permanent or temporary sequestration varies among the participating countries. In Canada, it is interpreted as permanent sequestration. In Australasia, two values of degradable organic carbon fraction (DOCf) for softwood timber are allowed: NZ applied the lower value of 0.1% while AU applied the higher value of 10% (Australian Government, 2016; Wood Solutions, 2020), which results in 99.9% and 90 % assumed permanent sequestration in NZ and AU, respectively. The implications of this 100-fold difference is described in section 4.4.

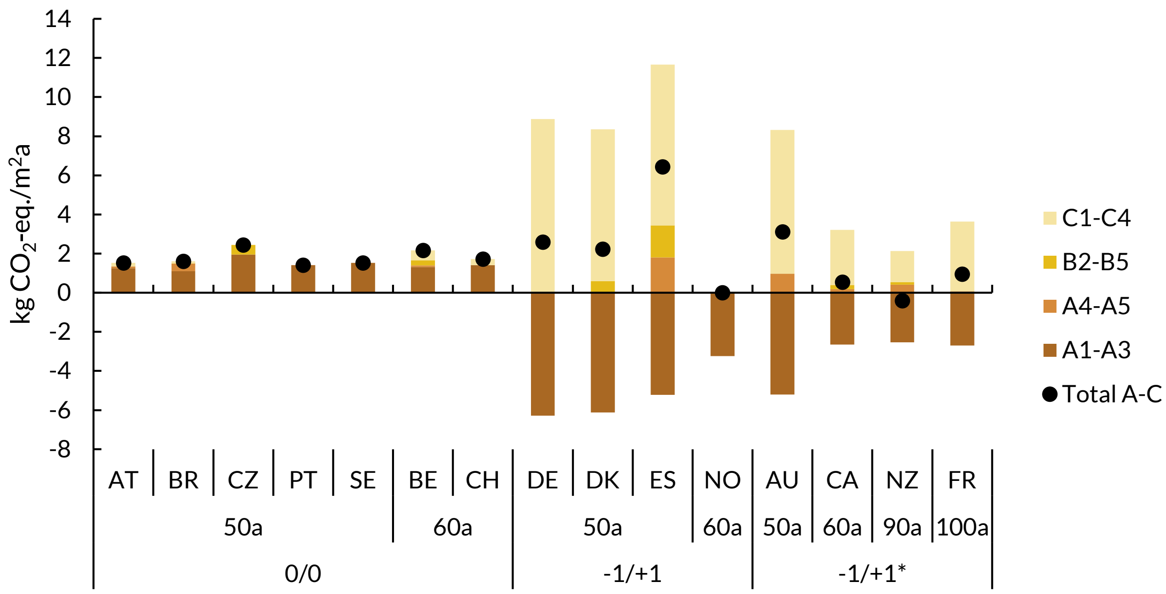


Figure 4: Greenhouse gas emissions of the superstructure of the PAL 6 building assessed

4.2 Total building and its building components

The analyses of the whole building show variations in the results (Figure 5) and there is less variability among the approaches. In the 0/0 approach, the greenhouse gas emissions per square meter per year have a mean value of 5.96 $kgCO_2eq/m^2a$ for the total A-C, with the national methods of BR and PT that have obtained the highest and lowest results with 10.3 $kgCO_2eq/m^2a$ and 3.99 $kgCO_2eq/m^2a$, respectively. In the case of the + 1/-1 approach, the values obtained had a means of 7.17 $kgCO_2eq/m^2a$, with the national methods of ES and NO that have obtained the highest and lowest results, with 12.9 and 4.80 $kgCO_2eq/m^2a$ respectively. In the 0/0 and the -1/+1 approach, the data in the LCA model create variability in the results. With the -1/+1* approaches, the total A-C impact averaged 4.35 $kgCO_2eq/m^2a$ with a high value of 8.86 $kgCO_2eq/m^2a$ for Australia and 1.87 $kgCO_2eq/m^2a$ for New Zealand. Within the four -1/+1* assessments (AU, CA, FR, NZ), the difference in the share of wood being incinerated at end-of-life and the mismatch in carbon contents of wood products and its corresponding end of life treatment datasets are the main reasons for the large variability in greenhouse gas emissions.

In most assessments, the superstructure contributes most to the specific greenhouse gas emissions. The foundations and the interior construction are significant construction systems in terms of greenhouse gas emissions and present similar values and deviations in both methods. The impacts of these building components also vary among countries. The foundations represent a mean value of 0.97 $kgCO_2eq/m^2a$, AU and FR have the highest and lowest values, with 1.7 $kgCO_2eq/m^2a$ and 0.42 $kgCO_2eq/m^2a$ respectively. The internal construction represents a mean value of 0.91 $kgCO_2eq/m^2a$, ES and NO have the highest and lowest values, with 2.4 $kgCO_2eq/m^2a$ and -0.23 $kgCO_2eq/m^2a$ respectively. NO and NZ are the only countries that obtain negative values in some building components. Norway divided the life cycle stages A1-A3 into the building elements, while the impacts of the other life cycle stages are summarized as "others".

