

Forecast of building materials and their related environmental impacts: comparing wood-based and conventional construction pathways

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Abstract

The building sector is a major contributor to global greenhouse gas emissions (GHGe), necessitating carbon mitigating strategies to reduce its environmental impact. This study investigates the environmental implications of two construction pathways in Denmark - wood-based and conventional - projecting material flows and emissions from 2025 to 2050. Using life cycle assessments (LCA) for 16 case buildings across multiple typologies, the study evaluates the potential for wood-based materials to reduce GHGe compared to conventional materials. The results highlight significant environmental benefits of wood-based pathways, particularly in reducing upfront GHGe and the reliance on non-renewable resources. However, the findings indicate that annual emissions account for 49% and 96% of Denmark's allocated share of the global carbon budget for the wood-based and conventional pathways, respectively, underscoring the pressing need for systemic changes in the construction industry. Comprehensive strategies integrating biobased solutions, circular economy principles, and reduced reliance on new construction are critical to achieving Denmark's climate goals.

1 Introduction

The building sector is one of the most significant contributors to global environmental challenges, accounting for approximately 37% of CO₂-emissions worldwide (UNEP, 2022). The sector's environmental footprint comes from its extensive use of resources and the emissions associated with the production, transportation, and disposal of construction materials. With global rise in population and rapid urbanisation driving an increase in construction activities, resource demands and material-related emissions are expected to grow substantially (UNEP, 2022). In response to the urgent need to reduce greenhouse gas emissions (GHGe) from the building sector, countries are now considering integrating carbon limit values into their building regulations. In 2023, Denmark was among the first countries to establish carbon limit values for new buildings based on the method life cycle assessment (LCA) (Danish Authority of Social Services and Housing, 2023), following the French introduction in 2020 (Barjot & Malmqvist, 2024). Other countries, such as Sweden and Finland, have followed by adopting LCA-based carbon limit values, with additional nations planning to follow suit (Barjot & Malmqvist, 2024; Železná et al., 2024).

These initiatives highlight the growing recognition of the building sector's critical role in mitigating global climate impact, with LCA as a method for quantification and measuring mitigation strategies (Säynäjoki et al., 2017). One mitigation strategy for reducing GHGe in the construction sector gaining attention in recent years is increasing the use of renewable materials instead of carbon intensive non-renewable products. Renewable materials, such as wood, bamboo, and other biobased resources, offer two key advantages over conventional, non-renewable alternatives. First, the production of renewable materials typically requires less energy, resulting in significantly lower upstream emissions compared to materials like steel, concrete, and brick (Gustavsson & Sathre, 2011; Sathre & O'Connor, 2010). Second, renewable materials possess the unique ability to capture and store atmospheric carbon during their growth phase (Forest Europe, 2020). When incorporated into buildings, the carbon sequestered in renewable materials

remains stored throughout the building's lifecycle, temporarily offsetting emissions from the construction sector (Sathre & O'Connor, 2010). Churkina et al. (2020) estimate that wooden buildings can temporarily store between 0.01–0.68 Gt of carbon per year globally. Additionally, UNEP (2023) suggests that replacing conventional building materials with mass timber could reduce global emissions by 14–31%. (UNEP, 2023), highlighting their major potential for reducing GHGe worldwide.

Despite their advantages, the adoption of renewable materials in construction remains limited (Gottlieb et al., 2023, 2024). Non-renewable materials continue to dominate the sector, comprising 89% of total material use, while renewable resources represent just 11% (UNEP, 2023). Additionally, the building stock has increasingly shifted towards concrete-based construction, dominating over traditional materials like brick and wood (Yuan & Lu, 2024). This disparity highlights the conflict between the emission-reduction potential of renewable materials and the building sector's entrenched reliance on conventional materials. Key challenges to the broader adoption of renewable materials include the availability and scalability of these resources, the development of suitable construction techniques, and ensuring their long-term durability and performance across various applications (Dace et al., 2024; Gottlieb et al., 2023). In addition, the so far singular focus on reducing GHGe through an increased use of renewable resources raises concerns about potential trade-offs, such as shifting burdens to other environmental impacts. Thus, insights are needed to assess which additional environmental impacts, if any, may arise on a larger scale when transitioning to renewable materials in construction.

