# Evaluating the Environmental Performance of 45 Real-life Wooden Buildings

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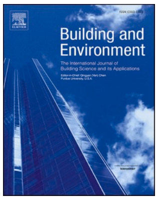

# Evaluating the environmental performance of 45 real-life wooden buildings: A comprehensive analysis of low-impact construction practices

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ABSTRACT

Buildings are responsible for 37 % of global Greenhouse Gas (GHG) emissions. Subsequently, stakeholders in this sector have introduced different strategies to reduce the environmental impact of buildings. One strategy focuses on increasing the use of wood in buildings as a low-impact material with the potential to act as a carbon sink. Although research shows a tendency towards lower GHG emissions from wood structures compared to conventional constructions, the existing literature is typically challenged by methodological inconsistencies and only assesses a limited number of building projects at a time. As a result, uncertainties are introduced about comparisons between them, how their background and modeling assumptions may vary, as well as the integrity of the assessed solutions. Hence, this study analyses 45 cases of buildings applying the same methodology to enable a comprehensive understanding of the environmental performance of wooden buildings, identifying common trends, challenges, and best practices. This study finds that the embodied impacts contribute highly to the environmental impact and thus remain essential to consider. However, there is a very weak correlation between the quantities of wood used in the buildings and the environmental impact for wooden buildings, but a strong correlation between the quantities of insulation, plastics, composites, and POCP, ODP, ODP and EP, respectively. Therefore, the use of these materials should be optimized to further reduce the environmental impact of wood buildings.

## 1. Introduction

In recent years, the global state of the environment has become a pressing concern. Worldwide, we experience significant environmental challenges, including climate change, resource depletion, and ecological degradation, which demand urgent attention for sustainable development [1]. The building and construction sector significantly contributes to the escalating environmental impact. Buildings account for around 37% of global $CO_2e$ emissions in 2021 and contribute substantially to the share of global energy consumption [2]. As a result, there is increasing recognition of the need for sustainable practices within the building and construction sector. While energy consumption in buildings has traditionally been a focal point for reducing environmental impacts in buildings, the significance of embodied emissions associated with raw material extraction, production, and the disposal of building materials is increasingly being documented [2]. This has led to potentially low-impact initiatives for building designs, such as designs for disassembly, reuse, recycling, renovation of existing buildings, and increasing the use of wood and bio-based materials.

Increasing the use of wood in buildings has gained considerable attention due to its inherent ecological advantages [3,4]. Trees sequester $CO_2$ through photosynthesis, popularly referred to as biogenic carbon, thus contributing to climate change mitigation [5,6]. In the decay or disposal of wood, the embedded biogenic carbon is again released into the atmosphere. Over the years, several studies have assessed the environmental potential of using wood in buildings as an alternative to other materials, for example, steel and concrete [7–13]. [13] compared the GHG emissions of five types of structural frames in timber and reinforced concrete and found that concrete alternatives may have up to 52 % increased embodied GHG emissions compared to the timber alternatives. There are various reasons for the relatively low impact of wood and biobased materials [1,14].Wood products typically require less energy-intensive manufacturing processes than conventional materials, resulting in lower GHG emissions when compared [14–16]. Another key

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argument is its carbon-storage potential. When using wood in buildings, the building will act as carbon storage until the building is demolished and the wood is disposed of [3]. argue that buildings are an *"overlooked opportunity for the long-term storage of carbon",* which could be realized through the increased use of wood. In fact [3], suggests that using wooden buildings for new urban dwellers may store up to 0.01–0.68 GtC annually, depending on the scenario considered, thereby holding enormous potential for carbon storage. Finally, an essential distinction between biobased and fossil-based materials is that the release of biogenic carbon is inherently a part of the biosphere-atmospheric system and would at some point occur irrespective of human activity, whereas the release of fossil carbon only occurs because of human activity [1,17].

Although there are strong indications of the environmental benefits of increasing the use of wood in buildings, the "true" environmental potential of doing so remains unclear because of methodological uncertainties. A comprehensive and standardized approach is necessary to evaluate and compare buildings' environmental performance accurately. Life Cycle Assessment (LCA) has emerged as a widely recognized method of quantifying the environmental impacts throughout a building's whole life cycle [18]. LCA provides a systematic framework for assessing the environmental burdens associated with raw material extraction, transportation, manufacturing, construction, use, and end-of-life modules following the European Standard EN15978 [19]. However, despite applying a standardized LCA method, modeling a building's life cycle is complex and requires extensive data on the material quantities and environmental impacts associated with construction products. Often, sufficient data are unavailable or inconsistent across studies and create uncertainties. A review of whole building LCAs finds that life cycle stages, characterization factors, and life cycle impact assessment methods, among others, can be sources of uncertainty [20]. Another study found significant differences in the Greenhouse Gas (GHG) emissions reported for the various building materials and the inputs related to construction and operational energy demand [21]. The biogenic carbon in wood adds further complexity to the LCAs of buildings and building products and, therefore, introduces more methodological uncertainty. A study from 2020 found that the transparency and conformity in biogenic carbon accounting methods are poor in case studies assessing the environmental impact of wooden buildings' but may have a significant effect on impact results [22]. This is supported by Ref. [23], which states that *"biogenic carbon emissions and sequestration related to the production and end-of-life stages of wood building products hold the most significant uncertainty in existing LCAs"*.

Considering large datasets is critical in providing generalized insights and recommendations [24]. However, the existing literature on LCAs of buildings typically only assesses a single or a few case studies at a time. Inherently, review studies join and compare studies, but comparing studies with different modeling approaches makes it difficult to discern the impact of the wooden building itself, the impact of the methodology and the optimal solutions [25]. Reviewing the existing literature on LCAs of wooden buildings shows that 59 out of 87 existing studies assess a single building [7,8,10,26–60], [61–81], while 28 studies asses more than one building [9,14,82–107]. Typically, such studies evaluate different variations of the same building cases, for instance, comparing a concrete and wood-based structure or comparing worst- or best-case scenarios. However, they usually focus only on Global Warming Potentials (GWP) and do not consider structural integrity, fire safety, acoustics, or other building requirements. Four of the reviewed studies assessed more than five different building cases [106,107], and two assessed more than ten [103–105], 20 and 24 different building cases, respectively [104,105]. The two studies, including more than ten building cases, both focus on comparing wood buildings and are conventional in their impact. However, they only consider two environmental indicators, greenhouse gas (GHG) emissions, and cumulative energy demand, thereby missing the impact on a broader range of environmental concerns. This study seeks to add to the understanding of the environmental impact of wooden buildings by investigating 45 such buildings using a consistent LCA approach. More specifically, the study will provide deeper insights into the environmental performance of wooden buildings by answering the following research questions:

- How are the embodied and operational impacts of wooden buildings distributed across a range of LCA impact categories as outlined in European Standards EN15804 and EN15978?
- What is the relationship between various material types and their influence on the environmental impact of wooden buildings, and how is this utilized in real-life low-impact design solutions?

The outcomes of this study contribute to the discourse on sustainable building practices and provides insights for decision-makers, architects, engineers, and stakeholders.

## 2. Methods

### 2.1. Data collection

The data used in this study were collected by collaborating with eight partners: five architectural companies, one engineering consultancy company, and two contractors. The building cases were selected from a mapping of wooden buildings in Denmark, where we included a mixture of buildings with different typologies, structural principles, sizes, and initial visions of the project. The building cases were designed and built from 2007 until now and include summerhouses, single-family houses, row houses, apartment buildings and other types of buildings. The "other types of buildings" category includes offices, daycare centers, schools, sports facilities, community centers and shops. In addition, the structural principle represented in the building cases is prefabricated elements, prefabricated boxes, cross laminated timber (CLT), wooden framing, glued laminated timber structure (glulam) and a combination (hybrid) (see Table 1). The complete inventory of all 45 wooden building cases is presented in the Supplementary Material.

