Embodied GHG Emissions of Wooden Buildings — Challenges of Biogenic Carbon Accounting in Current LCA Methods

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Buildings play a vital role in reaching the targets stated by the Intergovernmental Panel on Climate Change to limit global warming to 1.5 degrees. Increasing the use of wood in construction is a proposed upcoming strategy to reduce the embodied greenhouse gas emissions of buildings. This study examines existing life cycle assessments of wooden buildings. The aim is to investigate embodied greenhouse gas emission results reported, as well as methodological approaches applied in existing literature. The study applies the protocol for Systematic Literature Reviews and finds 79 relevant papers. From the final sample, the study analyses 226 different scenarios in-depth in terms of embodied emissions, life cycle assessment method, life cycle inventory modelling and biogenic carbon approach. The analysis shows that the average reported values of embodied greenhouse gas emissions of wooden buildings are one-third to half of the embodied emissions reported from buildings in general. Additionally, from the analysis of the final sample we find that the majority of wooden building life cycle assessments apply similar methods and often leave out biogenic carbon from the assessment or simply do not declare it. This implies that the focus on variability in the different methods applied in wooden building life cycle assessments needs to be increased to establish the relationship between methodological choices and embodied emissions of wooden buildings. Further, transparency and conformity in biogenic carbon accounting in life cycle assessments is essential to enhance comparability between life cycle assessment studies and to avoid distortions in embodied GHG emission results.

Keywords: GHG emissions, wood, biogenic carbon, buildings, LCA, sustainability, case studies

INTRODUCTION

Sustainability and the Built Environment

The anthropogenic impact on the basic functioning of the Earth System are increasing and the ecological stability may now be threatened (Steffen et al., 2004; Rockström et al., 2009; Steffen et al., 2015; Hildebrandt, 2016). Because of this, the sustainability agenda continues to gain attention by consumers, decision-makers and industries all over the world (Hildebrandt, 2016). In 2018, the Intergovernmental Panel on Climate Change stated that all anthropogenic activities must reach a level of net zero Greenhouse Gas (GHG) emissions by 2050 to limit global warming to 1.5 degrees and to avoid climate crisis (IPCC, 2018). Further, in 2015 measures on climate change mitigation were also integrated into the Sustainability Development Goals to support the sustainable transformation of our society (United Nations, 2015).
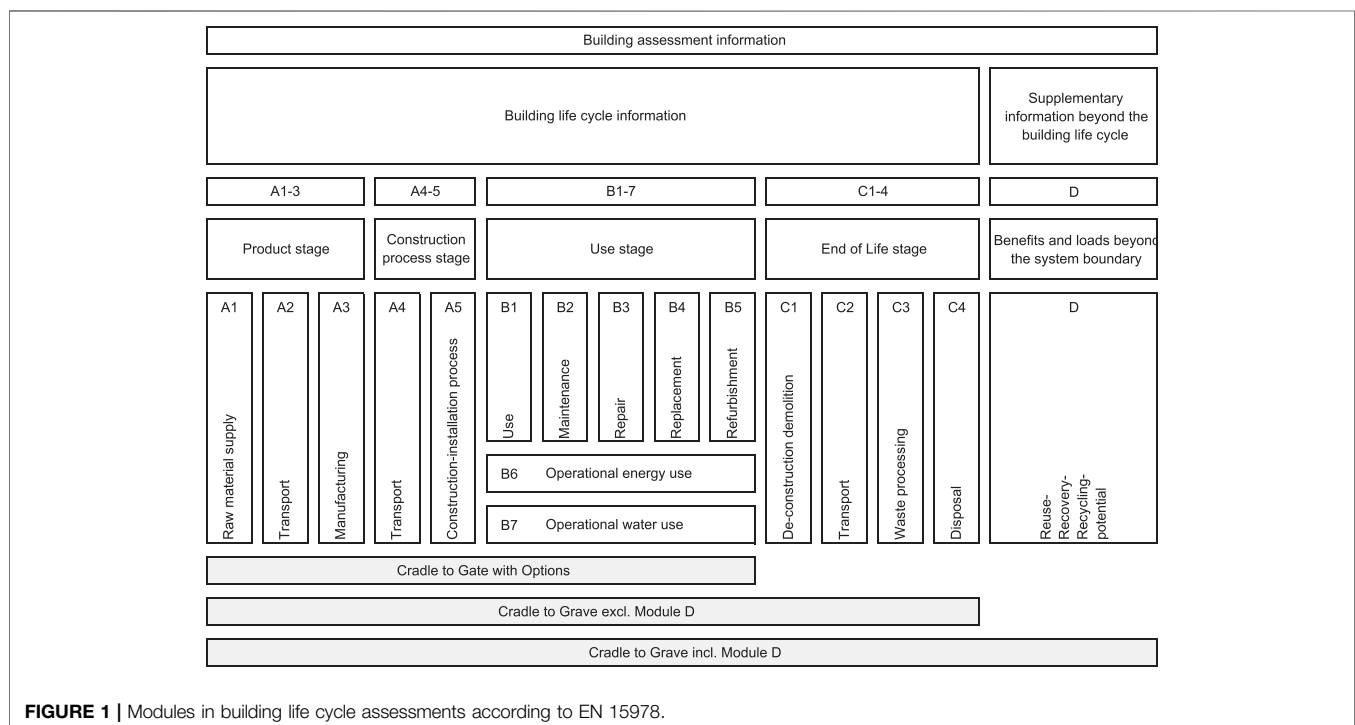
Buildings play an important role in reaching GHG emission reduction targets and in the transformation towards a sustainable society. Globally, buildings and construction account for 39% of global energy related GHG emissions (International Energy Agency for Global Alliance for Buildings and Construction, 2019). Of this sector contribution, 28% relates to the operational GHG emissions and the remaining 11% relates to the energy used to produce building and construction materials (also referred to as the embodied emissions) (International Energy Agency for Global Alliance for Buildings and Construction, 2019; World Green Building Council, 2019). Even though the building sector in many years have focused on reducing the operational energy emissions, recent studies suggest that buildings still hold a potential to reduce the GHG emissions from buildings by at least a factor 2.5 (Zimmermann et al., 2020a). To reach this potential, both the emissions from operational energy as well as the embodied emissions must be reduced.

An established method to quantify the emissions of a building is Life Cycle Assessment (LCA). LCA is a standardized method to assess the environmental impacts throughout the life cycle of a product or process under study (European Commission and Joint Research Centre, 2012; Hauschild et al., 2018). In an European context, the standards that frame LCAs on a building and building product level are EN 15978 and EN 15804 (CEN, 2019; CEN, 2012). The standards define the overall structure of building LCAs as well as relevant life cycle stages (see **Figure 1**). Traditionally, the standards as well as building LCAs in general take basis in the attributional approach to LCA, which focus on answering the question "*what environmental impact is the product responsible for?*" (Hauschild et al., 2018). However, another approach that is relevant in the context of building LCAs, but not as commonly applied, is consequential LCAs. Consequential LCA focus on answering the question "*what are the environmental consequences of consuming the product?*" (Hauschild et al., 2018). In other words, consequential LCAs consider future impacts that may happen due to a change in demand whereas attributional LCAs consider impacts that has happened and can be attributed to the product or activity under study (Weidema, 2003; Curran et al., 2005; Bamber et al., 2020).