Predicting future resource flows and emissions associated with construction activity is essential for guiding sustainable urban development, especially when considering the implications of various mitigation strategies. Numerous studies have examined the scale of future resource demands, employing diverse approaches. For example, Drewniok et al. (2023) modelled changes in the UK building stock and its environmental impacts, extrapolating population growth trends from historical patterns. Similarly, Deetman et al. (2020) used a dynamic stock model to analyse building stock trends from 1970 to 2050. Their projections indicated a 50% increase in residential building stock by 2050, driving substantial demand for construction material like steel and concrete compared to 2002 levels. Bergsdal et al. (2007) and Hu et al. (2010) also forecasted residential building stock using material flow analysis, focusing on concrete and wood demand in Norway and Beijing, respectively. While these studies provide valuable insights about the trajectory of the building sector, they primarily concentrate on residential buildings and lack spatial resolution in their analyses.

Hoxha et al. (2024) addressed this limitation by presenting spatially distributed projections of Denmark's construction activities between 2022 and 2050. Using the Holt-Winters forecasting method, their study categorized activities by building typologies and estimated an annual average addition of 8.2 million m² of floor area, with residential buildings accounting for nearly half of this growth (E. Hoxha et al., 2024). Specifically, single family and multi family homes were projected to contribute 27% and 29%, respectively, to the annual emission of 4 million tons CO₂ eq from new construction (E. Hoxha et al., 2024). However, this study's projections were based solely on current construction practices and did not

consider potential changes in these practices due to mitigation strategies, highlighting a significant gap in its analysis.

Arehart et al. (2022) explored future material needs and embodied carbon emissions across various construction techniques in the United States – wood-based, concrete-based, steel-based, and others – focusing on structural systems rather than entire buildings. Hansen et al. (2024) analysed the climate mitigation potential of transitioning from conventional construction techniques to those using renewable materials, employing a consequential LCA approach. Ipsen et al. (2024) similarly explored design strategies for the building sector in Quebec, Canada, using consequential LCA. These two papers are consequential, hence fundamentally different from the attributional LCA approach used in EN15804 and EN15978. For more details on the differences, we refer to the comprehensive explanation of Ekvall (2019). While the previous studies considered the entire buildings as well as different building typologies, they did not account for the future trajectory for each building type and practice. In addition, both Arehart et al. (2022), Hansen et al. (2024) and Ipsen et al. (2024) focused exclusively on GHGe, neglecting broader environmental impacts.

Kayo et al. (2019) presents a detailed model of the forest product flows and the substitution effect of concrete buildings. The study centers on Japan, hence it is not conforming to EN 15804. It uses a static forecast and omits building topologies such as office or institutional buildings. It applies a cradle-to-gate approach for materials, which limit the embodied impact assessment, expresses the environmental impact as a damage category in monetary terms, introducing value judgment further down the impact pathway. These constraints hinder their applicability for climate limit regulation.

Alaux et al. (2024) developed a comprehensive building stock model capable of capturing prospective scenarios and they use archetypes of various options for new and existing constructions. The use of macro components enables flexible modelling useful for many situations and scenario exploration. However, it introduces undefined generalisations that compromise needs for specific regulatory contexts. Its impact assessment scope presented is limited to global warming potential (GWP), restricting insights into other environmental impact categories.

Studies aligned with the Danish climate limit value regulations require detailed whole-building assessments, necessitating the use of complete case buildings for compliance and precision beyond archetypes. Further, most of the reviewed research using attributional LCA narrows the scope of impact categories to climate change, which highlights the importance of evaluating a wider range of environmental consequences to mitigate the risk of burden shifting and to inform decision-making about future construction strategies effectively.

1.1 Research aim and scope

Existing literature highlights the urgent need to mitigate GHGe from residential buildings, particularly as housing demand is expected to increase in the coming decades. Although resource demand forecasting has primarily focused on residential buildings, other building types are equally critical. Moreover, many

studies adopt a narrow focus on GHGe as the sole indicator of environmental sustainability. However, with six out of nine planetary boundaries already transgressed (Richardson et al., 2023), decision-making requires a broader understanding of the environmental opportunities and trade-offs associated with transitioning to renewable construction materials. In Denmark, this need is further amplified by regulatory requirements for climate limit values across building typologies. Providing the industry with operative pathways that reflect current practice and are immediately implementable thus carries serious policy implementation relevance.

This highlights a critical research gap: the role of renewable materials, particularly wood, as an environmental impact mitigation strategy across a broader range of building types remains underexplored. Therefore, this study follows the path of Churkina et al. (2020) but extends the assessment to include all environmental indicators, while providing more details on the individual building typologies broken down by life cycle stages and material types. Further, it addresses the transition from conventional to wood-based construction using attributional LCA applied in regulatory practice, which is currently missing in the literature.