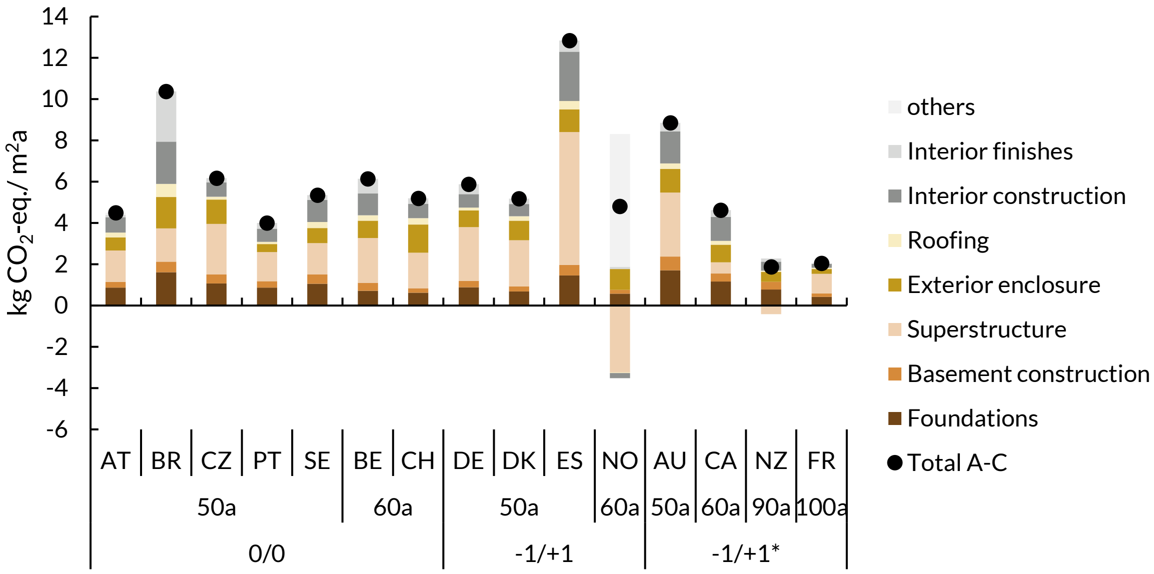


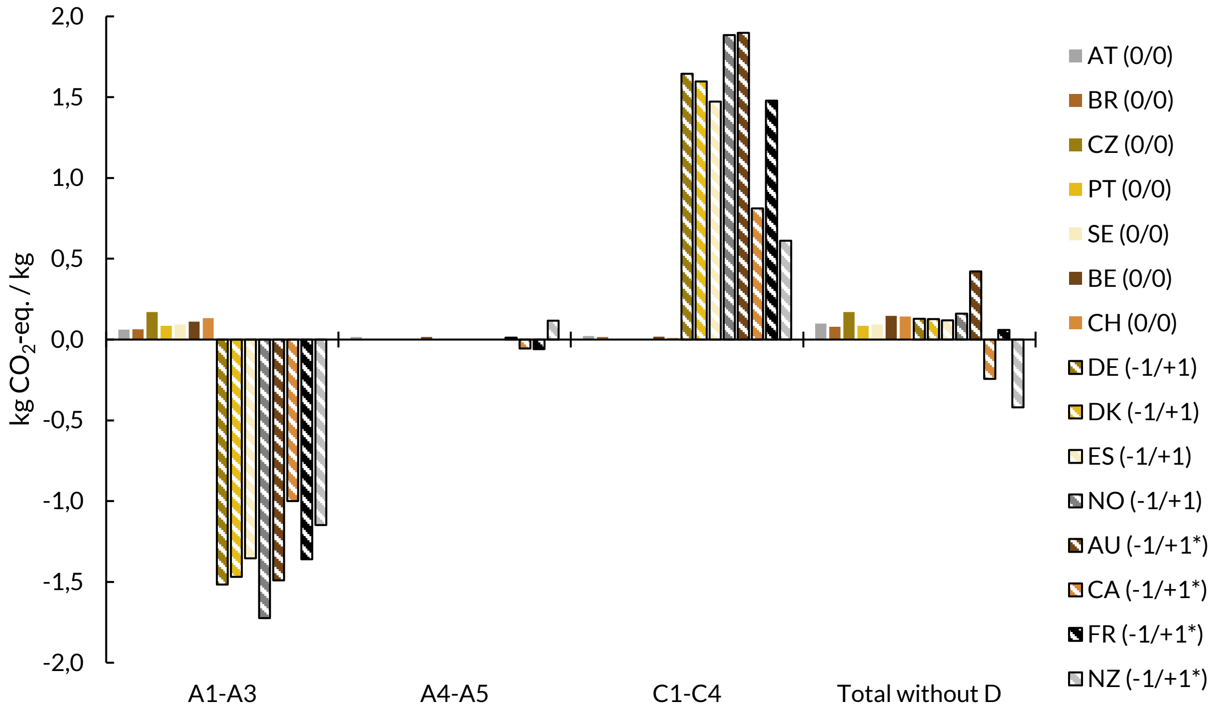
Figure 5: Multi-residential building assessment of greenhouse gas emissions, grouped according to the biogenic carbon modeling approach and the service life (Modules A-C included, B6 excluded; Norway divided the life cycle stages A1-A3 into the elements, while the impacts of the other life cycle stages are summarized as "others").

4.3 Wood products

The analysis of the wood products shows major differences in module A and C between the countries due to the approach to assess biogenic carbon. Figure 6a shows the life cycle greenhouse gas emissions associated with 1 kg of solid wood, as reported from the different assessments based on specific data sources. In total, 1896 m^3 softwood is used in the PAL6 building. The cradle-to-gate results (modules A1-A3) from the 0/0 approach vary by up to a factor of 2.8, whereas the results from the -1/+1 approach vary by a factor of 1.3, and a factor of 1.5 with the -1/+1* approach. With the 0/0 approach, the highest and lowest total impacts without D are for Czech Republic and Brazil having impacts of 0.17 and 0.08 kg CO_2eq/kg softwood, respectively. With the -1/+1 method, the highest and lowest impacts are for Norway and Spain having impacts of 0.16 and 0.12 kg CO_2eq/kg softwood, respectively. With the -1/+1* method, the highest and lowest impacts are for Australia and New Zealand having impacts of 0.42 and -0.42 kg CO_2eq/kg softwood, respectively.