Wooden Buildings and Reducing the Embodied GHG Emissions

As reducing the embodied GHG emissions of buildings become increasingly important different sustainability strategies gains significance. Examples of sustainability strategies, which are increasingly important in relation to the built environment, are circular economy (Fellner et al., 2017; Pomponi and Moncaster,

FIGURE 1 | Modules in building life cycle assessments according to EN 15978.

FIGURE 2 | Overview of biogenic carbon counting in a building life cycle according to the −1/+1 approach.
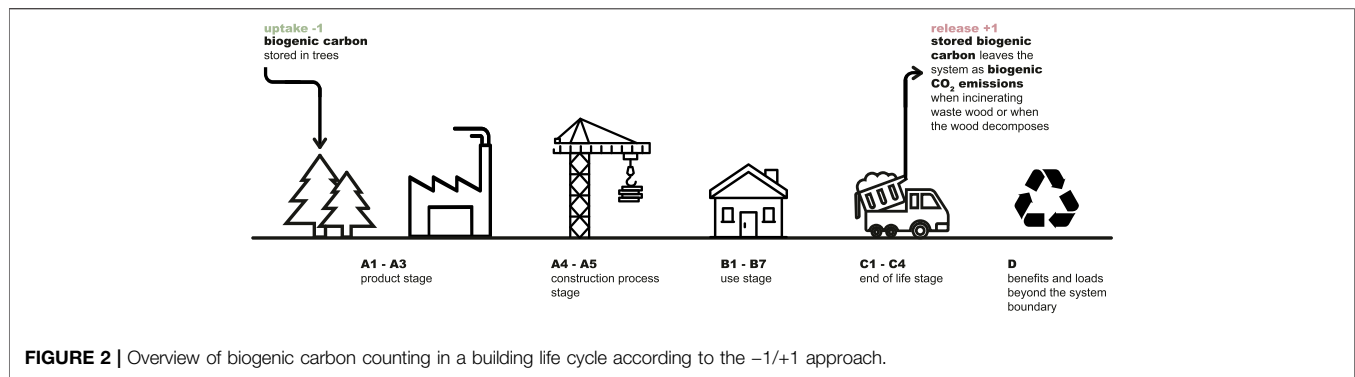
2017; Ghisellini et al., 2018; Nußholz et al., 2019; Andersen et al., 2020), design for disassembly (Densley Tingley and Davison, 2012; Eberhardt et al., 2019), renovating rather than building new and using more wood in construction (Salazar and Meil, 2009; Sodagar et al., 2011; Carcassi et al., 2020; Churkina et al., 2020).

In recent years in particular, the focus on wood in construction has increased, and buildings containing a larger share of wood-based materials are getting more and more common (Jensen and Craig, 2019). Through photosynthesis, wood absorbs and sequesters CO_2 from the air, resulting in a decrease of the atmospheric CO_2 level (Prentice et al., 2001). The carbon sequestered by wood and other bio-based materials are commonly referred to as biogenic carbon. At the end of life, when the wood either decomposes or is incinerated at incineration plants, the sequestered carbon is released back into the air, resulting in an equivalent increase of atmospheric CO_2 (Prentice et al., 2001; Brandão et al., 2013; Hoxha et al., 2020). Due to woods' inherent ability to absorb and release CO_2 from and to the atmosphere, an increased use of wood in buildings is often promoted as a strategy to reduce the embodied GHG emissions of buildings (Prentice et al., 2001). However, when seeking to quantify the embodied GHG emissions of a building, these inherent mechanisms of wood cause further complexities and as a consequence, skepticism regarding the 'true' environmental potential of wood in construction remains.

Methodological Challenges of Wooden Building LCAs

In traditional building LCAs, two different approaches to account for biogenic carbon uptake and release in wood-based materials exist. The first approach excludes biogenic carbon completely from the assessment under the assumption that wood is carbon neutral. The approach is commonly referred to as the 0/0 approach, where the CO_2 uptake during trees' growth is equivalent to the CO_2 released at the end of life (Hoxha et al., 2020). In contrast, the second approach to account biogenic carbon of wood products is referred to as the −1/+1 approach. The −1/+1 approach includes biogenic carbon in the assessment and as for the 0/0 approach, the −1/+1 approach accounts biogenic carbon as carbon neutral during the life cycle (Hoxha et al., 2020). Even though, the −1/+1 approach includes biogenic carbon following the standardized method to calculate the

biogenic carbon content in wood (CEN, 2014). In the product stage the uptake of CO_2 is accounted as −1, whereas in the end of life stage the release of CO_2 is accounted as an equivalent +1 (see **Figure 2**) (Hoxha et al., 2020). If applied correctly, the two different approaches should provide the same results. However, the −1/+1 approach poses a risk of misleading results in cases where only the uptake of biogenic carbon is included in the assessment. On the other hand, the −1/+1 approach has the advantage of increasing the transparency of the biogenic carbon flows throughout the life cycle, although the representation of the biogenic carbon flow - and the timing of it - is simplified. Further, it should be noted that the fundamental assumption that wood is carbon neutral throughout the life cycle only proves correct if the wood is harvested sustainably.

A further complexity regarding LCA of wooden buildings is the timing of biogenic carbon uptake and release. Traditional building LCAs aggregate all emissions that occur during the life cycle of a building into one point in time, typically corresponding to the production year (Hellweg et al., 2003; Ryberg et al., 2018; Hoxha et al., 2020). This means that the time in which the emissions occur are insignificant and that all emissions are given the same weight no matter when they occur (Hellweg et al., 2003). To accommodate this issue (Levasseur et al., 2010), developed the dynamic LCA (DLCA) approach, where emissions are provided with a characterization factor for the point in time they occur (Levasseur et al., 2010).

Finally, another discussed issue regarding increasing the use of wood in buildings is the sole focus on one environmental aspect, namely GHG emissions. The sole focus on GHG emissions poses a risk of burdens shifting to other environmental aspects. For instance, human managed land has proven to have an enormous impact on the environments' ability to sequester carbon (Jørgensen, 2014; De Rosa et al., 2018; Stiebert et al., 2019; Hoxha et al., 2020). Therefore, land use and land use change are important aspects to consider when evaluating if increasing the use of wood in buildings can, in fact, reduce the environmental impact of buildings.

Research Questions

To eliminate some of these uncertainties regarding the methods, it is relevant to assess which methods existing literature apply, and how different methodological approaches affect the reported embodied GHG emissions. Thus, this study investigates LCA case

TABLE 1 | Keywords used for literature search.