To address this research gap, the present study investigates the potential of renewable materials, specifically wood, to reduce environmental impacts across eight different building types. As climate limit values have recently been made stricter, identifying immediate pathways and solutions for sectoral application are crucial. By leveraging national-scale material demand forecasts from Hoxha et al. (2024), resembling the cyclical nature of the construction sector, this study evaluates the environmental benefits of substituting conventional construction materials with wood-based alternatives. This analysis is based on recent real-world whole-building case studies that are representative of regulatory conditions at the time of data collection. Ultimately, this study provides a foundation for decision-support, facilitating the transition toward a low-impact, resource-efficient building sector.

2 Methods

2.1 Case studies

The study analysed data from 16 case buildings distributed across various building typologies, including single family homes, multi family homes, office buildings, daycares, schools, retail spaces, sports centres, and cultural buildings. The selection of buildings was based on case and data availability for each building typology. This is an explorative study where the buildings represent approaches to constructing two categories of building technologies. This case study approach is not inclusive of all Danish building typologies, but it provides valuable insights to the trade-offs and similarities of environmental impacts in a the real-word context (Flyvbjerg, 2011). The remaining building typologies not included in this study represents less than 14% of newly constructed building area, hence likely having a peripheral impact.

The case buildings were categorised into two groups: wooden and conventional, which represent two pathways. The focus is on new buildings for those two pathways because a change to timber construction has gained traction to mitigate climate impacts, as unfolded in the introduction, but evaluating this change using a broader scope impact categories remains unexplored in the literature. Wooden buildings were defined as those with at least 50% of structural components made of wood. Conventional buildings were primarily constructed using concrete, bricks, and steel, reflecting traditional Danish construction practices. The cases were derived from existing datasets and previous studies (Andersen et al., 2024a, 2024b; Tozan et al., 2023; Zimmermann et al., 2020) and are presented in Table 1. The buildings were located across different regions of Denmark to account for geographical variations.

Table 1
Building case study information for the conventional and wooden pathway.

Building typology	Conventional pathway			Wooden pathway		
	Construction	No. of storeys	Area [m ²]	Construction	No. of storeys	Area [m ²]
Single family house	Lightweight concrete blocks	One	< 1,000	CLT	One	< 1,000
Multi family house	Concrete in-situ element and columns	Three-six	> 10,000	CLT	Three	1,000–10,000
Office	Concrete in-situ element, columns, beams/steel beams	Five	> 10,000	Wood frame	One	1,000–10,000
Day care	Concrete precast and in-situ element	Five	< 1,000	Hybrid: Glulam columns-wood frame	One	< 1,000
School	Concrete in-situ element and columns/steel beams	Four	> 10,000	Glulam	One-two	1,000–10,000
Retail	Concrete in-situ element	One	1,000–10,000	Hybrid: Glulam columns/wood frame	One	1,000–10,000
Sports centre	Concrete precast element/steel columns	One-two	1,000–10,000	CLT	One-two	1,000–10,000
Cultural building	Concrete precast element/sandwich panel	Four	1,000–10,000	Hybrid: Glulam column/wood frame	One-two	1,000–10,000

The LCA of all case buildings included the below listed building parts, structured into three main categories:

- External envelope: Foundations, ground floor slabs, external walls, roofs, beams and pillars, windows, doors, glazing systems, and balconies.
- Internal elements: Internal walls, floor slabs, stairs and ramps, and other interior components.
- Systems and equipment: Heating, ventilation, and cooling systems, drainage and water systems, and technical installations (e.g., solar cells and elevators).

2.2 Life cycle assessment

Since the 1990s, international standards such as ISO 14044 and ISO 14040 (ISO, 2022a, 2022b) have provided standardised methodologies for LCAs. LCAs aim to evaluate environmental impacts across a product's entire life cycle, from raw material extraction to disposal by the end of life (JRC-IES, 2010), ensuring a comprehensive analysis by incorporating all relevant processes and impacts within predefined impact categories (Hauschild et al., 2018). These international standards (ISO, 2022a, 2022b) have been further complemented by European standards EN 15804 and EN 15978 tailored to LCAs of construction products (CEN, 2012a, 2012b, 2019).