Negative results in A4-A5 reported from the Canadian and France cases relate to the assumption that 5% of the needed material is wasted. Production of this wood surplus, which leads to additional carbon fixation, is accounted for in A5. The value remains very small. Further, the waste is modelled as landfilled, assuming some permanent sequestration of biogenic CO_2, resulting in an overall negative balance of biogenic CO_2. In modules C1-C4, the biogenic carbon contained in wood products is modelled as a release of biogenic CO_2 in the -1/+1 approach. The release balances the biogenic CO_2 uptake modelled in the production modules, as seen in the figures for 'total without D'. In the -1/+1* approach, both the Canadian and the New Zealand modeled the end-of-life route of wood as being landfilled (40 % and 75 %, respectively). They consider also limited decomposition rates of wood in landfills (NZ: 0.1%, CA: 0 %), thereby resulting in an overall negative value of biogenic CO_2 emissions and biogenic greenhouse gas emissions for the total life cycle. Module D is only addressed in four of the national approaches reported in this study.

Figure 6b shows the plots of minimum and maximum values from the current assessments into the schematic overview of balanced approaches first introduced in Figure 2. Figure 6b shows that several assessment values are distributed around the balanced numbers (dots in black color, see also Section 2), the minimum (blue dot) and maximum values (orange dot). However, specifically for the -1/+1* approach, the reported values are unevenly distributed due to the methodological specifications concerning landfills and (partly) permanent sequestration as detailed in section 4.1 and Table S1, as well as service life.



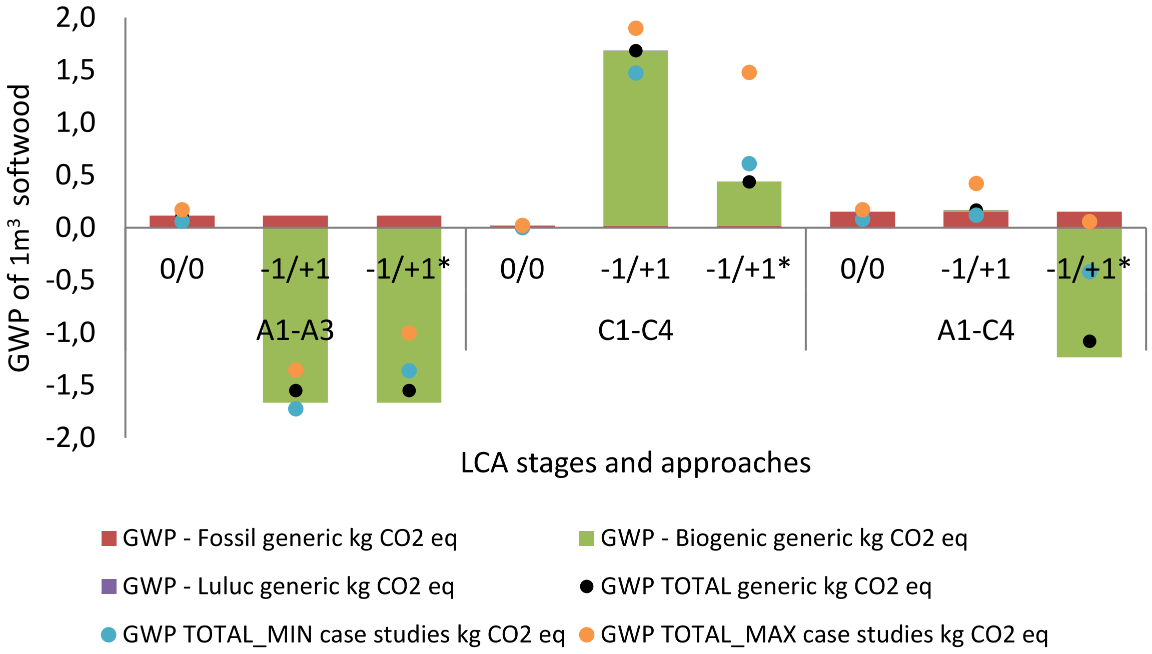


Figure 6: a) Greenhouse gas emissions in kg CO_2-eq per kg solid softwood as assessed by the different countries and grouped according to the 0/0 and -1/+1 approaches, b) GWP of 1 m^3 planed, dried (MC=20%) softwood beam (density (wet) = 465 kg/m^3, carbon content 0.494 kg/kg dry wood) (The modules A4-A5 and D are intentionally removed for clarity).