Primary keywords	Sustainability	Wood	Construction	Case study
Secondary keywords	Low carbon	Timber	Building	—
	Environmental impact	Bio-based materials	Building material	
	Life cycle assessment	Wooden buildings	Built environment	
	Input output		Civil engineering	
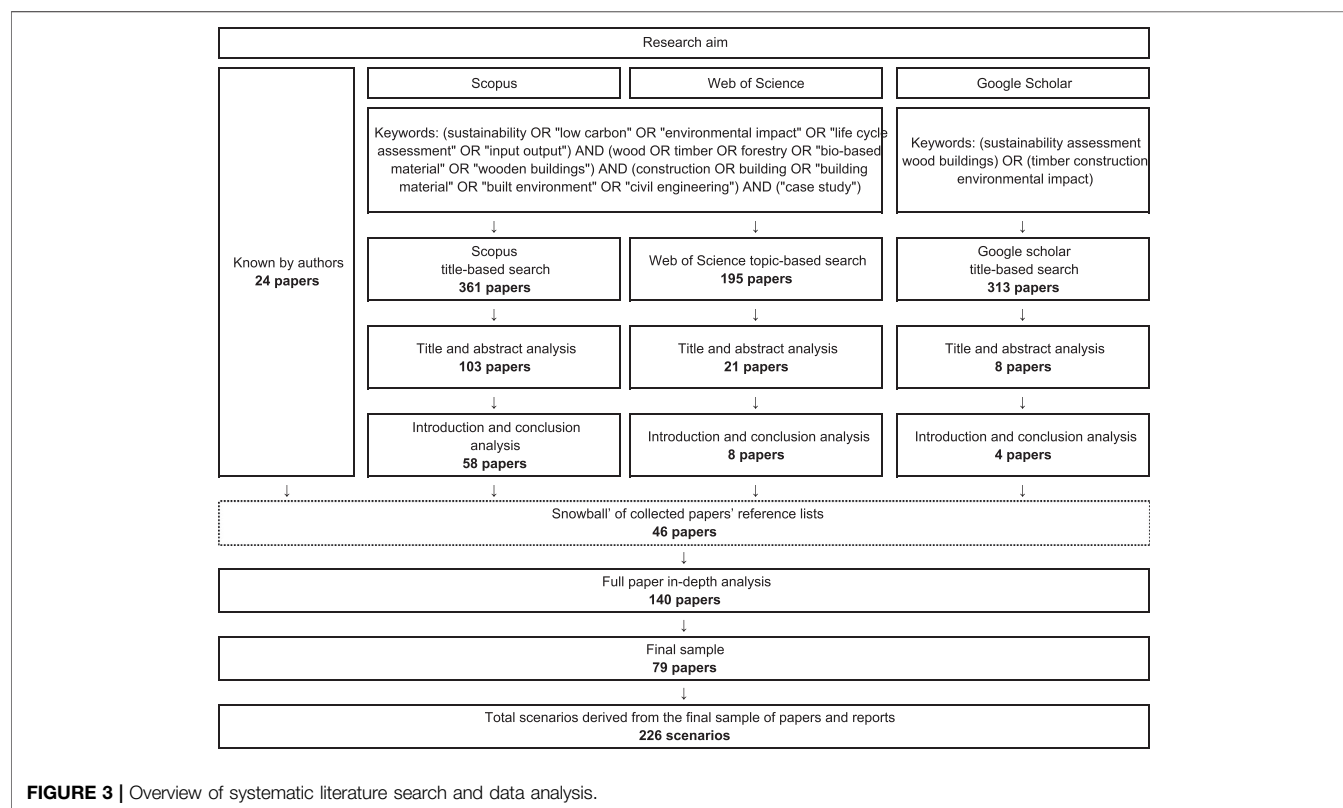
FIGURE 3 | Overview of systematic literature search and data analysis.

studies of wooden buildings to answer the following research questions:

I. Which embodied GHG emission results are reported in existing literature for wooden building LCAs?
II. How are methodological issues related to wooden building LCAs addressed in existing literature?

METHODS

Systematic Compilation of Literature

The literature was collected and analyzed following the protocol for Systematic Literature Review (SLR) as well as the 'snowball' approach (de Almeida Biolchini et al., 2007; Higgins and Green, 2008; Wohlin, 2014). Based on the research aim, we carried out a systematic literature search using four primary keywords and a list of secondary keywords (see **Table 1**).

From the search, we matched the keywords to the title, abstract or keywords on the databases "Scopus", "Web of Science" and

"Google Scholar". The search was limited to English-written journal papers, however due to the authors' native language, also reports and grey literature in Danish, Swedish and Norwegian was also accepted. Furthermore, no time boundaries were set, and therefore some literature dates back to the early 1990s. The initial search based on keywords resulted in 893 papers, reports and grey literature (see **Figure 3**).

Data Filtering Process and Exclusion Criteria

After the initial literature search, we first filtered the literature based on an analysis of the abstracts, and second filtered the literature based on an analysis of the introduction and conclusion. Moreover, we filtered the literature to meet the criteria listed. We performed the filtering process conservatively, meaning that literature where it was uncertain whether it met the following criteria, was retained.

- The study must be specific to the building sector

- The study must focus on embodied environmental impacts in the built environment
- The study must focus on whole buildings, building elements, building components or building materials in wood
- The study must provide a sufficient level of information regarding the type of wood in construction, methodological choices and environmental performance—more specifically embodied GHG emissions
- The study must solely focus on new constructions excluding building renovations and building extensions

After the filtering process, we found 70 papers from the databases "Scopus", "Web of Science" and "Google Scholar" relevant. In addition to the literature search in the three databases, we added 24 relevant papers that the authors knew beforehand. Afterwards, the collected literature was used for a snowball search, where the authors checked the reference lists of the literature to assure that no relevant sources were left out. The snowball search resulted in another 46 papers and reports.

The literature was then transferred to a reference management software from which we carried out the third filtering process—a full paper/report in-depth analysis. Studies that only focused on the product level, as well as studies that did not provide sufficient information to complete the analysis, were excluded. In this study, "sufficient information" was defined as information on the built area, the reference study period and the total embodied GHG emissions. From the in-depth analysis, 79 papers and reports were found relevant (Salazar and Meil, 2009; Sodagar et al., 2011; Hoxha et al., 2020), (Buchanan and Honey, 1994; Buchanan and Levine, 1999; Börjesson and Gustavsson, 2000; Aye et al., 2012; Dahlstrøm et al., 2012; Brown et al., 2013; Buchanan et al., 2013; Darby et al., 2013; Ajayi et al., 2015; Fouquet et al., 2015; Ding and Forsythe, 2016; Skullestad et al., 2016; Balasbaneh and Bin Marsono, 2017; Amiri Fard et al., 2019; Emami et al., 2019; Svortevik et al., 2020), (Gustavsson et al., 2006; Gustavsson and Sathre, 2006; Gerilla et al., 2007; Frenette et al., 2008; Gustavsson and Joelsson, 2010; Kahhat et al., 2011; Griffin et al., 2013; Fu et al., 2014; Grant et al., 2014; Islam et al., 2015; Liu et al., 2016; Häfliger et al., 2017; Lessard et al., 2018; Kamali et al., 2019; Rønning et al., 2019), (Peuportier, 2001; Monahan and Powell, 2011; Nässén et al., 2012; Van Ooteghem and Xu, 2012; Damvad Analytics, 2016; Larsson et al., 2016; Motuzienė et al., 2016; Peñaloza et al., 2016; Sinha et al., 2016; Milaj et al., 2017; Schiavoni et al., 2017; Moncaster et al., 2018; Sandanayake et al., 2018; Petrovic et al., 2019a; Moschetti et al., 2019; Pierobon et al., 2019; Schneider-Marin et al., 2020), (Wallhagen et al., 2011; Passer et al., 2012; Iddon and Firth, 2013; Ximenes and Grant, 2013; Takano et al., 2014; Hofmeister et al., 2015; Takano et al., 2015; Švajlenka et al., 2017; Švajlenka and Kozlovská, 2017; Švajlenka and Kozlovská, 2018; Tavares et al., 2019; Zeitz et al., 2019), (Winistorfer et al., 2005; Hacker et al., 2008; Carre, 2011; Monteiro and Freire, 2012; Mosteiro-Romero et al., 2014; Stephan and Crawford, 2014; Tonooka et al., 2014; Kurkinen et al., 2015; Laura Tschümperlin et al., 2016; Lawania and Biswas, 2016; Bukoski et al., 2017; Ohta, 2017; Lavagna et al., 2018; Lobaccaro et al., 2018; Petrovic et al., 2019b; Pittau et al., 2019).