The LCAs in this study are based on the methodology employed (Andersen et al., 2024a, 2024b; Andersen, 2024). The assessment follows the standards EN 15804 and EN15978 and covers the life cycle stages A1-A3 (product stage), A4 (transportation to the construction site), A5 (construction process), B4 (replacements during the use phase), and C3-C4 (end-of-life processing), as presented in Fig. 1. A reference study period of 50 years was used for all assessments, consistent with standard practice in Denmark for building LCAs (Danish Authority of Social Services and Housing, 2023). The inventory modelling is based on the gen_dk database integrated into the LCAbyg tool (BUILD, 2025), which builds on the Ökobaudat database. This was supplemented with Environmental Product Declarations (EPDs) for concrete and wood products to enhance the representativeness of current Danish conditions (Andersen et al., 2024a, b). The information about end of life from EPDs and gen_dk for conventional pathway see Hoxha et al. (2024) and for the wooden pathway EPDs are also provided in the Supplementary Information (SI) F9.

For life cycle stages A4 and A5, case-specific data were unavailable, and generic assumptions were therefore applied. For A4, a transportation distance of 500 km by lorry (standard) was assumed. However, transportation distances for concrete and wood products were based on data provided in the respective EPDs. For A5, a waste rate of 10% was assumed for all materials except for concrete and wood products, where a reduced rate of 5% was applied (see SI F9). Energy consumption at the construction site was omitted from the assessment due to data unavailability. A complete list of EPDs used in the assessments, along with assumptions regarding transportation and waste rates, is provided in Supplementary Materials by (Andersen et al., 2024a, b) and in SI F9.

Material replacements during the study period were modelled using the Danish guideline for the expected service lives of building components (Haugbølle et al., 2021), aligning with national practices for building LCAs (Danish Authority of Social Services and Housing, 2023). Biogenic carbon was accounted for using the – 1/+1 approach, as specified in the European Standard EN 16485:2014 (CEN,

2014). This method accounts for carbon sequestration during material growth (-1), attributed to the A1-A3 stages, and emissions during end-of-life processing (+ 1), attributed to the C3-C4 stages, entailing that the biogenic CO₂ emissions are zero over the entire life cycle. Any annualised climate impact considers the sequestration and emission equally distributed over the number of years, i.e., zero sequestration and emissions from biogenic CO₂.

To provide a comprehensive perspective on environmental impacts across construction pathways, indicators specified in EN 15804 + A1 (CEN, 2012a) were included in the assessment. The limit values in the Danish regulation are based on this version of the standard, which the industry must use and comply with, hence this study follows that policy decision. The indicators are:

- Global Warming Potential (GWP): kg CO₂ eq
- Ozone Depletion Potential (ODP): kg CFC-11 eq
- Photochemical Ozone Formation Potential (POCP): kg Ethene eq
- Acidification Potential (AP): kg SO₂ eq
- Eutrophication Potential (EP): kg PO₄³⁻ eq
- Abiotic Depletion Potential – Minerals and Metals (ADPE): kg Sb eq
- Abiotic Depletion Potential – Fossil Fuels (ADPF): MJ
- Total use of non-renewable primary energy resources (PENRT): MJ
- Total use of renewable primary energy resources (PERT): MJ

The updated Danish climate limit values in kg CO₂ eq/m²/year: Single family homes is 6.7; multi family homes, office buildings and retail spaces are 7.5; daycares, schools, sports centres, and cultural buildings are 8.

2.3 Forecasting model

We used the forecast of construction activity in Denmark for 2025–2050 developed by Hoxha et al. (2024). The forecast model uses historical time series of construction activity from 1982–2021 using the additive method of Holt-Winter (E. Hoxha et al., 2024). That method is suitable for historical data series where you can capture a trend component based on annual levels of construction activity, which at the same time is influenced by seasonality i.e., the cyclability that governs the construction sector. Therefore, the method comprehends historical cyclicity in construction activity so the forecasting will make the future built area to follow similar behaviour. The estimates of annual floor areas (Fig. 2) is coupled with the material and environmental impact intensities of the 16 case buildings representing each building type. The steps used for forecasting is presented in Fig. 3. The forecasting considers the two what-if scenarios of conventional and wooden construction, i.e., a complete change to wooden construction, which present the two boundaries of where other scenarios remain within. This is previously analysed for climate impact but not for a broader range of impact categories. Further, the

market for Denmark of forest available for wood supply has plenty of availability for implementing timber in buildings in Denmark (Hansen et al., 2025).