The partners collected material amounts based on a predefined list of building elements (see Table 2). Our goal was to obtain an exhaustive overview of the material quantities in the building cases, but it was challenging, as the partners could not access all the necessary data. Data on technical installations was particularly difficult to collect; consequently, we excluded this from the assessment.

### 2.2. Life Cycle Assessment

This study uses the LCA method following the European standard EN15978 [19] to assess the environmental impact of the 45 wooden building cases. The European standard breaks down the building into its life cycle modules: A1-A3, A4-A5, B1–B7, C1–C4, and D (see Fig. 1). The scope of this study is limited to modules A1-A3, A4-A5, B4, B6, C3, and C4 (marked in blue in Fig. 1). This selection of life cycle modules is in line with the standard approach in Danish building LCAs, where the primary focus has been on the life cycle stages related to production, use, and end of life (A1-A3, B4, B6, C3–C4) to comply with the DGNB certification scheme. Recently, there has been an increased focus on the life cycle stages related to the construction phase (A4 and A5) and therefore, these modules were also included [108]. To assess the processes from modules A4 and A5, we made generic assumptions for the transport and waste of all building products. Data on energy consumption on the construction site (in A5) has been disregarded in the assessments, as data was unavailable. For wood- and concrete-based products, we used the specific data for transport and waste available in EPDs (see Supplementary Table 1). We assumed 10 % waste and 500 km of transportation in a standard lorry for all other products and used generic environmental data for the various transportation types available in LCAbyg [109,110]. This process is aligned with the approach of the Danish Voluntary Sustainability Class [111].

**Table 1**
Characteristics of building cases are divided into the building typologies summerhouses, single-family houses, row houses, apartment buildings, and others.

| Case number | Typology | Year of construction | Construction type | Height | Area | Weight [kg/m$^2$] |
|---|---|---|---|---|---|---|
| #1 | Summer house | 2015–2019 | Wooden framing | One floor | <1000 m$^2$ | 1316.5 |
| #2 | Summer house | 2020- today | CLT | One floor | <1000 m$^2$ | 570.3 |
| #3 | Single-family house | 2010–2014 | Hybrid | One floor | <1000 m$^2$ | 460.9 |
| #4 | Single-family house | 2020-today | Prefabricated elements | One floor | <1000 m$^2$ | 838.8 |
| #5 | Single-family house | 2015–2019 | Prefabricated elements | Two to four floors | <1000 m$^2$ | 866.5 |
| #6 | Single-family house | 2020-today | Prefabricated elements | One floor | <1000 m$^2$ | 590.1 |
| #7 | Row house | 2010–2014 | Prefabricated boxes | Two to four floors | 1000-10,000 m$^2$ | 319.3 |
| #8 | Row house | 2015–2019 | CLT | Two to four floors | 1000-10,000 m$^2$ | 631.4 |
| #9 | Row house | 2015–2019 | CLT | Two to four floors | 1000-10,000 m$^2$ | 506.2 |
| #10 | Row house | 2015–2019 | Prefabricated boxes | Two to four floors | >10,000 m$^2$ | 295.9 |
| #11 | Row house | 2015–2019 | Prefabricated boxes | Two to four floors | 1000-10,000 m$^2$ | 362.2 |
| #12 | Row house | 2015–2019 | Prefabricated boxes | Two to four floors | 1000-10,000 m$^2$ | 278.4 |
| #13 | Row house | 2015–2019 | Prefabricated boxes | Two to four floors | 1000-10,000 m$^2$ | 347.0 |
| #14 | Row house | 2020-today | Prefabricated boxes | Two to four floors | 1000-10,000 m$^2$ | 532.0 |
| #15 | Row house | 2020-today | Prefabricated elements | One floor | >10,000 m$^2$ | 461.8 |
| #16 | Apartment buildings | 2015–2019 | Hybrid | Two to four floors | 1000-10,000 m$^2$ | 892.4 |
| #17 | Apartment buildings | 2020-today | CLT | Two to four floors | 1000-10,000 m$^2$ | 341.8 |
| #18 | Apartment buildings | 2020-today | Prefabricated boxes | Two to four floors | >10,000 m$^2$ | 307.7 |
| #19 | Apartment buildings | 2020-today | Prefabricated boxes | Two to four floors | >10,000 m$^2$ | 625.8 |
| #20 | Apartment buildings | 2020-today | Prefabricated elements | Two to four floors | >10,000 m$^2$ | 434.5 |
| #21 | Apartment buildings | 2020-today | Hybrid | Above four floors | >10,000 m$^2$ | 625.4 |
| #22 | Apartment buildings | 2020-today | Hybrid | Two to four floors | 1000-10,000 m$^2$ | 949.2 |
| #23 | Apartment buildings | 2020-today | Hybrid | Two to four floors | 1000-10,000 m$^2$ | 405.1 |
| #24 | Apartment buildings | 2020-today | Hybrid | Two to four floors | 1000-10,000 m$^2$ | 479.4 |
| #25 | Apartment buildings | 2020-today | Hybrid | Two to four floors | 1000-10,000 m$^2$ | 484.5 |
| #26 | Apartment buildings | 2020-today | Hybrid | Two to four floors | 1000-10,000 m$^2$ | 1317.5 |
| #27 | Other | 2015–2019 | Wooden framing | One floor | 1000-10,000 m$^2$ | 1035.7 |
| #28 | Other | 2020-today | Prefabricated elements | Above four floors | >10,000 m$^2$ | 1189.6 |
| #29 | Other | 2020-today | Wooden framing | Two to four floors | >10,000 m$^2$ | 649.0 |
| #30 | Other | 2015–2019 | CLT | One floor | 1000-10,000 m$^2$ | 491.4 |
| #31 | Other | 2010–2014 | Prefabricated boxes | One floor | <1000 m$^2$ | 650.1 |
| #32 | Other | 2020-today | CLT | Two to four floors | >10,000 m$^2$ | 427.5 |
| #33 | Other | 2005–2009 | Wooden framing | Two to four floors | <1000 m$^2$ | 837.9 |
| #34 | Other | 2020-today | CLT | Two to four floors | <1000 m$^2$ | 602.5 |
| #35 | Other | 2020-today | CLT | Two to four floors | >10,000 m$^2$ | 736.9 |
| #36 | Other | 2020-today | LVL | One floor | >10,000 m$^2$ | 1090.1 |
| #37 | Other | 2015–2019 | Prefabricated boxes | Two to four floors | <1000 m$^2$ | 592.9 |
| #38 | Other | 2020-today | Wooden framing | Two to four floors | 1000-10,000 m$^2$ | 1228.9 |
| #39 | Other | 2020-today | Glulam | Two to four floors | 1000-10,000 m$^2$ | 550.9 |
| #40 | Other | 2020-today | Hybrid | Above four floors | >10,000 m$^2$ | 1300.4 |
| #41 | Other | 2020-today | Wooden framing | One floor | <1000 m$^2$ | 1793.4 |
| #42 | Other | 2020-today | Prefabricated boxes | One floor | <1000 m$^2$ | 691.5 |
| #43 | Other | 2020-today | Wooden framing | Two to four floors | >10,000 m$^2$ | 725.8 |
| #44 | Other | 2020-today | Wooden framing | Two to four floors | 1000-10,000 m$^2$ | 676.7 |
| #45 | Other | 2020-today | Glulam | Two to four floors | 1000-10,000 m$^2$ | 514.8 |