Most of the collected papers and reports examine a number of different scenarios. For instance, papers and reports may assess different scenarios that vary in building types, biogenic carbon approaches (i.e. 0/0 approach or −1/+1 approach), LCA approaches (i.e. attributional or consequential) and LCI modelling approaches (i.e. process, hybrid, input-output). The three LCI modelling approaches relates to how the LCI database is composed. Process-based LCI include all relevant inputs and outputs for a process from literature and research and can be costly and time-consuming affair. In contrast, input-output LCI is based on economic models from statistical data and is typically a fast and low-budget way of calculating emissions. Finally, hybrid LCI combines process-based and input-output LCI to get the advantages of the two methods (Suh and Huppes, 2005; Müller and Schebek, 2013). All relevant scenarios in the final sample of 79 papers were included, resulting in a total amount of 226 scenarios (see **Figure 3**).

Data Extraction and Classification

In the in-depth analysis, meta-data from the studies were extracted systematically in a data extraction table. The data extraction table was established to collect all relevant meta-data regarding building case type, building characteristic, LCA method and embodied GHG emissions (see data extraction table in Supplementary Information). The building cases in the studies were categorized in the following building typologies: "residential—single family", "residential—multi family", "office" and "other". Further, in line with the study aim, the data extraction table was established to focus especially on the LCA approach, the LCI modelling approach and the biogenic carbon approach (see **Table 2**). In terms of biogenic carbon approach, the studies were categorized both according to the biogenic carbon approach (i.e. including or excluding biogenic carbon) and according to the system boundaries (i.e. "Cradle to Gate with Options", "Cradle to Grave excl. module D" or "Cradle to Grave incl. module D") (see **Table 2**). Finally, as the study mainly aims to investigate methodological approaches in regards to embodied GHG emissions in wooden building LCAs, details on the operational energy was excluded from the data extraction.

Data Normalization

After we extracted all data, we normalized the total embodied GHG emissions of each scenario to kg CO_2e per m^2 annually based on the built area and the reference study period. However, as the studies assume different reference study periods and are therefore not directly comparable, the total embodied GHG emissions were also normalized to a reference study period of 50 years (**Eq. 1**). This reference study period is an arbitrary point in time selected to compare across studies rather than representing the actual building service life and atmosphere.

$$kgCO_2e/m^2a_{50} = kgCO_2e/m^2a \cdot (RSP/50) \qquad (1)$$

$kgCO_2e/m^2a_{50}$ is the annualized embodied GHG emissions *after* the 50-years reference study period normalization, $kgCO_2/m^2a$ is the annualized embodied GHG emissions *before* normalization, and *RSP* is the reference study period applied in the individual study.

TABLE 2 | Categories as defined in data extraction table regarding LCA approaches, LCI modelling approach and biogenic carbon approaches.

LCA approach	LCI[a] modelling	Biogenic carbon approach		
Attributional	Process	Including biogenic carbon	+	Cradle to Gate with Options[b]
Consequential	Hybrid	Including biogenic carbon	+	Cradle to Grave excl. module D[c]
	Input-Output	Including biogenic carbon	+	Cradle to Grave incl. module D[d]
		Excluding biogenic carbon	+	Cradle to Gate with Options[b]
		Excluding biogenic carbon	+	Cradle to Grave excl. module D[c]
		Excluding biogenic carbon	+	Cradle to Grave incl. module D[d]
		Biogenic carbon approach not specified	+	All life cycle stages

[a]LCI = Life Cycle Inventory.

[b]'Cradle to Gate with Options' is defined as module A1-3 (mandatory) as well as other modules within the Product stage, Construction and Process stage or Use stage (optional).

[c]'Cradle to Grave excl. module D' is defined as module A1-3 and C3-4 (mandatory) as well as other modules within the Product stage, Construction and Process stage or Use stage (optional).

[d]'Cradle to Grave incl. module D' is defined as module A1-3, C3-4 and D (mandatory) as well as other modules within the Product stage, Construction and Process stage or Use stage (optional).

TABLE 3 | Meta data for final sample of scenarios.

World region		System boundary		Biogenic carbon reporting		Timing in LCA		Environmental aspects	
Europe	139	Cradle to Gate with Options	91	Reported separately	4	Dynamic	27	Only GHG	72
Asia	18	Cradle to Grave excl. Module D	114	Not specified	222	Not specified	199	GHG and (Indirect) Land use and Land use Change	10
Oceania	37	Cradle to Grave incl. Module D	21						
North America	32							GHG and others	144

RESULTS AND DISCUSSION

Final Sample Meta-analysis

The meta-analysis of the studies in the final sample reveals that the majority of the scenarios are from European countries (61%), whereas only 16% of the scenarios are from Oceania followed by 14% from North America and 8% from Asia. None of the studies are from countries in South America, Africa or other regions (see **Table 3**).

Further, the meta-analysis showed that only 9% of the scenarios in the final sample consider all life cycle stages including module D. In contrast, most of the scenarios (91%) exclude module D from the assessment. These scenarios either include modules within all other life cycle stages, namely the Product, Construction process, Use and End of Life stage (51%), or only include modules within the Product, Construction process, Use stage (40%).

In terms of biogenic carbon, we find that only 2% of the scenarios report the impacts from biogenic carbon separately, whereas 98% do not specify the biogenic carbon content in details. In the same way, only 12% of the scenarios account for the timing of biogenic carbon throughout the life cycle by assessing the impacts according to the dynamic LCA approach.

As one concern of increasing wood consumption is the impact caused on environmental aspects such as land use and land use change, we analyzed the environmental indicators considered in the scenarios. The meta-analysis reveals that most of the studies include environmental indicators related to GHG emissions and other indicators related to energy demand, acidification, toxicity or ozone depletion, as example. In contrast, only 4% of the scenarios include environmental indicators related to direct or indirect land use and land use change.