2.4 Mapping of material flows and life cycle stages

Material flows and life cycle stages were further classified into categories to facilitate a comprehensive and consistent mapping. Materials were grouped in the following categories: biobased materials, mortar, aluminium, glass, steel, plastic, concrete, insulation, fired clay, clay, bitumen, paint, plaster, zinc, aggregate, and copper. EoL scenarios were modelled based on Danish conditions, assuming materials followed one of three dominant pathways: recycling, incineration, or landfilling. Materials with mixed EoL outcomes were categorised under their most dominant pathway for simplification. Additionally, the life cycle stages were grouped into two categories: construction and use. The construction category cover life cycle stage A1-A3 (product stage), A4 (transportation), A5 (construction process), C3 (waste processing), and C4 (disposal). The use category includes life cycle stage B4 (replacements during the use phase).

3 Results and discussion

3.1 Material intensity and flow analysis

The material intensity analysis in Fig. 4 shows clear differences between wood-based and conventional construction pathways. In wood-based pathways, the external envelope accounted for a much larger share of the total weight, averaging 91%, compared to 59% in conventional pathways. Conversely, the internal elements represented only 8% in wood-based pathways but a significantly higher 41% in conventional ones. Systems and equipment contributed minimally to the total weight in both pathways, averaging just 0.5%.

Significant variations were also observed within each construction pathway. In wood-based cases, the external envelope contribution ranged from 82% to 99.7%, while in conventional cases, it varied considerably more, from 26% to 95% (Fig. 4). These differences can be partly attributed to inconsistent categorisation of building elements between cases. For example, some slabs may have been misclassified as ground slabs, impacting the weight distribution between the external envelope and internal elements. Building design and type also played a critical role in these variations. For example, single-storey buildings without slabs and sports centres with few or no internal walls results in lower weight for the internal envelope. In contrast, multi-storey buildings with numerous internal partitions gave higher internal element contributions. These findings highlight the influence of both classification practices, design features, and functional purpose of building types on material intensity outcomes impacting both the wood-based and conventional pathways.

Single family homes, multi family homes, and offices are the primary building typologies projected for future construction, representing 14%, 16%, and 14% of planned projects, respectively (Fig. 2). These typologies also account for the largest share of material weight in both wood-based and conventional

construction pathways. Figure 5 presents the material flows on building elements, material groups, life cycle stages, and waste management activity at the end of life. In the wood-based pathway, single family homes contribute 26% of the total weight, followed by multi family homes at 21% and offices at 39% (Fig. 5). In the conventional pathway, single family homes constitute 20%, while multi family homes and offices account for 38% and 29%, respectively (Fig. 5).

The distribution of material weight among building elements also differs significantly between the pathways. In the wood-based pathway, the foundation contributes the largest share at over 40%, followed by the ground slab at 24% (Fig. 5). Together, these elements account for 68% of the total weight, driven by the high amount of concrete used in their construction. External walls and roofs contribute smaller proportions in the wood-based pathway, at 12% and 9%, respectively, while the remaining building elements make up less than 3%. By contrast, the conventional pathway shows a more equal distribution, with the slabs contributing the most weight at 29%, while the foundation, internal walls, ground slab, and external walls each contribute more than 10% (Fig. 5).

Concrete remains the dominant material in both pathways due to its density and widespread use. It accounts for 68% of the total weight in the wood-based pathway and 85% in the conventional pathway. Further, wood and bio-based products comprise a significantly larger share in the wood-based pathway with 23% of the total weight, compared to just 2% in the conventional pathway. Other materials, such as steel and fired clay, contribute marginally to both scenarios, each making up less than 3% of the total weight (Fig. 5).

At the end of the building lifecycle, most materials are recycled or repurposed according to established practices in Denmark. Concrete is typically recycled as road filling, reflecting the standard approach to construction waste management (Danish Environmental Protection Agency, 2015). Wood and bio-based materials are assumed to be incinerated by EoL, with the recovered energy feeding into the district heating systems (Sørensen et al., 2019).

3.2 Environmental Impacts of Construction Pathways

The comparison of environmental impacts on Fig. 6 reveals distinct patterns between wood-based and conventional pathways across various impact categories. Conventional pathways generally exhibit larger impacts for categories such as GWP, POCP, AP, ADPF, and PENRT. For example, the GWP of conventional pathways is nearly double that of wood-based pathways, while POCP and AP are approximately twice and 1.5 times greater, respectively (Fig. 6). Similarly, for the resource indicators ADPF and PENRT, the impacts are about 1.3 times larger in conventional pathways. Wood-based pathways, on the other hand, demonstrate larger impacts in categories like ODP, EP, ADPE, and PERT. However, for ODP, EP, and ADPE, the differences between the two pathways are minor, with wood-based impacts only slightly exceeding conventional ones. The most notable difference lies in resource category PERT, where wood-based pathways contribute significantly more than conventional ones. This difference primarily reflects wood's embedded energy and potential as a renewable energy source, leading to a higher impact in this indicator when used in buildings.