**Table 2**
Building elements included in data collection.

| Balconies | Primary building structure, surfaces, railings, and other completions |
|---|---|
| Columns and beams | Primary building structure, surfaces, and other completions |
| Electrical installations | Solar cells and elevators |
| External walls | Interior surfaces, primary building structure, insulation, exterior surfaces, and surface treatments |
| Floor decks | Lower surface, primary building structure, insulation, top surface, and surface treatments |
| Foundations | Strip foundations, slab foundations, sheet piles, pile foundations, or pad foundations |
| Ground floor slabs | Insulation, primary building structure, flooring structure, and flooring |
| Internal walls | Interior surfaces, primary building structure, insulation, interior surfaces, and surface treatments |
| Other | Anything else |
| Roofs | Surfaces, ceiling, primary building structure, insulation, roof cladding |
| Stairs and ramps | Primary building structure, surfaces, railings, and other completed items |
| Windows, doors, glazing systems | Doors, glazing systems, windows |

Replacements in B4 were calculated considering reference life spans obtained from generic Danish data [112]. In cases where recycled materials are used as input in the A1-A3 modules, we modeled these using the allocation cut-off approach [18]. The study omitted the life cycle stage D concerning reuse and recycling potential, as including this is not in line with the current Danish LCA practice.

This study uses environmental data from the database gen_dk, available in the Danish tool LCAbyg [109]. Gen_dk uses generic environmental data from the German database Ökobau [113]. Recently, the focus on developing environmental product declarations (EPDs) for building products has increased in Denmark, and comparisons between the environmental impact stated in the Ökobau database and the Danish EPDs have shown significant differences for some materials [114,115]. As this study focuses on wood, which is often compared to concrete-based alternatives, we use EPD data for these two product categories to match Denmark's geographical and technological scope (see Supplementary Table 1).

This study applies the $-1/+1$ rule for biogenic carbon accounting of wood and bio-based products, following the European standard EN16485:2014 [116]. The $-1/+1$ rule states that in module A1 biogenic carbon uptake is credited with a negative impact ($-1$) and balanced out when released by the end of life with an equivalent positive impact in C3 ($+1$). In this way, the biogenic carbon is considered neutral throughout

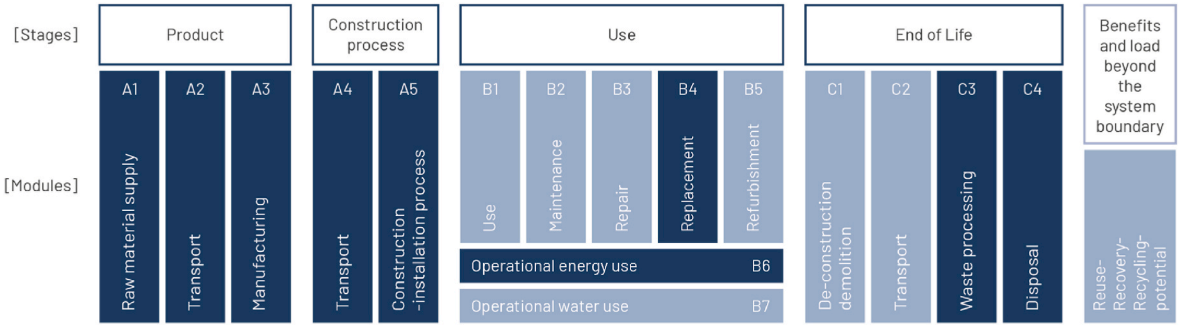

**Fig. 1.** Life cycle stages according to EN15978 [19]. The modules included in this study are marked in dark blue. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the life cycle of the assessed product under the assumption that the wood originates from a sustainably managed forest [116].

The operational impact of the energy consumption is modeled in LCAbyg using a projected energy mix. The projected energy mix goes towards a continuously larger share of renewable resources towards 2040 for district heating and electricity production (from approximately 50 % in 2020 to approximately 90 % in 2040) [109,117]. From 2040 and onwards, the energy mix for 2040 is used. For electricity, this approach gives a carbon intensity value of 0.264 kg $CO_2$ eq per kWh in 2020 and 0.0403 kg $CO_2$ eq per kWh by 2040 [109]. For district heating, the carbon intensity is 0.0365 kg $CO_2$ eq per kWh in 2020 and 0.0189 kg $CO_2$ eq per kWh by 2040 [109]. The energy consumption for each building is based on energy performance estimations following the Danish building regulations gathered as part of the data collection

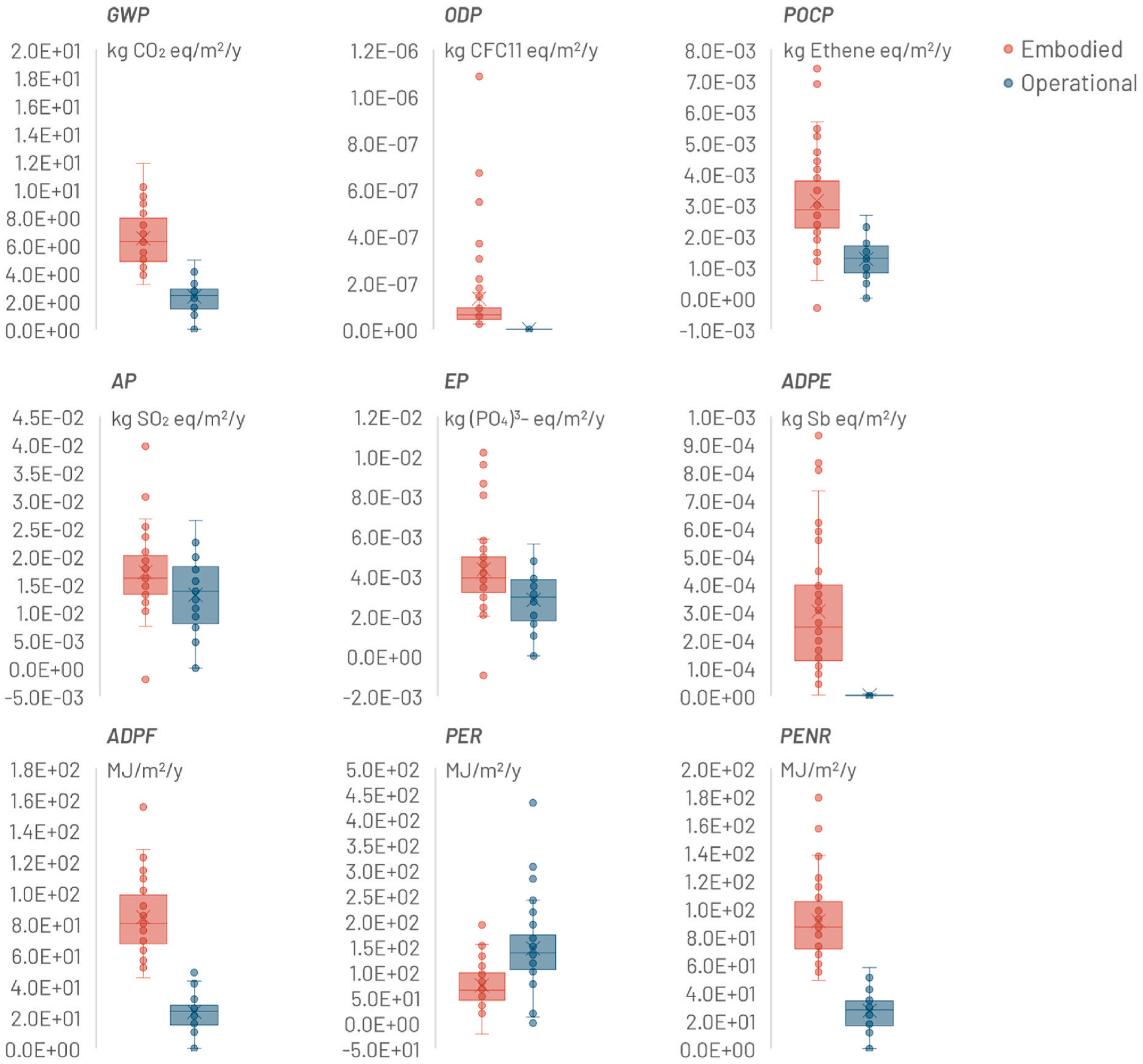

**Fig. 2.** Environmental impact results from building cases divided into impact from building elements, embodied (modules A1-3, A4, A5, B4, C3, C4), and operation (module B6) for each impact category.

process [118].