Figure 7 shows the life cycle greenhouse gas emissions associated with 1 kg of plywood, as reported from the different assessments. In the case of plywood, the countries with the 0/0 approach reported higher greenhouse gas emissions than the countries with the -1/+1 approach and -1/+1*; their results are also more variable. The total reported greenhouse gas emissions (without module D) are notably higher for the plywood than for softwood, with an average of 0.71, 0.45, 0.40 kg CO_2eq/kg for the 0/0, -1/+1, -1/+1* approaches respectively. This difference reflects the additional manufacturing processes and fossil sourced raw materials associated with the production of plywood compared to sawn wood. With the 0/0 approach, the highest and lowest impacts are noted for Switzerland and Sweden at 1.17 and 0.20 kg CO_2eq/kg plywood, respectively. With the -1/+1 approach, the highest and lowest impacts are for Norway and Spain at 0.77 and 0.24 kg CO_2eq/kg plywood, respectively, especially due to the transportation distance and the energy use in the processes. With the 1/+1* approach, the highest and lowest impacts are for Australia and New Zealand at 1,0 and -0.15 kg CO_2eq/kg plywood, respectively. Only New Zealand reports net-negative emissions for the total greenhouse gas emissions (without module D), arising from landfill emissions based on a DOCf value of 1.4% reported in the Australasia EPD for plywood (Wood Solutions, 2017). If landfills were not considered as a permanent carbon sequestration or if the wood was incinerated, there would be net greenhouse gas emissions, like in Australia and France, for example.

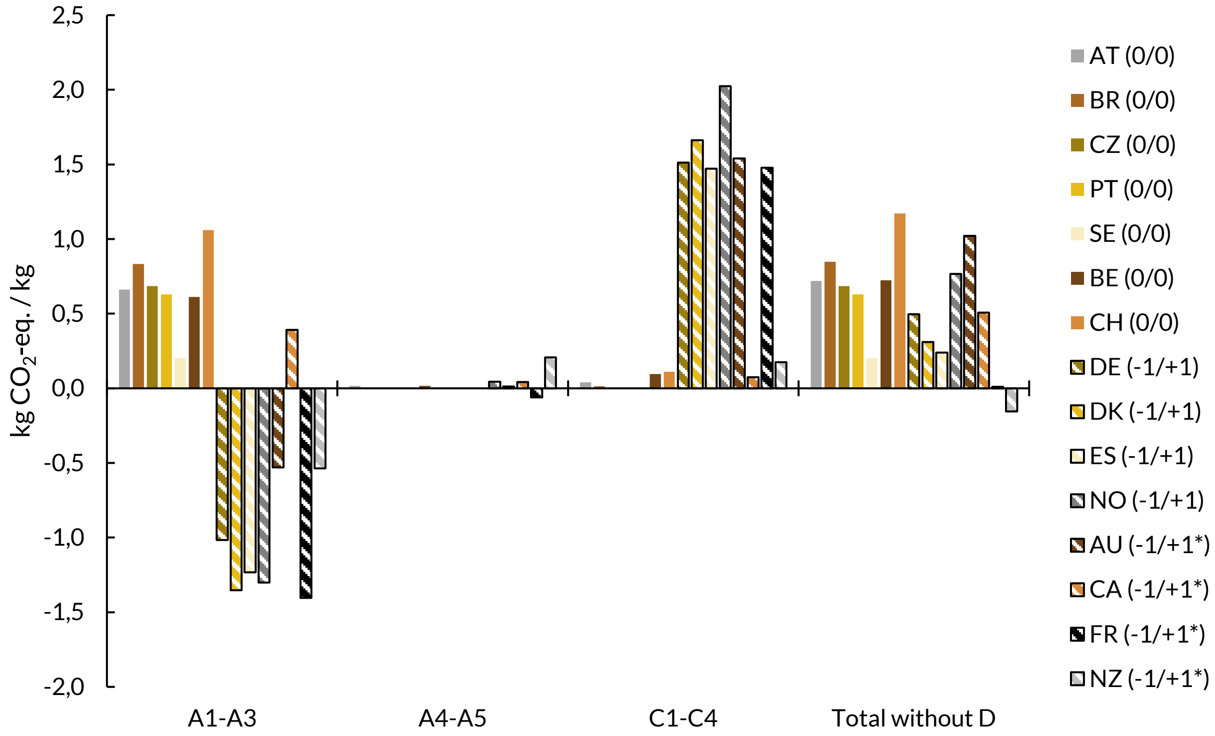


Figure 7. Greenhouse gas emissions in kg CO2-eq per kg plywood as assessed in the different countries and grouped according to the 0/0 and -1/+1 approaches (The modules A4-A5 and D are intentionally removed for clarity).

4.4 Discussion on biogenic carbon modelling

4.4.1 Different perception of biogenic carbon sequestration in traditional landfill sites

The assessment of the wood-frame superstructure clearly shows a difference between the three approaches (0/0, 1/+1, 1/+1*). In the 1/+1 and 1/+1* approaches, there is significant uptake of biogenic CO_2 in the raw wood material extraction and manufacture of building materials (A1-A3 stages). At the same time, there is a lot of release of biogenic CO_2 at the end of life (C1-C4 stage). Canada and New Zealand, both countries with a -1/1* approach, have a net negative biogenic CO_2 balance because they consider biogenic carbon of not decomposed wood in landfills as permanently sequestered. Other countries using the -1/+1 approach may well have shares of landfilled biogenic carbon, but do not consider it as permanently sequestered. In some countries, like Denmark and Switzerland, landfilling of wood is not an option. Negative emission technologies are needed for long-term carbon sequestration. The comparison between New Zealand and Australia shows the impact of applying two different DOCf scenarios in landfilling, because the share of biogenic carbon released at end-of-life by incineration and degraded carbon in landfills is nearly the same (AU: 10.5%, NZ: 10.1%). Both countries use the same EPD datasets, which supply two different DOCf values for landfilled softwood timber: one option is a DOCf value of 10% estimated from Australia's National Greenhouse Accounts (Australian Government 2016), and the other option is a DOCf value of 0.1% based on the bioreactor laboratory research on Australian Radiata Pine (Wang et al., 2011). The results from Australia are based on a 50-year-building service life and 55% wood landfilling (using the 10% DOCf value), while those from New Zealand are based on a 90-year service life and 75% wood landfilling with permanent carbon sequestration (0.1% DOCf value). It should be noted that extensive research in Australia over many years involving both bioreactor laboratory research and actual landfill studies of several softwood timber species and various types of engineered wood products (Ximenes et al., 2019) have largely supported the earlier results of (Wang et al., 2011). Summing up numerous studies and accounting for uncertainties, Ximenes at al. (2019) recommended a 1.4% carbon loss for wood in landfills in Australia and noted that "disposal of wood in landfills in Australia results in long-term storage of carbon, with only minimal conversion of carbon to gaseous end products".