A deeper examination of upstream environmental impacts - those associated with material extraction and production - reveals significant differences, particularly for GWP (Fig. 6). In wood-based pathways, the upstream GWP is negative due to the biogenic carbon credit applied during A1-A3, which accounts for temporary carbon storage in wood materials when using the - 1/+1 rule. This results in net-negative impacts of -0.16 Mt CO₂ eq per year. Conversely, conventional pathways exhibit net-positive upstream GWP impacts of 1.40 Mt CO₂ eq per year, as fossil-based emissions outweigh the temporary biogenic carbon storage (Fig. 6). This creates a significant contrast, with conventional pathways showing upstream GWP impacts that are 8.37 times greater than those of wood-based pathways. Upstream impacts for conventional pathways also dominate in other categories, such as POCP, AP, ADPF, and PENRT, where they are consistently larger than those of wood-based pathways by factors ranging from 1.5 to 2.2. In contrast, upstream impacts for wood-based pathways are slightly higher than those of conventional pathways in ODP, EP, and ADPE, though the differences are close to negligible. The only category where wood-based pathways show a substantially larger upstream impact is PERT, where their reliance on renewable resources results in impacts over twice as high as those of conventional pathways.

Downstream impacts - those occurring during the use phase and end-of-life stages - also vary between the two pathways, as displayed on Fig. 5. The conventional pathway exhibits higher impacts for ODP, POCP, and AP, with the greatest difference observed in ODP (Fig. 6). The downstream ODP of the conventional pathway is nearly six times greater than that of wood-based pathways, primarily due to the higher utilization of materials like solar panels, EPS insulation, aluminium, and steel. However, while the relative difference is significant, the absolute ODP impact for both pathways remains small, limiting its overall environmental significance. Conversely, wood-based pathways have higher downstream impacts in GWP, EP, ADPE, ADPF, PENRT, and PERT. For GWP, wood-based pathways show nearly double the downstream impact of conventional pathways due to emissions associated with incineration of wood materials at the end of life. Similarly, wood-based pathways contribute substantially more to PERT downstream, reflecting the significant renewable energy content associated with biogenic materials.

The most notable differences between the two pathways occur in upstream GWP and downstream ODP. For GWP, the wood-based pathway benefits from the substantial biogenic carbon storage credited during material production, leading to net-negative upstream impacts due to the - 1/+1 rule. In contrast, the conventional pathway's reliance on fossil-based materials results in substantial positive GWP impacts from manufacturing. For ODP, the higher downstream impacts in conventional pathways are driven by the greater use of certain materials, such as solar panels and insulation, which contribute disproportionately to this category. Despite the large relative difference in ODP, the absolute impact remains minimal for both pathways, reducing its overall environmental significance. Overall, these findings highlight critical trade-offs between the two construction pathways. Conventional scenarios tend to have higher fossil fuel-based impacts, while wood-based pathways rely more on renewable resources and show specific downstream challenges, particularly related to renewable energy and release of biogenic carbon at incineration.

3.3 Greenhouse Gas Emissions and Material Contributions

Addressing global goals for reducing GHG emissions, requires comparison of the GWP related to wood-based and conventional pathways in more detail. In Fig. 7, the two approaches show remarkably different impacts, with the conventional pathway contributing 2.03 million tons of CO₂ equivalents, nearly double the 1.04 million tons of CO₂ equivalents coming from the wood-based pathway.

A closer look at building typologies reveals notable variations in GWP distribution between the two pathways. In the wood-based pathway, multi family homes contribute the most, making up 35% of total impacts, followed closely by single family homes at 34% and office buildings at 13% (Fig. 7). Other typologies, such as schools, daycare centers, retail spaces, sports centers, and cultural buildings collectively represent smaller shares. Conversely, in the conventional pathway, single family houses become the dominant typology, accounting for 31% of total GWP, while offices account for a substantial 29% - more than double their contribution in the wood-based pathway (Fig. 7). These considerable differences likely arise from the specific material choices and design characteristics specific for each case building.