Embodied GHG Emissions of Wooden Buildings

The analysis of the studies in the final sample shows that the majority of the scenarios are residential buildings (73%), followed by other types of buildings (19%) and office buildings (8%) (see **Figure 4**). However, the analysis shows no clear difference in embodied GHG emissions across building types. This result is also supported by the findings in (Zimmermann et al., 2020b; Wiik et al., 2020). The average embodied GHG emissions ranges from 3.9 $kgCO_2e/m^2a_{50}$ for the category "Residential—multi family" to 4.0 $kgCO_2e/m^2a_{50}$ for the category "Office", 4.3 $kgCO_2e/m^2a_{50}$ for the category "Other" and 4.7 $kgCO_2e/m^2a_{50}$ for the category "Residential—single family".

Figure 4 compares the embodied GHG emissions of the considered studies to the findings in the review study by Röck et al. (Röck et al., 2020). In brief, the review study by (Röck et al., 2020) seeks to establish the relationship between embodied and operational GHG emissions by investigating the life cycle GHG emissions in a comprehensive sample of residential and office buildings reported in literature. The sample studied by (Röck et al., 2020) distinguishes from the sample considered in this study by not only considering wooden buildings, but considering
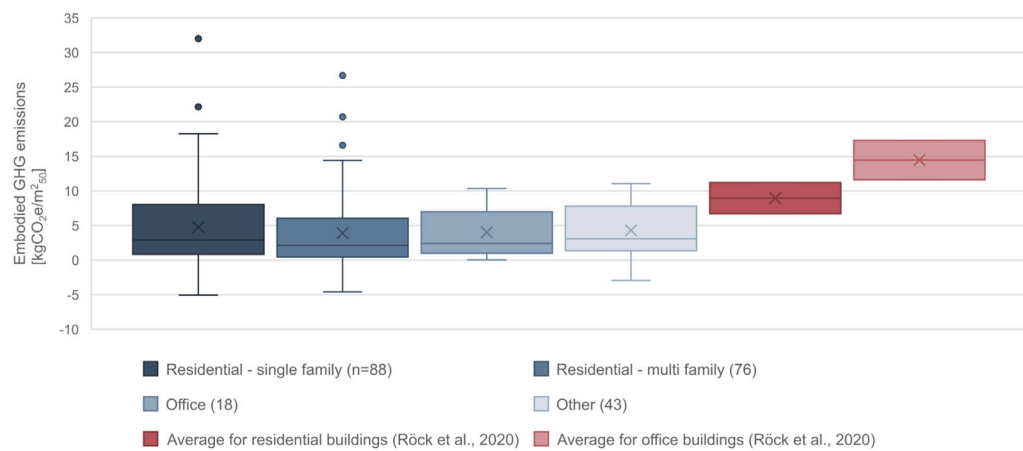
FIGURE 4 | Embodied GHG emissions distributed on building types and compared to the results from (Röck et al., 2020). The red boxes represent the average range in embodied GHG emissions for residential and office buildings found by (Röck et al., 2020). The dots in the plot indicate the outliers of the dataset. The boxes and the line within the boxes indicate the quartiles of the dataset (25 percentile, 50 percentile (median) and 75 percentile). The x indicates the average. The error bars outside the boxes indicate the deviation in the data.
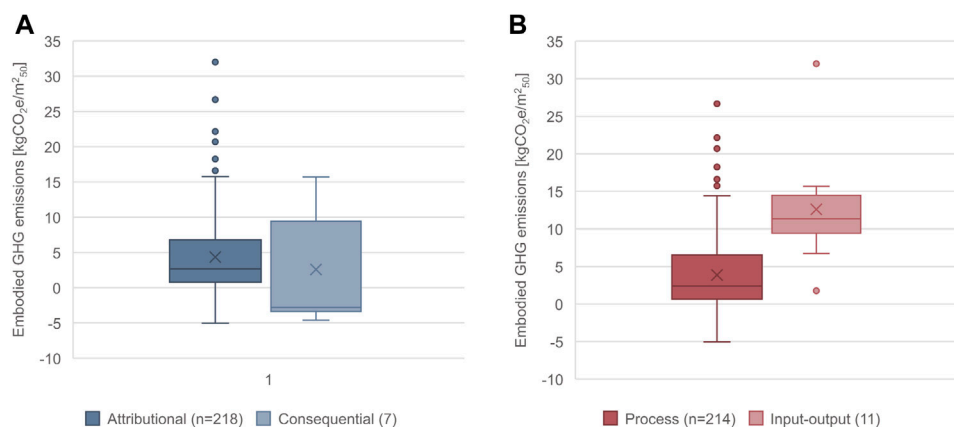
FIGURE 5 | Embodied GHG emissions distributed on LCA method **(A)** and LCI modelling **(B)**. The dots in the plot indicate the outliers of the dataset. The boxes and the line within the boxes indicate the quartiles of the dataset (25 percentile, 50 percentile (median) and 75 percentile). The x indicates the average. The error bars outside the boxes indicate the deviation in the data.

buildings with all types of materials. The red boxes in **Figure 4** present the range in average embodied GHG emissions for residential and office buildings found by (Röck et al., 2020). For residential buildings (Röck et al., 2020), finds that the embodied GHG emissions range from 6.7 $kgCO_2e/m^2a_{50}$ to 11.2 $kgCO_2e/m^2a_{50}$, whereas for office buildings the embodied GHG emissions range from 11.6 $kgCO_2e/m^2a_{50}$ to 17.3 $kgCO_2e/m^2a_{50}$ (see **Figure 4**) (Röck et al., 2020).

The results clearly show that the scenarios investigated in this study provide lower embodied GHG emissions when compared to studies examined by (Röck et al., 2020). Based on the weighted average, we find that the embodied GHG emissions of the residential buildings in this study is almost a factor 0.6 lower than the residential buildings in (Röck et al., 2020). Likewise, **Figure 4** shows that the embodied GHG emissions of the office buildings in this study is

approximately a factor 0.3 lower than the office buildings in (Röck et al., 2020) based on the weighted average.

Embodied GHG Emissions and LCA Method

The analysis reveals that the included studies in the final sample are rather homogeneous in regard to which LCA methods they apply. As presented in **Figure 5**, 96% of the scenarios considered in the analysis apply an attributional LCA method. In contrast only 4% of the scenarios apply a consequential approach and these scenarios originate from just two individual studies. On average, the attributional LCAs result in 4.4 $kgCO_2e/m2a_{50}$. This is higher than the average embodied GHG emissions for the consequential scenarios, which is 2.6 $kgCO_2e/m^2a_{50}$. However, as the final sample only includes seven consequential scenarios (as presented in **Figure 5**), no clear tendency can be identified.