To investigate how the environmental impacts of wooden buildings are distributed across a broad range of indicators, this study includes the total set of indicators provided by the European Standards EN15804 and EN15978 [19,119]. The indicators considered are Global warming potential (GWP), Ozone depletion (ODP), Photochemical ozone creation (POCP), Acidification for soil and water (AP), Eutrophication (EP), Depletion of abiotic resources – elements (ADPE), Depletion of abiotic resources – fossil fuels (ADPF), Total use of renewable primary energy resources (PER), and Total use of non-renewable primary energy resources (PENR). The impact is harmonized based on the gross floor area and a 50-year reference study period, hence making up the functional unit.

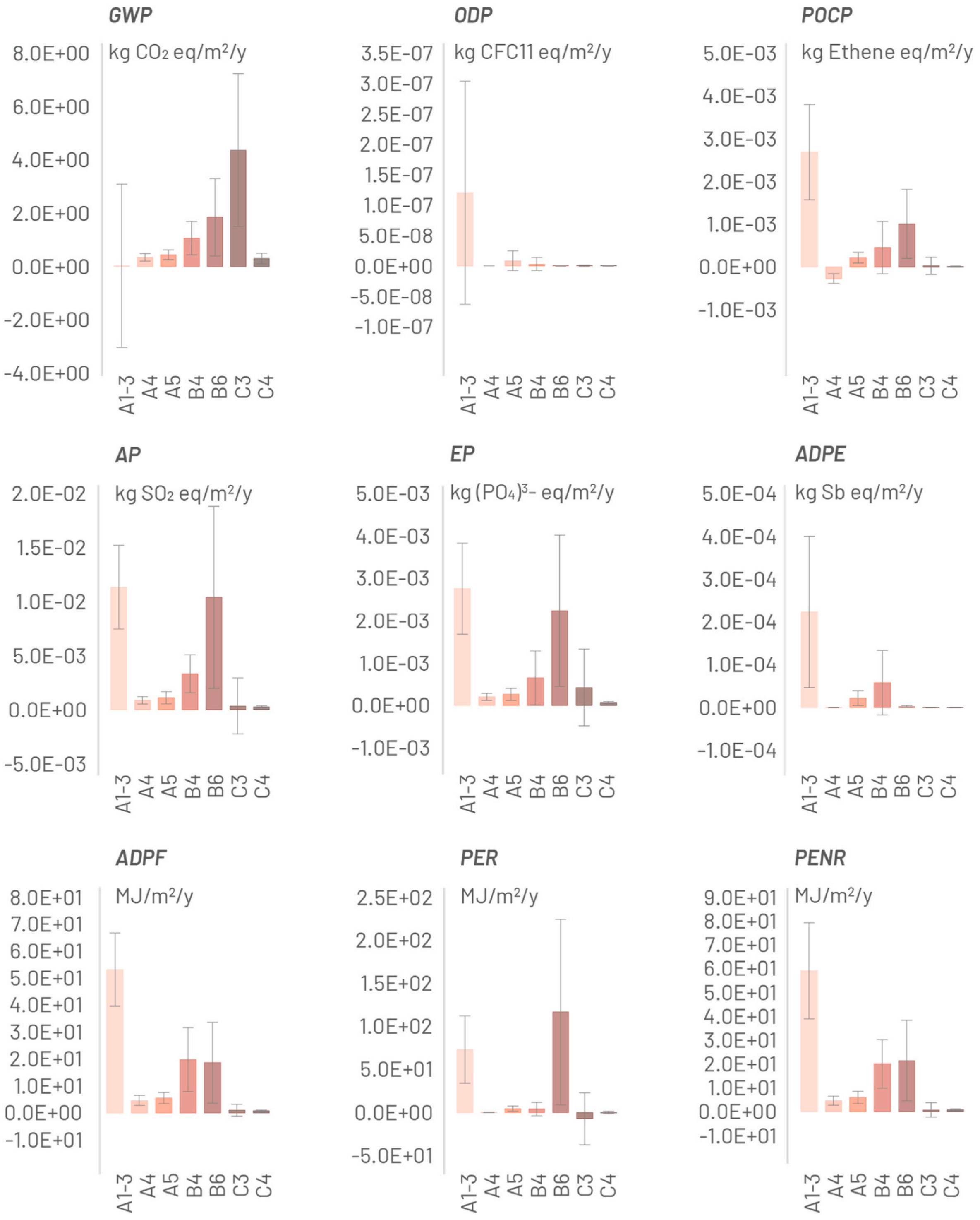

**Fig. 3.** Environmental impact results from building cases divided into life cycle modules (A1-3, A4, A5, B4, B6, C3 and C4). The error bars show the standard deviation for the 45 building cases within each life cycle module.

## 3. Results and discussion

### 3.1. Wooden buildings and environmental impact

The results for the 45 wooden building cases show that the embodied impacts cause a more significant impact, but also have a larger variation compared to the operational impacts for almost all impact categories, the only exception being the indicator PER. For GWP, the median embodied impact is approximately 2.5 times higher than the operational impact. For POCP, AP, EP, ADPF and PENR, the median embodied impact vary from being a factor 1.2 to a factor 3.1 higher than the median operational impact, whereas for the impact category PER, the median impact for operation is approximately 2.1 times larger than the embodied impact (see Fig. 2). The high impact of the operation on PER is due to a high share of renewables in the grid mix (from 50 % to 90 % of renewables in the 2040 grid mix for district heating and electricity production [120]). Although a projected energy mix considering more renewable energy is considered, the results related to the relative share of embodied impacts are imilar to those presented in other studies for advanced building projects [121–123] representative for other European countries. However, in countries where the energy mix consists of a lower share of renewables, the operational impacts may outweigh the embodied impacts as shown in Refs. [124,125]. The embodied impact is expected to vary considerably, as it relates to the buildings' physical design and thus has many variational factors, such as geometry and choices of materials. On the other hand, the operational impact is based on standardized requirements for energy consumption in buildings; therefore, the impact is much steadier across building cases. Thus, this underlines the importance of reducing emissions related to material consumption and disposal in wooden buildings while reducing the operational impacts. It deserves to be highlighted that the projects with low operational environmental impacts are not necessarily the ones with high embodied impacts. As shown from previous studies it is possible to drastically reduce the impacts of operational stages without compromising those of materials and technical equipment of the building [126,127]. While related to the absolute values of embodied environmental impacts, the wooden buildings are similar to constructions designed under the new standards requirement for low energy consumption [128].