Therefore, the distribution of GWP among building elements on Fig. 6 also differ significantly between pathways. In wood-based scenarios, the roof, foundation, ground slab, external walls, and windows, doors, and glazing are the primary contributors, collectively accounting for over 74% of the total impacts. For the roof and external walls, the main impact is associated with bio-based materials. For conventional pathways, the slab is the largest single contributor at 20% of total GWP, followed by external walls, the ground slab, technical equipment, and internal walls, collectively impacting 66% (Fig. 7). These differences highlight the influence of materials used for different building elements where those relying on energy-intensive materials such as concrete and steel dominate the GWP contributions.

Considering the distribution of impacts on a material level on Fig. 7 further illustrate the differences in impact of building elements. In the wood-based pathway, biobased materials and concrete are nearly equal contributors, responsible for 22% and 21% of GWP, respectively. Glass, steel, and insulation each contribute between 10% and 16% (Fig. 7). Consequently, despite the focus on wood, concrete remains a significant contributor due to its extensive use in elements like foundations and slabs and its energy-intensive production processes. In the conventional pathway, concrete is the single most dominant material, responsible for 40% of total GWP, followed by glass, steel, and insulation, which account for 14%, 12% and 10%, respectively. In contrast to the wood-based pathway, biobased materials play a minor role, contributing only 2% of the total GWP. This differentiation highlights the environmental trade-offs between the two pathways, where the wood-based pathway has a plausibly larger GWP impact from bio-based materials, but it still reduces the absolute building impact compared to constructing with more conventional materials. Regardless of the beneficial substitution effect of using wood, the non-renewable materials like concrete, glass, steel, and insulation emerge as critical materials to address in reducing environment impacts for both pathways, where technological advancements and more efficient, strategic use of these materials could significantly mitigate their environmental footprint.

3.4 Distribution of Material Impacts

As outlined in Section 3.3, certain material categories – bio-based materials, concrete, plastic, insulation, steel, and glass - demonstrate the largest differences in GWP impact. To better understand material contributions to environmental burdens in a holistic perspective, an analysis is needed of a wider scope of impact categories in relation to the GWP difference occurring in the wood-based and conventional construction pathways. Here, we focus on the impact categories with the most significant differences: GWP, POCP, AP, ADPF, and PERT.

As Fig. 8 presents, most materials exhibit higher impacts in the conventional pathway for GWP, which is then also the case for the impacts on POCP, AP, and ADPF. Bitumen and bio-based materials are an exception, meaning when their GWP impact rises in the wood-based pathway, the impact on POCP, AP, and ADPF increases likewise. Consequently, constructing in wood leads to the trade-off that when GWP impact of bio-based materials increases, then the impact on POCP, AP, and ADPF rises as well. For PERT, the use of bio-based materials in the wood-based pathway leads to high impacts because it is a renewable energy source.

Concrete remains a major contributor to environmental impacts in both pathways. However, its impact is generally higher in the conventional pathway, consistent with its extensive use and energy-intensive production. An exception occurs in the POCP category, where the wood-based pathway shows impacts 5.6 times greater than the conventional pathway (Fig. 8). This difference arises from transportation processes (module A4), where negative characterisation factors for lorry transport (Ökobaumat, 2018a, 2018b), combined with larger material weights in conventional cases, reduce total POCP contributions for concrete in the conventional pathway.

Bitumen also stands out as a material with significant differences between the pathways. In the wood-based pathway, bitumen contributes substantially more to ADPF due to its use being five times greater than in the conventional pathway, driven by design decisions. The extraction and processing of bitumen are energy-intensive, relying heavily on fossil fuels, which amplifies its environmental impact (Martinho et al., 2023).

3.5 Methodological limitations

This study projects Denmark's material flows and GHGe for wood-based and conventional construction pathways. The analysis builds on forecasts by Hoxha et al. (2024), which estimate the floor area for primary building typologies from 2025 to 2050 across Denmark. Although the included typologies account for a significant share of new construction in Denmark (single family houses, multi family houses, and offices account for 72% (E. Hoxha et al., 2024)), the exclusion of other typologies results in an underestimation of national material requirements and emissions. Despite this limitation, the selected typologies provide a solid foundation for understanding the predominant impacts of new construction across both wood-based and conventional pathways.

Another key methodological limitation of the study is a single case building representing each building typology and pathway. The findings reveal significant differences in material intensity distribution across building typologies and between the two pathways (Section 3.1, Fig. 4). For multi family homes and offices in particular, these differences stem from the specific designs and material choices of the case buildings used for forecasting. Geometry, design, and material selection strongly influence total weight. However, relying only on a single case building for each typology overlooks variability in designs, materials, and construction practices, which can significantly influence forecasted material flows and emissions.