FIGURE 6 | Embodied GHG emissions distributed on approach to biogenic carbon counting and system boundaries. The dots in the plot indicate the outliers of the dataset. The boxes and the line within the boxes indicate the quartiles of the dataset (25 percentile, 50 percentile (median) and 75 percentile). The x indicates the average. The error bars outside the boxes indicate the deviation in the data.
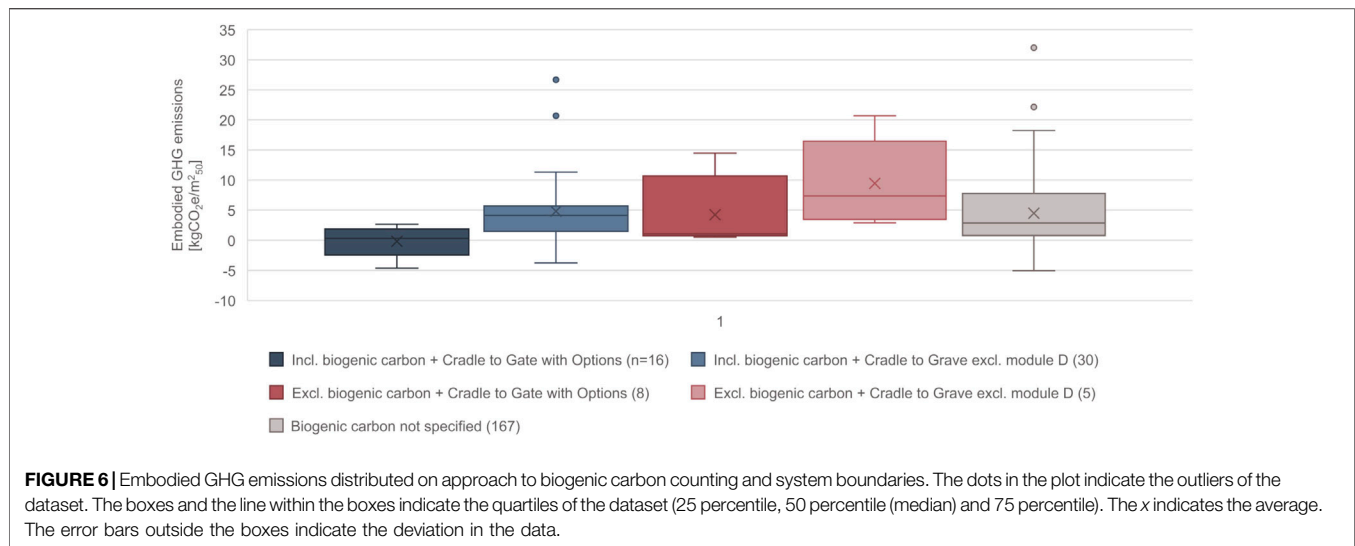
Moreover, **Figure 5** shows that most of the scenarios use a process-based life cycle inventory (LCI) modelling approach (95%). Conversely, only 5% of the 226 scenarios use an input-output-based LCI and these originate from just seven individual studies. Also, from **Figure 5** it is noticeable that no studies apply a hybrid-based LCI. This homogeneous approach to LCI modelling in wooden building LCAs makes it difficult to identify how the LCI modelling affect the embodied GHG emissions of wooden buildings. However, **Figure 5** indicates that scenarios using an input-output-based LCI generally results in higher embodied GHG emissions compared to scenarios using a process-based LCI. The scenarios using a process-based LCI result in 3.9 $kgCO_2e/m^2a_{50}$ on average, whereas the scenarios using an input-output-based LCI result in 12.6 $kgCO_2e/m^2a_{50}$ on average. Altogether, the results indicate that studies applying an input-output-based LCI provide a factor 3.2 higher embodied GHG emissions compared to studies that apply a process-based LCI. This divergence between process-based and input-output-based results mirrors the fundamental difference in the completeness of scope by the two LCI approaches (Crawford, 2008).
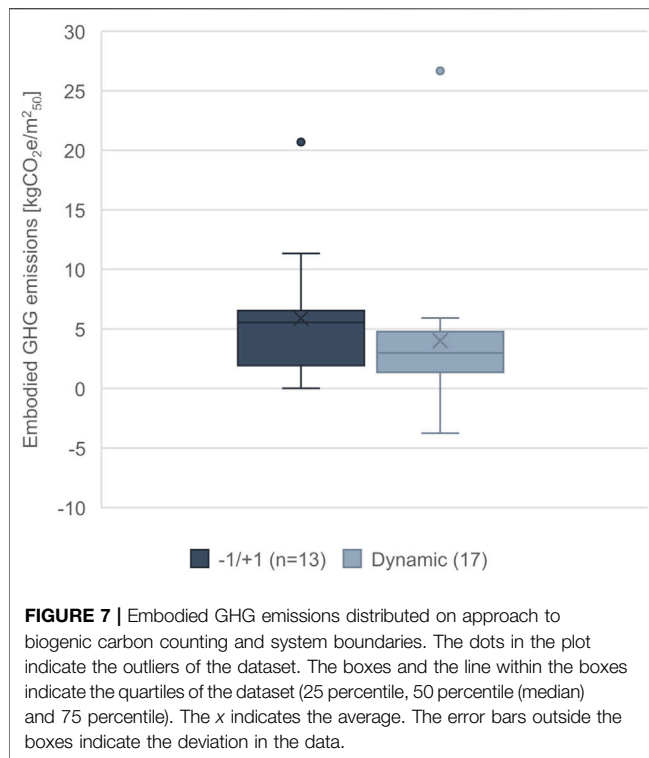
Biogenic Carbon Approaches in LCA

Figure 6 reveals that 74% of the 226 scenarios in the final sample does not specify how biogenic carbon is assessed in the study. Only 26% of the scenarios clearly state if - and how - biogenic carbon is assessed in the building LCA.

The analysis of the studies shows, as presented in **Figure 6**, that scenarios within the category 'Incl. biogenic carbon + Cradle to Gate with Options' result in the lowest embodied GHG emissions when compared to the other approaches analyzed in this study. The average embodied GHG emissions of the scenarios within the category 'Incl. biogenic carbon + Cradle to Gate with Options' is −0.2 $kgCO_2e/m2a_{50}$. The negative embodied GHG emissions within this category is due to the studies applying the −1/+1 approach to account for biogenic carbon while at the same time disregarding the End of Life stage from the assessment. Thereby, only the uptake of carbon in the Product stage is

included in the assessment, and is not counterbalanced with a release of biogenic carbon at the End of Life as recommended by European standards. Hence, the biogenic carbon is not considered carbon neutral throughout the life cycle, but rather carbon negative.

Since both the −1/+1 and the 0/0 approach assumes that biogenic carbon is counted as carbon neutral throughout the building life cycle, applying the −1/+1 approach or the 0/0 approach in a 'Cradle to Grave excl. module D'-study should provide the same results. However, as presented on **Figure 6**, the category 'Incl. biogenic carbon + Cradle to Grave excl. module D' has markedly lower embodied GHG emissions on average compared to the category 'Excl. biogenic carbon + Cradle to Grave excl. module D'. The category 'Incl. biogenic carbon + Cradle to Grave excl. module D' results in embodied GHG emissions of an average 4.8 $kgCO_2e/m2a_{50}$, whereas the category 'Excl. biogenic carbon + Cradle to Grave excl. module D' results in embodied GHG emissions of 9.5 $kgCO_2e/m2a_{50}$ on average. This difference between the two categories is distinct. Nonetheless, it is noticed that the category 'Incl. biogenic carbon + Cradle to Grave excl. module D' do not just includes scenarios applying the −1/+1 approach, but rather covers a variety of different approaches to biogenic carbon counting, including several types of dynamic modelling. Therefore, the average embodied GHG emissions for this category becomes lower than the embodied GHG emissions for the category 'Excl. biogenic carbon + Cradle to Grave excl. module D'. The category 'Incl. biogenic carbon + Cradle to Grave excl. module D' and the different approaches to include biogenic carbon are further analyzed in *Including biogenic carbon in LCA*.