Regarding the total building assessment, at first glance, one would think that the choice of the modelling approach of biogenic carbon flows would not show a significant variation in the total results. The 0/0 assessment results are less variable than those with the +1/-1 approach. Only the Spanish assessment shows considerably more GHG than the country's assessments based on the 0/0 approach, which is mainly due to longer transportation distances of wood products from factories in northern Europe to the site as well as the energy consumed during the assembly process and building disassembly; the "Kellenberger" method implies a scenario of very high energy consumption in comparison with the scenario considered by the rest of the countries. The lowest impacts were observed in the -1/+1* approach applied in New Zealand. When comparing the results of the softwood timber in Figure 6b to the theoretical case presented in Figure 2, there is more variation in the 1/+1* approachas the results are strongly influenced by the end-of-life scenario. Canada and New Zealand are the two countries with an overall "removal" of biogenic CO_2 because a relevant share of the wood is assumed to be landfilled and that the carbon contained in landfilled not decomposed wood is permanently sequestered (assumed in Canada's case and based on bioreactor laboratory studies in NZ's case). Like in the case of softwood, the plywood results show different trends in the module contributions depending on the method. When landfill is considered to offer permanent carbon sequestration, the net biogenic CO_2 balance may be negative when considering the -1/+1* approach.

4.4.2 Harmonisation needs

The comparative assessment of a multi-residential wooden building from the method applied in 16 countries shows a large potential for harmonization of the LCA methods. The full life cycle approach is needed to assess the impact of wood products, in particular and as a minimum stages A1-A3, B4 and corresponding C1-C4, if the -1/+1 and -1/+1* approaches are applied. The mass balance of biogenic carbon must be checked: the amount of biogenic CO_2 fixed (withdrawn) in wood material manufacture must match with the amount of biogenic CO_2 released (-1/+1 approach) and/or considered fixated (-1/+1* approach) in the EOL treatment of those materials. The main difference between the assessments was due to different interpretations of the potential effect of landfilling and recycling wood. The LCA must specify if landfilled biogenic carbon is considered permanently sequestered and what timeframe is applied.

If we consider the published evidence on DOCf value for wood products based on laboratory-scale reactor studies under ideal conditions and/or actual landfill field assessment under uncertainties (Wang et al., 2011; Ximenes et al., 2019), then the implication for standards harmonization is that the -1/+1* method is the more general case and the -1/+1 method is a specific case of the former. The method applied in a country or jurisdiction will depend on product EOL industry practice and whether relevant DOCf value is known, or just assumed.

Awareness of the implication of the share of the end-of-life scenarios, as presented in Table 5, can better position the wood industry in the circular economy and product stewardship. Applying the +1 on recycling is because of the precautionary principle. Recycling or reusing wood at EOL prolongs the fixation of biogenic carbon in the wood. As per the -1/+1 approach described by EN 15804+A2, wood recycled at the EOL is reported as an emission (export) of biogenic CO_2. The -1 is passed to the next life cycle in which recycled wood is being used. Similarly, the forest gets a +1 when a tree is cut, and the carbon is transferred to the building. For as long as the wood products are in service in a building, they lock biogenic carbon in, and buildings therefore function as carbon storage facilities. This temporary 'lock in' period buys time for developing negative emission technologies applied at EOL to separate, capture, and permanently sequester biogenic CO_2.

The questions that must still be resolved are concerning the permanent carbon sequestration at the EOL of wood products and during wood regrowth, methane production in landfills, and the next reuse cycle in the circular economy. Currently, the most accepted method, 0/0 is not modelling temporary carbon fixation in buildings nor assuming permanent carbon sequestration in construction landfill sites. The -1/+1 model temporary carbon fixation when building with wood and other bio-based products. Regrowing a tree (i.e. the products resulting from it) will serve future life cycles, i.e. the life cycles of future products made from regrowing trees. The level and extent of permanent sequestration of biogenic carbon in landfills depend on the wood chemical composition, the physical and chemical conditions in the landfill, the time frame considered and the methane production (Wang et al., 2011; Ximenes et al., 2019). These previous studies show clear evidence of long-term carbon sequestration in landfill and more studies in other parts of the word are needed to ensure a global understanding and a harmonised methodology. A joint effort of governments and the wood-industry can provide guidance on the EOL. The temporality of carbon emission and fixation during the initial growth and the regrowth and its appropriate modelling and assessment in buildings' LCA are still open to discussion and to long-term experimental studies on carbon sequestration, as they happen during more than one generation. One of the challenges is to develop assessment methods that can be passed on over generations.