In Fig. 2, we found that the embodied as well as the operational impact is significant considering the various impact categories. Therefore, we considered the impacts divided into life cycle modules to further understand how wooden buildings' embodied and operational impacts are distributed. From Fig. 3, we find that A1-A3 has a small impact on GWP due to the biogenic carbon being characterized as −1 in life cycle module A1-A3 following the −1/+1 rule from EN 16485 [116]. However, as the amount of wood varies significantly in the building cases, the standard deviation within this life cycle module is large (shown as the variation interval in Fig. 3). Instead, for GWP, life cycle module C3 contributes the most due to the +1 characterization of biogenic carbon. This differs from the typical LCA result of buildings and will shift the focus of stakeholders from focusing on reducing the impacts of the product stage to in this case reduce the impacts of the future end of life stage. Life cycle module A1-A3 has the highest contribution for the remaining impact categories except PER (as previously explained). This is in line with [129] that found that the manufacturing phase dominate the environmental impact.

After the A1-A3 and C3 modules, the most impactful life cycle modules are B6 and B4. However, with the indicator, it varies significantly which life-cycle module has the largest impact. Life cycle module B6 is the second largest contributor for the impact categories POCP, AP, EP, PER and PENR, whereas for ADPE and ADPF, B4 is the second largest contributor. The relatively large impact in B4 is primarily due to the replacements of photovoltaic panels, glazing, roofing felt and paint during the building's lifetime. For indicators ADPE and ADPF, we also find that polyester membranes and plywood constitute a significant share of the impact. Life cycle modules A4 and A5 have a minimal impact within all impact categories compared to the other life cycle modules. However, it is important to note that, even though the life cycle modules may seem insignificant, they are in this study based on generic transportation distances and waste amounts from EPDs and do not include energy consumption on the construction site.

### 3.2. Building elements and environmental impact

Previous studies have shown that structural building elements constitute a major part of the embodied impact of conventional buildings [130,131]. Cement in concrete is typically the predominant material with high impacts [131] and therefore, changing from cement-based to wood-based materials in structural elements may lower the impact of the building. To understand how building elements may contribute to the environmental impacts, we investigated the impact of the 45 building cases distributed among building elements. Fig. 4 shows that for GWP, the primary building elements, *foundation, ground floor decks, floor decks, external walls, internal walls, columns and beams, windows, doors and glazing systems,* and *roofs* together constitute approximately 95 % of the median impact. Across all impact categories, the primary building elements contribute with approximately 80 % of the median impact, where the primary building elements *ground floor decks, floor decks, external walls, roofs, windows, doors, and glazing systems* each constitute at least 10 % of the impact across indicators. Here we also find that the primary building elements, where it is rarely possible to change the cement-based materials with wood-based materials namely *ground floor decks* and *floor decks*, are ranked as the largest contributors. Generally, the impact distribution of the primary building parts is proportionate in the various impact categories, but for POCP and ADPE, the *ground floor deck* and *roofs* respectively have a significantly higher contribution. For both POCP and ADPE, the use of EPS insulation and polyester insulation causes a significant impact. This is supported by Ref. [121], which finds that insulation materials significantly contribute to the impact, but also hold large uncertainties. Again, this indicates that focusing on reducing the quantity and impact of other materials than wood may reduce the impact of buildings more considerably. The building element group's *internal walls, foundations, and electrical installations* constitute 4 %–7 % of the total impact across categories. In contrast, only 1 % of the impact comes from the building element groups *balconies, pillars, beams, stairs, ramps,* and the building element group *others*. Even though the primary building elements contain a high degree of wood in the 45 building cases, the primary building elements are still the main contributors within all impact categories. This highlights the importance of prioritizing the primary building elements when optimizing the environmental impact of the buildings.

To understand how the choice of structural system affects the impact

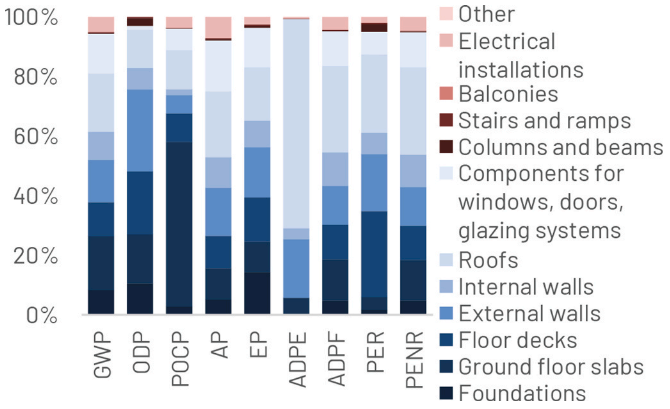

**Fig. 4.** Share of environmental impact from building elements for each impact category. The share is based on the medians of the 45 building cases.

contribution of the primary building elements, we investigated the relationship between the type of structural system and the environmental impact. In Fig. 5, we categorized all 45 building cases into different structural systems and related them to their environmental impacts. For GWP, the results show a trend that the building cases composed of prefabricated box elements may have the lowest environmental impact. This is the case for the indicators GWP, POCP, AP, EP, ADPF, and PENR. For PER, the wooden framing has the lowest median impact and for ODP and ADP, the hybrid structures have the lowest median impact. However, considering the indicators collectively, identifying the optimal solution for a low-impact structural system is impossible. For the indicators ODP, POCP, EP, ADPE, ADPF and PER, the results show large variations, specifically for the structural systems in glulam, prefabricated elements and CLT or LVL. This may both be due to the sample size within these categories, but also the building variations. Previous studies have shown a relationship between the structural system and the environmental impact, although they primarily focus on concrete and steel structures [132]. Therefore, uncertainties remain, and more detailed analysis is required to understand the relationship between the structural system of wood buildings and the environmental impact.

### 3.3. *Correlation of material types and environmental impact*

To understand the relationship between the increased use of wood in buildings and its environmental impact, we investigate the material's contribution to the embodied impact of the 45 wooden buildings. Fig. 6

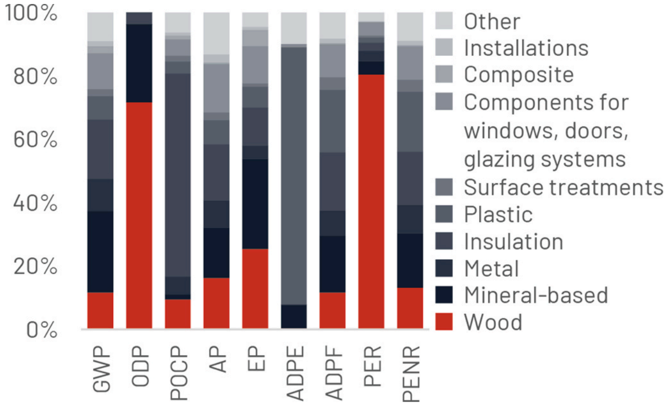

**Fig. 6.** Share of environmental impact from material types for each impact category. The share is based on the medians of the 45 building cases.