Additionally, **Figure 6** shows that the scenarios within the category "Biogenic carbon not specified" result in embodied GHG emissions of 4.5 $kgCO_2e/m2a_{50}$ on average and that the scenarios included in this category highly vary in terms of embodied GHG emissions. These variations in embodied GHG emissions are most likely a result of different methodological approaches to biogenic carbon accounting in the different studies.

FIGURE 7 | Embodied GHG emissions distributed on approach to biogenic carbon counting and system boundaries. The dots in the plot indicate the outliers of the dataset. The boxes and the line within the boxes indicate the quartiles of the dataset (25 percentile, 50 percentile (median) and 75 percentile). The x indicates the average. The error bars outside the boxes indicate the deviation in the data.

Including Biogenic Carbon in LCA

Looking further into the category 'Incl. biogenic carbon + Cradle to Grave excl. module D', the results show a high variation in embodied GHG emissions due to different ways to account for biogenic carbon. In **Figure 7**, the scenarios within this category is further divided into two categories: scenarios that apply a −1/+1 approach, and scenarios that apply a dynamic approach. The results presented in **Figure 7** suggest that dynamic LCA studies typically provide lower embodied GHG emissions when compared to LCA studies that apply the −1/+1 approach to account for biogenic carbon. The average embodied GHG emissions for the dynamic studies are $4.0\ kgCO_2e/m2a_{50}$, whereas the studies applying a −1/+1 approach results in average embodied GHG emissions of $5.9\ kgCO_2e/m2a_{50}$. Also, from **Figure 6** it is noticeable that the dynamic LCA studies result in a wide range of both positive and negative embodied GHG emissions. However, analyzing the dynamic LCAs within the category 'Incl. biogenic carbon + Cradle to Grave excl. module D' shows that the scenarios originate from just three individual studies. Thus, it is difficult to conclude how the two approaches affect the embodied GHG emissions.

DISCUSSION

Wooden Buildings in LCA Studies

One aim of the study was to investigate how existing literature on wooden building LCAs reports embodied GHG emission results. In *Embodied GHG Emissions of Wooden Buildings* we found that irrespective of building type, the building cases in this study generally present lower values of embodied GHG emissions than the building cases included in (Röck et al., 2020). Both studies, this study as well as the one by (Röck et al., 2020), consider a broad sample of building LCAs. In addition, the studies examine building cases with different building characteristics such as year of construction, region, building type and energy performance. Finally, the studies also include case studies that apply various methodological approaches. Altogether, this study and the study by (Röck et al., 2020) both include a broad sample of data with similar variations in building characteristics as well as methodological approaches. Therefore, it is argued that the lower average embodied GHG emissions in this study when compared to (Röck et al., 2020) can be ascribed to the extensive use of wood in the building cases included in this study. The findings are supported by (Hart et al., 2021) which found that from a sample of 127 configurations, timber frames has a 43% reduced GHG impact potential when compared to concrete and steel frames (Hart et al., 2021). Likewise (Hafner and Schäfer, 2017), suggest that timber construction has a reduced GHG impact potential of 9–56% when compared to mineral alternatives (Hafner and Schäfer, 2017). A study for the UK's Committee on Climate Change found that substituting masonry with timber frames pose an approximately 20% reduction in embodied GHG emissions (Spear et al., 2019). These studies highlight that the choice of materials in buildings matter and has the potential to reduce the embodied GHG emissions of a building considerably. Again, this is supported by a study by (Zimmermann et al., 2020b) that shows that the embodied GHG emissions per m^2 vary by a factor 1.8–2.6 when assessing 60 different building cases with the same scope and LCA method (Zimmermann et al., 2020b).

Variability in Building LCA Methods

The analysis of the existing literature reveals a lack of variability in LCA studies of wooden building types. From the meta-analysis in *Final Sample Meta-Analysis*, we found that the sample primarily include case studies of residential buildings, followed by building cases within the category 'Other' and 'Office'. Even though the meta-analysis reveals a research gap, where mostly residential buildings are examined in existing literature, the sample reflects the actual distribution quite precisely between residential buildings and non-residential buildings in Europe as well in the U.S. The European distribution between residential buildings and non-residential buildings is 74 and 26% respectively (EU Buildings Datamapper, 2020) while the U.S. distribution in 2015 was 72 and 28% for residential and commercial buildings respectively (U.S. Energy Information Administration, 2015; U.S. Energy Information Administration, 2018). In comparison, the sample in this study distributes as 73% residential buildings and 27% non-residential buildings (including both categories: "Office" and "Other"). Moreover, the FOREST EUROPE report from 2015 states that the majority of the wooden buildings constructed in Europe are residential buildings (FOREST EUROPE, 2015). Especially in Northern Europe, between 85 and 95% of the single family houses are wooden buildings (more specifically in Norway, Sweden and Finland) (FOREST EUROPE, 2015).

This is also supported by the 2018 IEA Global Status Report that reports a markedly larger use of wood as structural material in residential buildings compared to non-residential buildings (International Energy Agency and Global Alliance for Buildings and Construction, 2018).

Further, the study presents a clear absence of variability in the methodological approaches applied in wooden building LCAs. As presented in *Embodied GHG Emissions of Wooden Buildings*, the majority of the studies (83%) apply a static and attributional LCA approach using a process-based LCI, whereas few studies (17%) apply methods such as consequential or dynamic LCA. Altogether, the literature assessed in this study takes a quite narrow approach to LCA methods, thus outlining a significant gap in knowledge. Therefore, it is difficult to establish the relationship between methodological approaches and the embodied GHG emissions. The narrow approach to wooden building LCA case studies should be the focus of future research. Ultimately, building LCA case studies should investigate consequential approaches to gain an understanding of the market dynamics and supply scenarios when increasing the use of wood in buildings, as well as investigating the dynamic approaches to understand the details of the timing in biogenic carbon accounting. Additionally, future studies should focus on examining different types of inventory data in-depth to identify pros and cons of using the types of inventory data in relation to wooden building LCAs.

Increasing Awareness on Biogenic Carbon in Building LCAs

The approach to biogenic carbon accounting in LCA can affect the total embodied GHG emissions of a building. In *Biogenic Carbon Approaches in LCA*, we found that the scenarios within the category 'Incl. biogenic carbon + Cradle to Gate with Options' has lower embodied GHG emissions compared to the other categories. From the further analysis, we found that 16 out of 226 scenarios apply the −1/+1 approach to account for biogenic carbon while assessing Cradle to Gate with Options. By doing so, these studies do not assume carbon neutrality throughout the life cycle despite it being a fundamental premise of the −1/+1 approach. Instead, these studies include uptake of carbon in the product stage while do not include the release of carbon at the end of life. This way of accounting biogenic carbon disregards mass balances within the system, skews the embodied life cycle emissions and typically results in unrealistic low embodied GHG emissions.