5. Conclusions and outlook

The assessment of the same multi-residential wooden frame building in 16 countries using the national methods shows that the approaches 0/0, -1/+1, and -1/+1* are currently being used to consider biogenic carbon accounting. The choice of the approach has the most impact of the variability of the results. The 0/0 method considers neither removal nor releases of biogenic carbon. The –1/+1 method considers biogenic carbon fixation in the production stage and its release in the end-of-life irrespective of the end-of-life treatment. The mismatch of the biogenic carbon balance is a major source of variability in this method and of deviation to the results based on the 0/0 approach. The -1/+1* approach considers a variable treatment of permanence of biogenic carbon sequestration at the EOL in landfill sites and continuing biogenic carbon fixation in the case of recycling (thus not passing the -1 to the next life cycle of recycled wood). The version of database did not affect the final results as much as the choice of the approach.

From the study, we recognize the challenges of doing a comparative study from different countries most prevailing national methods. Different shares of the end of life waste incineration of wood and wood-based products are a major source of variability. Within the same method, the other causes of variation are the assumed reference service life of the building and the source of data. The main difference between the methods is in the treatment of biogenic carbon fixation in landfilled timber products. Experimental studies show evidence of long-term carbon sequestration in landfills and more studies are needed in other parts of the world to obtain nationally relevant data on carbon loss rate. The appropriate measures to improve the biogenic carbon accounting in LCA methodology are still open for discussions.

This comparative case study shows different perspectives on biogenic carbon consideration in life cycle assessment. Different options are currently followed in the assessment and it can influence the outcome of a study and the decisions and actions of some stakeholders. The LCA analysts must be well trained to ensure correct biogenic carbon balances. Permanent sequestration of biogenic carbon at the end of life will result in a net negative balance of biogenic CO_2. Extensive experimental studies in Australia over many years and more limited studies in the US essentially confirm that wood in landfills result in long-term sequestration of carbon, with only minimal conversion of carbon to gaseous end products, but additional studies in other parts of the world with differing conditions and landfilling practice are needed. Finally, buildings can serve as a carbon fixation facility. The assumed building service life of typically

50 years and more gives us time to develop and install negative emission technologies applied in the end-of-life stage to permanently sequester biogenic CO_2.

6. Acknowledgements

This publication has received funding from Swiss Federal Office of Energy (grant number SI/501549-01); the European Union's Interreg 2 Seas 2014-2020 Programme under grant number 2S05-036 CBCI; the French Agency for Ecological Transition (ADEME); in Germany, from Project Management Organisation Jülich (Projektträger Jülich: PtJ) and the German Federal Ministry for Economic Affairs and Energy (Bundesministerium für Wirtschaft und Energie: BMWi) (grant number 03ET1550A) and in Austrian by the Austrian Ministry for Transport, Innovation and Technology (BMVIT) via IEA Research Cooperation via the Austrian Research Promotion Agency (FFG) Grant #864142. Czech Ministry of Education, Youth and Sports within and within project Interexcellence No. LTT19022. The LCA analysts Adeline Beaudoin and Julie-Anne Chayer from Canada, Holger König from Germany supported the respective country representatives with modelling, calculations and assessments.

7. References

Andersen, C.E., Rasmussen, F.N., Habert, G., Birgisdóttir, H., 2021. Embodied GHG Emissions of Wooden Buildings—Challenges of Biogenic Carbon Accounting in Current LCA Methods. Frontiers in Built Environment 7(120).

Association for the Conservation of Energy, 2013. Financing energy efficiency in buildings: an international review of best practice and innovation. p. 97.

Audet, M., 2020. Cadre méthodologique pour le développement d'un outil d'aide à la prise de décision appliqué à l'optimisation du système de gestion des résidus de CRD au Québec. Ecole Polytechnique, Montreal (Canada).

Australian Government, 2016. National Greenhouse Accounts Factors – August 2016. Department of Environment, Canberra, ACT, Australia.

Bataille, C., 2020. Low and zero emissions in the steel and cement industries: Barriers, technologies and policies.

Birgisdottir, H., Moncaster, A., Wiberg, A.H., Chae, C., Yokoyama, K., Balouktsi, M., Seo, S., Oka, T., Lützkendorf, T., Malmqvist, T., 2017. IEA EBC annex 57 'evaluation of embodied energy and CO2eq for building construction'. Energy and Buildings 154, 72-80.

Brunner, C., 2022. Climate effect of temporarily stored CO2 within building materials, in: Association, L.F. (Ed.) 80. LCA Forum. ETH Zürich, Zürich, Switzerland.

BSI, 2011. PAS 2050 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. BSI, United Kingdom.

Cerame Unie, 2012. The Ceramic Industry Roadmap: paving the way to 2050.

Chen, Z., Gu, H., Bergman, R.D., Liang, S., 2020. Comparative Life-Cycle Assessment of a High-Rise Mass Timber Building with an Equivalent Reinforced Concrete Alternative Using the Athena Impact Estimator for Buildings. Sustainability 12(11), 4708.

Churkina, G., Organschi, A., Reyer, C.P.O., Ruff, A., Vinke, K., Liu, Z., Reck, B.K., Graedel, T.E., Schellnhuber, H.J., 2020. Buildings as a global carbon sink. Nature Sustainability 3(4), 269-276.

City of Munich, 2013. Münchner Förderprogramm Energie-Einsparung.