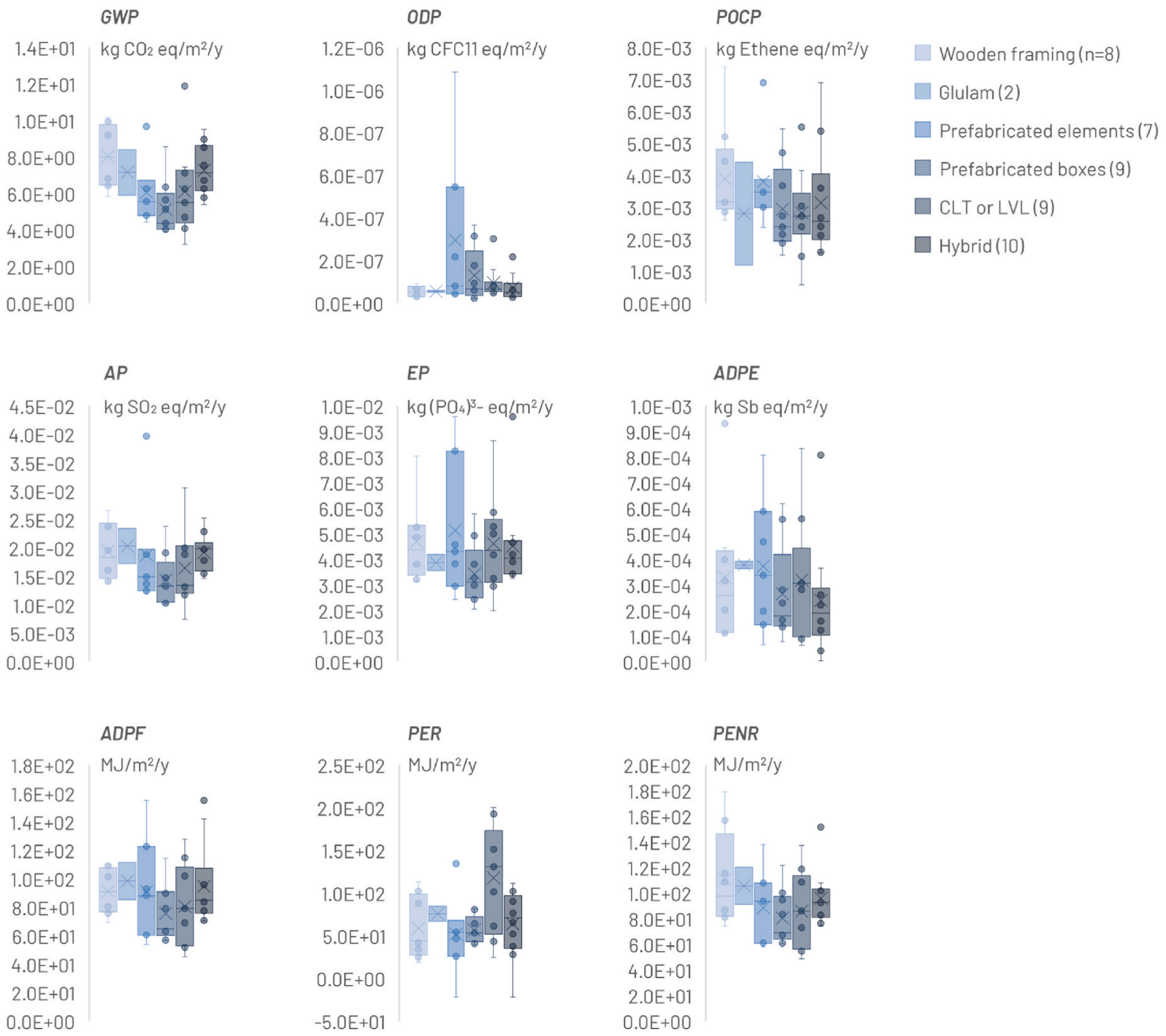

**Fig. 5.** Environmental impact for the 45 building cases divided into construction types, *wooden framing, glulam, prefabricated elements, prefabricated boxes, cross laminated timber (CLT) or laminated veneer lumber (LVL),* and *hybrid* (a combination of two of the structural systems mentioned above).

shows that the material categories mineral-based, insulation and wood are the main contributors to the overall impact. The three categories of materials account for approximately 56 % of the impact for GWP, and across all impact categories, they contribute around 43 % of the median impact. Despite the high use of wood in the building cases, mineral-based materials constitute the highest share of the GWP, with a median impact share of 28 %. Across all impact categories, mineral-based materials account for around 19 % of the impact. This high impact share from mineral-based materials is well-known in the existing literature, where, in the use of non-renewable energy, for instance, cement production processes have a significant impact [121,133]. However, the results also show a considerable variation in the types of material that contribute the most within impact categories. Most notably, wood is the main contributor in the impact categories ODP and PER, accounting for approximately 72 % and 80 % of the impact respectively. The impact on ODP and PER may relate to sawmill processes, renewables in electricity production and the inherent energy in the wood [134]. This distinct difference between impact categories shows that including a broad range of impact categories when optimizing the environmental impact of buildings is crucial. The material categories metal, plastic, components for windows, doors, glazing systems, and others account for 3 %–7 % across impact categories, and the remaining material categories for less than 1 %. The impact from metal and windows, doors, and glazing systems aligns with the findings by Ref. [121] where the relative contribution to GWP is found to be between 5 and 10 %.

Although we find a relationship between some material types and impact categories, investigating the direct correlation between material types and the impact within each indicator may provide more clarity in how choosing various materials affect the environmental impact. Fig. 7 shows the correlation between the material quantities and impact category across the 45 building cases. A strong positive correlation (in Fig. 7, marked with a large bullet in clear blue) indicates that the environmental impact within an impact category increases significantly if the material amount increases. Likewise, a strong negative correlation (in Fig. 7, marked with a large bullet in clear red) suggests that the environmental impact within an impact category decreases significantly if the material amount increases. If no bullet is present, it means that the correlation is close to zero.

For GWP, we find a weak or no correlation for all material types. For wood specifically, the correlation between the quantity and GWP is weak and negative indicating that increasing the quantity of wood in a building may contribute to a reduced impact in GWP. However, even though this and other studies [14,46,103] suggest that an increased amount of wood in buildings will help reduce the environmental impacts of buildings, there are also other studies that indicate that increasing the amount of wood in buildings will lead to higher impacts on the

**Fig. 7.** Correlation between the quantities of materials in the buildings and the environmental impact results. A large circle and intense color represent a strong correlation, whereas a small circle and vague color represent a weak correlation in a positive (blue) or negative (red) direction. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

environment due to increased harvest and forest management [135]. Therefore, the quantity of wood used in buildings should rather be optimized to minimize the overall environmental impacts. In the remaining impact categories, the correlation between wood and environmental impact is ambiguous, showing both positive and negative, weak correlations. Thus, minimizing the quantity of wood by, for example, changing the structural system does not necessarily lead to further environmental impact reductions from wooden buildings.

The weak correlation is consistent across the different material types, with a few exceptions. We find a strong and positive correlation between *plastics* and POCP, *insulation* and ODP, *composite* and ODP, as well as EP. Therefore, instead of optimizing the quantity of wood used in buildings in relation to the environmental impact, it seems to be more efficient to focus on reducing the quantity of other materials, such as insulation, plastics, and composite, to reach considerable impact reductions [136]. finds quasi-similar results, suggesting that materials constituting less than 1 % of the weight (cut-off rule recommended by EN15978 [19]) may cause significant environmental impacts and thus should be considered in LCAs. This could for example be aluminum, mineral wool and bitumen felt [136].