Further, by looking into the different approaches to include biogenic carbon we found that the dynamic LCAs vary greatly in terms of the embodied GHG emissions. A thorough analysis of these results reveals that the variation in embodied GHG emissions is because the studies apply different dynamic approaches to account for biogenic carbon. This is supported by a study by (Resch et al., 2021) that finds that methodological uncertainties in dynamic LCAs affect the embodied emissions heavily (Resch et al., 2021). In this study, some of the scenarios consider either biogenic carbon uptake *before* harvesting or *after* harvesting (Peñaloza et al., 2016). Biogenic carbon uptake *before*

harvesting is the business-as-usual in building LCAs, where the trees are assumed to sequester carbon before harvesting and production processes. Conversely, biogenic carbon uptake *after* harvesting assumes that the equivalent amount of trees start to regrow after harvesting and production processes (Hoxha et al., 2020). Another dynamic LCA included in this study applies GWP$_{bio}$ factors developed by Guest, Cherubini and Strømman to account for the timing of biogenic carbon (Guest et al., 2013; Pomponi and Moncaster, 2018). The GWP$_{bio}$ factors are characterization factors that account for the rotation period in the forests as well as the storage period (Guest et al., 2013). The many different approaches to dynamic LCA underline the need for investigating the dynamics of biogenic carbon accounting in-depth and include biogenic carbon in the most suitable way. In addition, the many different methodological approaches point to the need of developing standardized methods to assess biogenic carbon in dynamic as well as static building LCAs.

Also, as presented in **Figure 6**, we found that the majority of the studies do not specify how they include biogenic carbon in the assessment. As the results within the "not specified"-category vary from negative to quite high embodied GHG emissions, it indicates that this category is a mix of studies that include biogenic carbon and studies that exclude biogenic carbon from the assessment. Some studies most likely include biogenic carbon as a part of the inventory data and impact assessment. Likewise, other studies might exclude biogenic carbon completely from the assessment without clearly stating it. Even though it would be expected that the literature included in this study would be of higher quality as it is primarily academic and peer-reviewed literature, the issues related to biogenic carbon accounting clearly illustrates a lack of transparency and conformity in LCA studies. A study by (Crawford, 2008) also underlines these issues in building LCAs in general and stress the need for immediate action to ensure that embodied emissions will not become a ""*second wave*" of performance gap in environmental assessments of buildings" (Crawford, 2008).

However, in relation to environmental assessments of wooden buildings, the issues of transparency and awareness on biogenic carbon accounting might also lie in the poor quality of environmental data available in Environmental Product Declarations (EPDs) and in public databases. In previous European Standards concerning environmental assessments of building products only life cycle modules A1-3 should be declared in EPDs and no requirements to separately declare the biogenic carbon content was stated (CEN, 2012). As a consequence, biogenic carbon was usually accounted as carbon neutral and did not gain much attention or there was a risk of skewed embodied emissions if biogenic carbon was not accounted for correctly (as seen in cases within the category 'Incl. biogenic carbon + Cradle to Gate with Options'). Now, the issues regarding biogenic carbon accounting is gaining attention within the European Standards as well as within the LCA community. The new version of the European Standard is developed to address some of the issues regarding biogenic carbon accounting and to increase the transparency on reporting biogenic carbon impacts. According to the new European standard EN15804:2012 + A2:2019 new EPDs should declare

the life cycle modules A1-3, C1-4 and D as well as report the fossil and biogenic GHG emission results separately in the categories GWP$_{biogenic}$ and GWP$_{fossil}$ (CEN, 2019). This new approach to assessing and reporting GHG emissions for building materials increases the transparency regarding biogenic carbon accounting and helps standardizing the environmental data on a product level.

Limitations of Sample

A limitation of this study is that the synthesis did not account for differences in the inventory scope of the case studies. In the data extraction table, studies were categorized according to which building parts they included following the categories: "Structure only", "Structure, shell and cladding", "Whole building", "Other" and "Not specified". However, the results in *Results and Discussion* were not analyzed by category and consequently, the embodied GHG emission results are a mix of all categories. Even though this is a limitation of the study, this is not considered a limitation that alters the conclusions of the analysis as there is no clear relationship between the building parts that are included in the studies and the methods that are applied.

Similarly, we categorized the studies in regards to system boundaries (see *Data Filtering Process and Exclusion Criteria*). While excluding all emissions from operational energy and water use from the analysis (life cycle stage B6 and B7), we included all other life cycle stages in the synthesis of the results. As a consequence, the studies do not include the same life cycle stages and this affects the total embodied GHG emissions. Even though this is dealt with by categorizing the studies in the three categories "Cradle to Gate with Options", "Cradle to Grave excl. module D" and "Cradle to Grave incl. module D", there is still a risk that studies, which include many life cycle stages, result in high embodied GHG emissions. On the contrary, the analysis shows no clear coherence between system boundary and methods applied and therefore it is not considered as a limitation that affect the conclusions.

A final limitation of the study is that we did not account for differences in the defined built area in the investigated studies. For studies that do report a built area there are several ways of defining the area depending on the country's definition. For instance, the built area can be defined as the gross floor area, net floor area, heated floor area and internal floor area. Currently, there is no standardized way of calculating the different types floor areas across countries (Dario Trabucco and William Douglas Miranda, 2019; Miranda and Trabucco, 2019) and therefore we did not account for the differences in floor area in the assessment. However, this can potentially have a significant impact on the results. For instance, Richard Jackson found a difference of 24% in the measured floor area in Dubai due to the different measurements models applied because no standardized measurements model existed (Jackson, 2016). As comparing studies across countries gains importance not only in regards sustainability targets, but also in regards to energy consumption targets, construction cost, occupancy ratio etc., it is crucial that the denominators such as the floor area are comparable and reported transparently.

CONCLUSION

This study investigated 79 papers of wooden building LCAs in a Systematic Literature Review. The 79 papers feature a total of 226 different scenarios varying in types of building cases and applied LCA methods. All scenarios were analyzed in-depth and data from each paper were extracted in a data extraction table. From the analysis we found that the wooden building LCA studies generally result in a factor 0.3–0.6 of the embodied GHG emissions found in a review study of a mixed sample of building cases. Additionally, the analysis reveals that existing LCA studies apply a rather narrow approach to LCA and lacks variability in the methods applied. In fact, 95% of the scenarios considered apply an attributional LCA method and use a process-based LCI modelling approach. Thus, it is difficult to establish a clear relationship between the applied methodological approach in LCA and the embodied GHG emissions of wooden buildings. Moreover, the analysis shows that only 26% of the studies clearly specify if—and how - they assess biogenic carbon. Again, this underlines the lack of variability as well as transparency on biogenic carbon accounting in wooden building LCAs. For future research, it is recommended that the relationship between different methodological approaches and the embodied emissions of wooden buildings are investigated to eliminate uncertainties within the industry regarding the environmental potential of wooden buildings. Further, the focus on biogenic carbon accounting in building LCAs should be increased to enhance the comparability between wooden building LCAs and to limit concerns regarding the "true" environmental potential of wooden buildings.

AUTHOR CONTRIBUTIONS

CA: conceptualization, methodology, data curation, visualization, writing—original draft FR: conceptualization, data curation, supervision, writing—reviewing and editing HG: supervision, writing—reviewing and editing BH: conceptualization, supervision, writing—reviewing and editing.

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