Crucke, J.L., Bue, V.D., 2019. Arrêté ministériel portant exécution de l'arrêté du Gouvernement wallon du 4 avril 2019 instaurant un régime de primes pour la réalisation d'un audit, de ses rapports de suivi des travaux et des investissements économiseurs d'énergie et de rénovation d'un logemen, in: Wallonie, S.p.d. (Ed.). Namur, Belgium

Eurofer, 2019. Low carbon roadmap: Pathways to a CO2-neutral European steel industry.
European Commission, 2017. PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3. p. 238.
European Committee for Standardization (CEN), 2014. EN 16449:2014 Wood and wood-based products. Calculation of the biogenic carbon content of wood and conversion to carbon dioxide.
European Committee for Standardization (CEN), 2019. EN 15804:2012+A2:2019, Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products.
Foliente, G.C., 2000. Developments in performance-based building codes and standards. Forest Products Journal 50(7/8), 12.
Food and Agriculture Organization (FAO), 2020. Status of public policies encouraging wood use in construction– an overview. Draft Background Paper prepared for the 61st Session of the FAO Advisory Committee on Sustainable Forest-based Industries.
Francart, N., Larsson, M., Malmqvist, T., Erlandsson, M., Florell, J., 2019. Requirements set by Swedish municipalities to promote construction with low climate change impact, Journal of Cleaner Production. pp. 117-131.
Frischknecht, R., Birgisdottir, H., Chae, C.U., Lützkendorf, T., Passer, A., Alsema, E., Balouktsi, M., Berg, B., Dowdell, D., García Martínez, A., Habert, G., Hollberg, A., König, H., Lasvaux, S., Llatas, C., Nygaard Rasmussen, F., Peuportier, B., Ramseier, L., Röck, M., Soust Verdaguer, B., Szalay, Z., Bohne, R.A., Bragança, L., Cellura, M., Chau, C.K., Dixit, M., Francart, N., Gomes, V., Huang, L., Longo, S., Lupíšek, A., Martel, J., Mateus, R., Ouellet-Plamondon, C., Pomponi, F., Ryklová, P., Trigaux, D., Yang, W., 2019. Comparison of the environmental assessment of an identical office building with national methods. IOP Conference Series: Earth and Environmental Science 323(1), 012037.
Frischknecht, R., Ramseier, L., Yang, W., Birgisdottir, H., Chae, C.U., Lützkendorf, T., Passer, A., Balouktsi, M., Berg, B., Bragança, L., Butler, J., Cellura, M., Dixit, M., Dowdell, D., Francart, N., García Martínez, A., Gomes, V., Gomes Da Silva, M., Guimaraes, G., Hoxha, E., Wiik, M.K., König, H., Llatas, C., Longo, S., Lupíšek, A., Martel, J., Mateus, R., Rasmussen, F.N., Ouellet-Plamondon, C., Peuportier, B., Pomponi, F., Pulgrossi, L., Röck, M., Satola, D., Verdaguer, B.S., Szalay, Z., Nhu, A.T., Veselka, J., Volf, M., Zara, O., 2020. Comparison of the greenhouse gas emissions of a high-rise residential building assessed with different national LCA approaches – IEA EBC Annex 72. IOP Conference Series: Earth and Environmental Science 588(2), 022029.
Goodland, H., 2016. Promoting sustainable building materials and the implications on the use of wood in buildings: a review of leading public policies in Europe and North America. UNECE/FAO.
Goulouti, K., Padey, P., Galimshina, A., Habert, G., Lasvaux, S., 2020. Uncertainty of building elements' service lives in building LCA & LCC: What matters? Building and Environment 183, 106904.
Government of Canada, 2019. Low-carbon assets through life cycle assessment initiative. https://nrc.canada.ca/en/research-development/research-collaboration/programs/low-carbon-assets-through-life-cycle-assessment-initiative.
Government of Spain, 2021. Ley de cambio Climático y Transición Ecológica de España.
Green, M.C., Karsh, J.E., 2012. The case for tall wood buildings: how mass timber offers a safe, economical, and environmentally friendly alternative for tall building structures. MgbARCHITECTURE+ DESIGN.
Habert, G., Miller, S.A., John, V.M., Provis, J.L., Favier, A., Horvath, A., Scrivener, K.L., 2020. Environmental impacts and decarbonization strategies in the cement and concrete industries. Nature Reviews Earth & Environment 1(11), 559-573.

Harte, A.M., 2017. Mass timber – the emergence of a modern construction material. Journal of Structural Integrity and Maintenance 2(3), 121-132.
Hens, H.S., 2016. Applied building physics: ambient conditions, building performance and material properties. John Wiley & Sons.
HERA, 2017. Sustainability in steel. Is there such a thing when it comes to climate change? www.hera.org.nz/sustainable-steel-climate/.
Himes, A., Busby, G., 2020. Wood buildings as a climate solution. Developments in the Built Environment 4, 100030.
Hoxha, E., Passer, A., Saade, M.R.M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., Habert, G., 2020. Biogenic carbon in buildings: a critical overview of LCA methods. Buildings and Cities 1(1), 504-524.
IPCC, 2018. Global warming of 1.5°C. *An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and*