### 3.4. *Comparing conventional and wooden building cases*

Altogether, the results presented in Sections 3.1, 3.2, and 3.3 show how the environmental impact of wooden buildings can be further reduced by considering the embodied impacts and optimizing the use of various types of material. Even though Section 3.3 did not show any strong and direct correlation between the quantity of wood and the environmental impact, several single case studies and review studies indicate that introducing more wood into buildings may contribute to reducing the environmental impact when compared to conventional buildings. However, as stated in Section 1.1, these studies typically only assess a few buildings at a time. To investigate whether such impacts are reduced if wood is used instead of conventional materials on a larger dataset, we compared the median GWP of the 45 wooden building cases to the median GWP, PER, and PENR of 60 conventional building cases previously reported in Ref. [137] (see Fig. 8). The 60 building cases we benchmark against are, as in this study, building cases of various building typologies, areas, and construction years, but the material composition is mainly traditional Danish building materials, such as concrete, brick and steel. Also, the 60 cases were modeled similarly to this study, the main difference being that an older version of the background environmental data is used in the 60 cases. Only nine of the 60

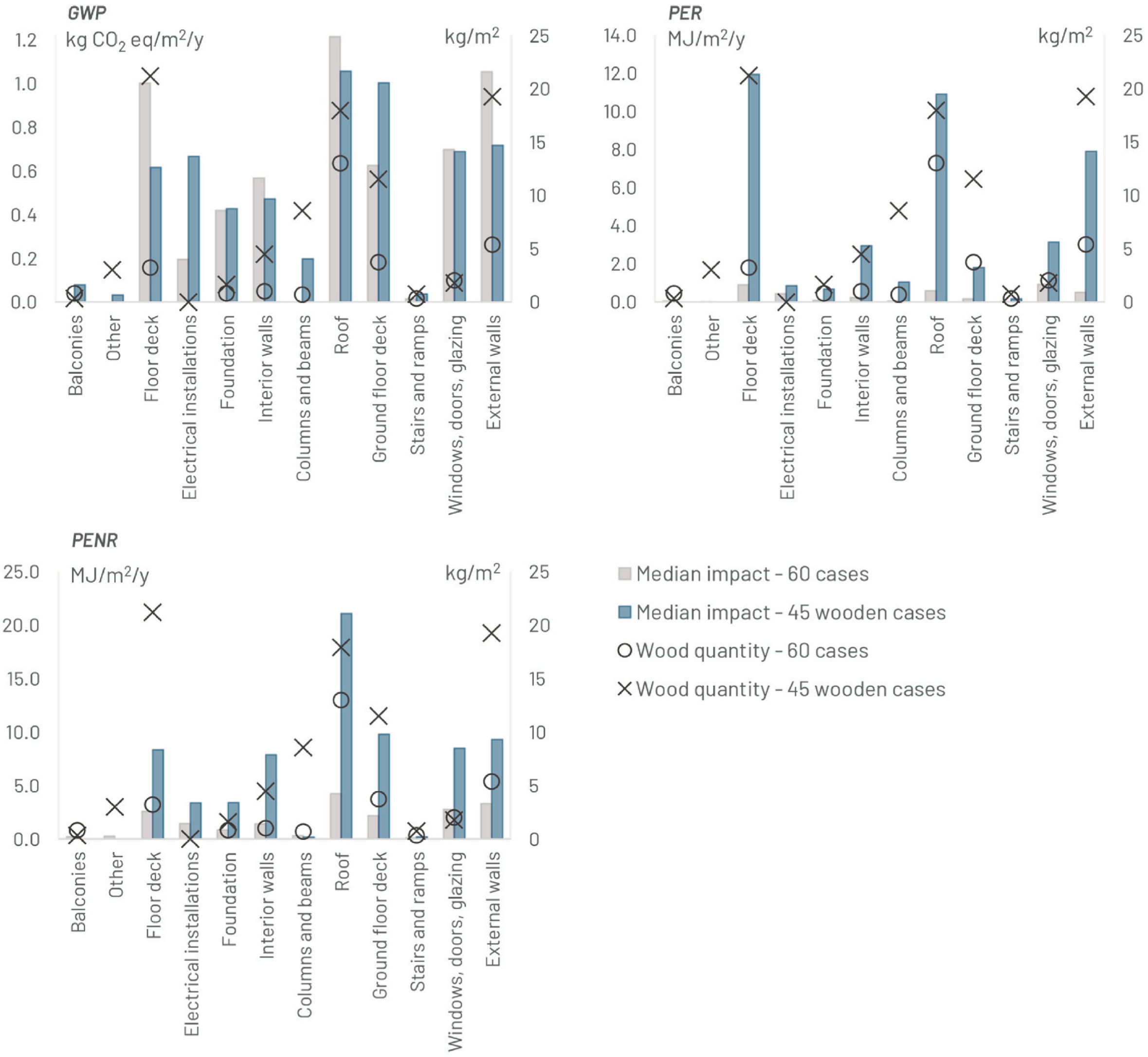

**Fig. 8.** Median environmental impact for the 45 wood building cases compared to 60 conventional building cases [137] divided into building element groups for indicators GWP, PER, and PENR. The wood quantity in each building element for the 45 wood building cases and the 60 conventional is marked with a circle and an x, respectively, and given in kg/m$^2$ on the secondary axis.

cases were wood buildings. The comparison in Fig. 8 shows that the building elements *ground floor deck, floor deck, external walls, roof,* and *electrical installations* experience the largest differences in GWP, PER and PENR between the two samples of building cases. For the building element groups *ground floor deck,* and *electrical installations,* the 45 wooden cases have higher GWP than the 60 building cases due to a few wooden cases having many photovoltaic panels and massive reinforced concrete ground-floor decks. In the building element groups *floor deck, external walls, and roofs,* the GWP is significantly lower for the 45 wooden building cases than the 60 traditional building cases, but for PER and PENR, the impact for the wooden buildings is higher than the conventional buildings across building element groups. The difference between conventional and wooden buildings is significant for *floor decks* and *roofs* in PER and PENR. This overall high impact on wooden buildings may be due, as previously stated, to sawmill processes, a high share of renewables in electricity production, and the inherent energy in the wood itself. Yet, the difference might also be due to the use of updated datasets in the 45 wooden cases, where, for instance, EPDs were used for concrete and wooden materials instead of generic data. This was not the case for the 60 conventional building cases, posing a challenge when comparing. However, comparing the impact to the quantity of wood in the two samples, Fig. 8 shows that the building element groups with large impact differences are, at the same time, the building element groups with large differences in wood quantity. This indicates that substituting conventional materials with wood and wood-based materials may lead to GWP reductions, as supported by other studies [3,25].

To understand how material types and building element compositions is used in real-life design solutions, Fig. 9 presents building element compositions for the primary building elements in the best-and worst-performing cases of the 45 wooden buildings and the 60 traditional building cases. For simplicity and as a limitation, we only focus on GWP. The figure presents the building element groups with the lowest and highest GWP and outlines the material composition of each building element. We find that two of the three best-performing conventional cases are wooden buildings, suggesting that the building element composition and material consumption does not differ significantly from the building element composition of wood buildings. Irrespective of considering the 45 wooden building cases or the 60 conventional building cases, we find that the worst-performing cases typically have a high impact from photovoltaic panels. Though the impact of photovoltaic panels seems significant, it should be balanced with the renewable energy they produce when assessing their overall environmental performance. Moreover, all the 60 conventional worst-performing cases use reinforced concrete elements and bricks for facades. One of the worst-performing wooden building cases, #3, has a high impact from roof and external walls with eelgrass insulation. However, as there was no generic data nor an EPD available for this product type, the environmental impact for eelgrass involves large uncertainties. Altogether, there appears to be a common trend between the best-performing cases and likewise for the worst-performing real-life building cases.