related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,

sustainable development, and efforts to eradicate poverty, in: Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla,, A. Pirani, W.M.-O., C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock,, M. Tignor, T.W. (Eds.). p. 630.
IPCC, 2021. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, in: Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L., Goldfarb, M.I.G., M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield,, O. Yelekçi, R.Y.a.B.Z. (Eds.). Cambridge, U.K., p. In Press.
ISO, 2010. 21931-1:2010 Sustainability in building construction — Framework for methods of assessment of the environmental performance of construction works — Part 1: Buildings.
ISO, 2017a. 21930:2017 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services.
ISO, 2017b. ISO 52000-1 (overarching EPB standard) Energy performance of buildings — Overarching EPB assessment — Part 1: General framework and procedures. International Organization for Standardization (ISO), Geneva, Switzerland.
ISO, 2018. ISO 14067:2018 Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification. ISO, Switzerland p. 46.
Johnstone, I.M., 1994. The mortality of New Zealand housing stock. Architectural Science Review 37(4), 181-188.
Kuczyński, T., Staszczuk, A., 2020. Experimental study of the influence of thermal mass on thermal comfort and cooling energy demand in residential buildings. Energy 195, 116984.
Kuittinen, M., Häkkinen, T., 2020. Reduced carbon footprints of buildings: new Finnish standards and assessments. Buildings and Cities 1(1).
Levasseur, A., Lesage, P., Margni, M., Samson, R., 2013. Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. Journal of Industrial Ecology 17(1), 117-128.
Mantesi, E., Cook, M., Glass, J., Hopfe, C., 2015. Review of the assessment of thermal mass in whole building performance simulation tools.
Ministère de la transition écologique, 2021. Réglementation Environnementale 2020. France
Ministry of Business Innovation & Employment, 2020 Whole-of-Life Embodied Carbon Emissions Reduction Framework. New Zealand, p. 21.

Ministry of Business Innovation Employment, 2022. Whole-of-life embodied carbon assessment: technical methodology. New Zealand Government p. 18.
Ministry of the Interior and Housing, 2021. National Strategy for Sustainable Construction The Danish Housing and Planning Authority ed., Copenhagen, Denmark p. 56.
Natural Ressources Canada, 2020. The State of Canada's Forests: Annual Report 2020 p. 96.
Peuportier, B., Kellenberger, D., Anink, D., Mötzl, H., Anderson, J., Vares, S., Chevalier, J., König, H., 2004. Inter-comparison and benchmarking of LCA-based environmental assessment and design tools.
Ramage, M.H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D.U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P.F., Scherman, O., 2017. The wood from the trees: The use of timber in construction. Renewable and Sustainable Energy Reviews 68, 333-359.
Rasmussen, F.N., Andersen, C.E., Wittchen, A., Hansen, R.N., Birgisdóttir, H., 2021. Environmental Product Declarations of Structural Wood: A Review of Impacts and Potential Pitfalls for Practice. Buildings 11(8), 362.
Region de Bruxelles-Capitale, 2011. Arrêté ministériel déterminant les modalités d'application de l'arrêté du Gouvernement de la Région de Bruxelles-Capitale du 4 octobre 2007 relatif à l'octroi de primes à la rénovation de l'habitat, 2011031471. Belgium
Röck, M., Baldereschi, E., Verellen, E., Passer, A., Sala, S., Allacker, K., 2021. Environmental modelling of building stocks–An integrated review of life cycle-based assessment models to support EU policy making.
Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Applied Energy 258, 114107.
Schweizerische Eidgenossenschaft, 2020. Bundesgesetz über die Verminderung von Treibhausgasemissionen (CO2-Gesetz).
Schweizerischen Eidgenossenschaft, 2017. Bundesgesetz über den Wald (Waldgesetz, WaG).
SIA, 2020. Graue Energie – Ökobilanzierung für die Erstellung von Gebäuden. Schweizerischer Ingenieur- und Architektenverein (SIA), Zürich, Switzerland.
Stamford, L., 2020. Chapter 5 - Life cycle sustainability assessment in the energy sector, in: Ren, J., Scipioni, A., Manzardo, A., Liang, H. (Eds.), Biofuels for a More Sustainable Future. Elsevier, pp. 115-163.
Swedish National Board of Housing Building and Planning, 2020. Utveckling av regler om klimatdeklaration av byggnader (Developing rules for environmental declaration of buildings). Karlskrona, Sweden, p. 142.
Swedish Parliament, 2021. Klimatdeklaration för byggnader (Climate declarations for buildings).
Takano, A., Hafner, A., Linkosalmi, L., Ott, S., Hughes, M., Winter, S., 2015. Life cycle assessment of wood construction according to the normative standards. European Journal of Wood and Wood Products 73(3), 299-312.
The Federal Government, 2016. German Sustainable Development Strategy: New Version 2016. pp. 252,.
UN Environment and International Energy Agency, 2017. Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2017.
Wang, X., Padgett, J.M., De la Cruz, F.B., Barlaz, M.A., 2011. Wood Biodegradation in Laboratory-Scale Landfills. Environmental Science & Technology 45(16), 6864-6871.
Wood Sector Alliance for the New European Bauhaus, 2021. https://wood4bauhaus.eu/.
Wood Solutions, 2017. Environmental Product Declaration Plywood. Forest and Wood Products Australia Limited, p. 31.

Wood Solutions, 2020. Environmental Product Declaration Softwood Timber Forest and Wood Products Australia Limited, Australia, p. 28.
World Green Building Council, 2019. Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon. p. 35.
World Green Building Council, 2021. WorldGBC Online Case Study Library. https://www.worldgbc.org/case-study-library. (Accessed 29 May 2021.
Ximenes, F.A., Björdal, C., Kathuria, A., Barlaz, M.A., Cowie, A.L., 2019. Improving understanding of carbon storage in wood in landfills: Evidence from reactor studies. Waste Management 85, 341-350.

Conflict of interest statement

The authors declare no conflict of interest statement.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryrevisedPreprint.pdf