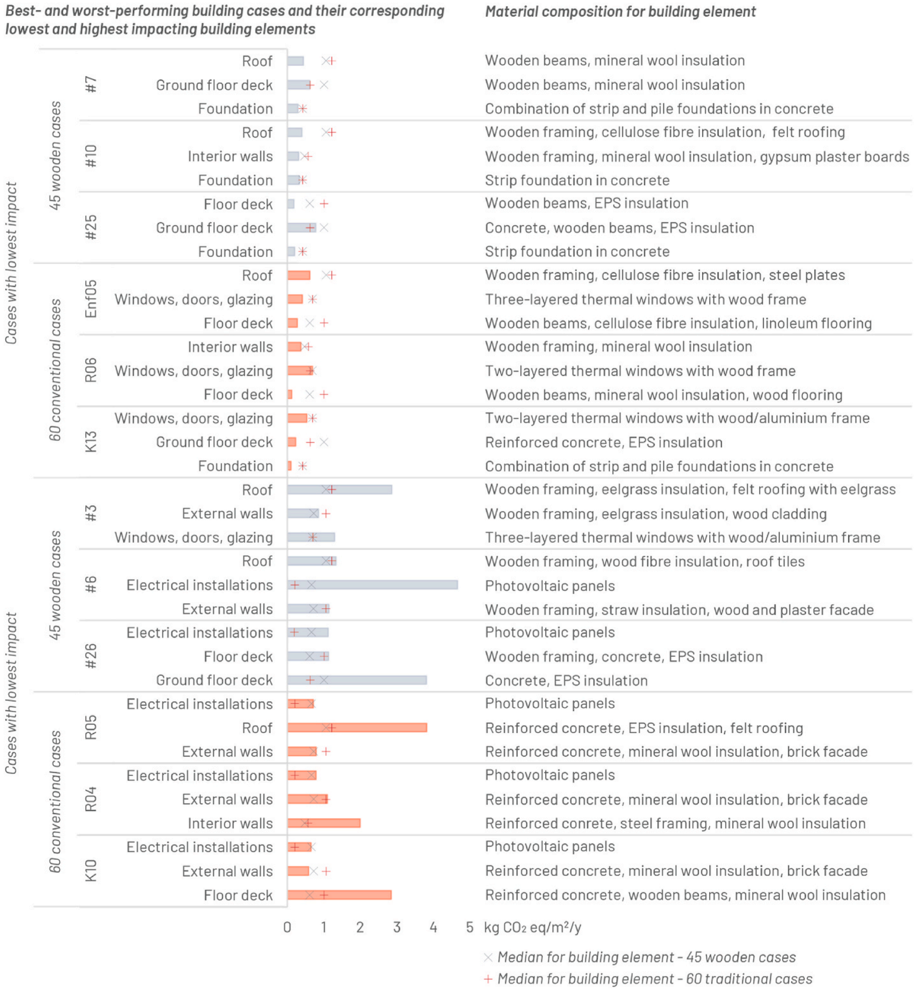

**Fig. 9.** GWP for the best- and worst-performing cases of the 45 wooden building cases and 60 conventional building cases [137] as well as material composition of the building elements.

### 3.5. *Limitations of comparing building cases*

As described in Section 2.1, we collected the data in collaboration with architects, engineers, and contractors for the building cases. However, as architects and engineers work with different levels of detail in their building models (early design models and detailed models), this poses a limitation to this study. Previous studies investigating the differences in impact between early design models and detailed models indicate that the different levels of detail can cause a difference of 14 %–24 % within the GWP indicator [47,138]. In this study, we especially experienced difficulties obtaining sufficient data on foundations and technical installations, as these are typically detailed later in the design process. However, despite different levels of detail challenging the data quality, we sought to ensure equal levels of detail between the building models through imputation. Together with our contact persons on the specific building cases, we ensured that all building elements listed in Table 2 were present (if relevant) and that detailing these building elements was as comprehensive as possible. Furthermore, the environmental database used for the modeling and specific LCA modeling assumptions, such as biogenic carbon accounting, were kept consistent when modeling the 45 building cases, providing a solid foundation for comparing impacts across the building cases.

### 3.6. *The risk of burden-shifting*

This study finds that material type and building element contribution varies a lot within each impact category. For instance, wood has a significant impact within the impact category ODP but not within the indicator GWP (see Section 3.3). Considering indicators in EN15804 and EN15978 [19], it becomes clear that a sole focus on one environmental indicator presents a risk of burden-shifting. A more comprehensive approach allows for a more accurate assessment of wooden buildings' overall environmental impact, which is also one of the strengths of LCA [18]. Applying a complete life cycle perspective and focusing on a broad range of environmental issues prevents impacts shifting across life cycle stages, processes, and environmental impact categories [18,139]. When evaluating whether an increased use of wood in buildings is environmentally beneficial, therefore, it is essential to take a holistic approach and consider all relevant environmental indicators. Several studies support this by stating the importance of considering various environmental indicators [18,140]. [140] highlight the indicators GWP, ADPE, and ADPF as important impact categories for the construction materials ready-mixed concrete, rebar, paint, glass, cement, insulation, and boards (gypsum and plywood). These were also found to be the most critical indicators in this study.

By considering a broad range of environmental indicators, researchers, policymakers and stakeholders develop a more comprehensive understanding of the environmental potential and possible trade-offs of using wood in buildings [139]. Moreover, it enables the identification of opportunities and challenges associated with wooden construction, helping to make informed choices on wood as an environmentally friendly alternative in the construction industry. However, in such an evaluation, it is also essential to consider the urgency of the different indicators. For example, the urgency of GWP is currently very high, and the IPCC states the importance of reducing global GHG emissions substantially to avoid potentially catastrophic consequences [1]. In contrast, the indicator ODP is currently less urgent due to the adoption of the Montreal Protocol in 1987 [141]. This states that the importance of the different indicators varies dynamically over time and that it can be challenging to address all environmental indicators simultaneously. Therefore, assessing the urgency of the environmental indicators and choosing the most urgent to focus on might be necessary to reduce emissions sufficiently within one very urgent environmental category, such as GWP.

## 4. Conclusion

This study contributes to understanding the environmental performance of wooden buildings by investigating a broad range of building cases using a consistent LCA approach. From the LCA of the 45 wooden building cases, this study finds that the embodied impact is significant within almost all impact categories outlined in the European Standards EN15804 and EN15978, the only exception being the impact category related to renewable energy consumption. Supported by other studies, this study finds that the primary building element groups *ground floor deck, floor deck, windows, doors, glazing systems,* and *external walls* contribute the most to the impact across impact categories. Despite wooden products generally possessing a low impact on global warming, this study does not find any direct correlation between material types and environmental impacts in the 45 building LCAs. Only three material types (insulation, plastic, and composite) correlates directly and positively with different impact categories (ODP, POCP, and EP). As a result, when increasing the quantity of these three types of materials in buildings, one may expect a similar increase in ODP, POCP, and EP. Thereby, our findings indicate that when seeking to optimize the environmental impact of wood buildings, it is important to consider all various types of materials and their quantity rather than merely focusing on the use of wood itself.

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## CRediT authorship contribution statement

**Camilla Ernst Andersen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Endrit Hoxha:** Writing – review & editing, Supervision, Conceptualization. **Freja Nygaard Rasmussen:** Writing – review & editing, Supervision, Conceptualization. **Christian Grau Sørensen:** Software, Data curation. **Harpa Birgisdóttir:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of competing interest

I, Camilla Ernst Andersen, state on behalf of all co-authors that the study does not relate to any sort of already published work. The study is supported financially by the Villum Foundation and Realdania, however the authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors have shared data in a format where the cases are not identifiable, as the data are confidential.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111201.

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