The uncertainties of having single case study MICs can be compared to Fishman et al. (2024), who developed MIC variations of different materials used in for buildings of various load-bearing structures (wood, concrete, steel structures etc.) in 15 EU countries. In the following, their 25% and 75% quartile MICs are presented and compared to the MIC in our study. Our study's values are in parentheses. Concrete in conventional single family houses, multi family houses, and non-residential buildings range approximately 700–1200 (706), 750–1150 (1387), and 800–1400 (1161) kg/m². The study's quartiles for wood used in wood-based single family houses, multi family houses and non-residential buildings range approximately 50–150 (235), 75–190 (116) and 5–20 (96) kg/m².

The conventional single and multi family houses are respectively close to the 25% quartile and beyond the 75% quartile indicating the concrete MIC is fairly small in the former and larger in the latter. Wood-based single family houses and non-residential buildings are well beyond the 75% signalling larger wooden MIC, which may likely influence the impacts related to wood products. Expanding the sample size for forecasting could mitigate these uncertainties by capturing a broader range of building designs.

This study uses current available EPDs for materials used later during the forecast period 2025–2050. The future environmental impact of the EPDs might look different when approaching 2050. However, the approach in this research primarily focusses on the differences in impacts of two construction pathways, and by using the conservative approach of current information the analysis does likely not overestimate benefits nor create less incentive for reducing relevant impacts.

While the chosen case buildings are assumed to be representative of typical practices in Denmark, employing a larger sample of case buildings could reduce uncertainties, as demonstrated by Tozan et al. (2025). Tozan et al. (2025) analysed 289 case buildings to identify emissions hotspots, offering a more detailed view of the variability in building performance. While the limited sample in this study introduces uncertainty, the chosen cases align well with typical emissions ranges reported in Denmark and other countries that follow the EN 15804 standard (Andersen et al., 2021, 2024a; Garnow et al., 2024; Passer et al., 2012; Röck et al., 2020; Tozan et al., 2023). For example, Tozan et al. (2023) report median embodied emissions of 8.31 kg CO₂ eq/m²/year for single family houses, 7.94 kg CO₂ eq/m²/year for multi family homes, and 8.52 kg CO₂ eq/m²/year for offices, aligning closely with this study's results (Fig. 9). However, two wood-based building cases – the office and the sports centre – stand out with considerably lower GHGe. In addition, the conventional single family house has markedly higher climate

impact compared to the average found in Tozan et al. (2023), these possibly overestimating the impact from this building typology. The deviations can be attributed to their simplified designs, such as minimal technical installations, low material intensities, and the single-storey, low-glass-area building designs, highlighting how specific design choices can significantly influence emissions.

3.6 Forecasting Future Construction Pathways and Policy Insights

Forecasting material flows and emissions inevitably involves uncertainties, especially when projecting future scenarios based on historical data. This study explores two distinct construction pathways for Denmark's building sector: wood-based and conventional construction pathways. These scenarios represent simplified extremes based on current building practice, offering insights into potential trends and emissions hotspots. However, real-world transitions are far more nuanced. In practice, the building sector is likely to adopt a hybrid trajectory, where wood-based solutions increasingly complement, rather than replace, conventional practices. The most environmental beneficial construction trajectory may also depend on the individual building typology. In this study, the day care and cultural buildings in wood do not show remarkably lower GWP impact. Hansen et al. (2024) get similar findings for other building typologies, despite applying a different LCA approach with high influence from various methodological parameters. To better reflect this complexity, future research should incorporate contemporary policy developments, market dynamics, and adoption rates of renewable materials into more representative baseline scenarios.

In light of wood availability, there is plenty of wood available in the market for Denmark, consisting of six countries (Hansen et al., 2025). Under the *ceteris paribus* assumption, the study finds that 100% timber implementation in Danish construction can be met 54 times over by the market for Denmark, and it is 103 for a 50% implementation, hence demand in Denmark does not seem to deplete resources in the foreseeable future. The *ceteris paribus* constraint is that in a dynamic and interconnected economy everything else is rarely constant. If all European countries simultaneously increased wood demand, the resource availability is of greater concern.

Göswein et al.(2021) can help addressing this concern. Their demand-driven building model towards 2050 illustrates how Europe's building stock evolves in response to shifting societal factors, focusing on roofs and exterior walls in new construction and renovation. The results show ample timber supply in the Continental, Nordic, and Northern Continental geoclusters, intersecting with the markets used in Hansen et al. (2025), and relevant for the Danish market. Wood availability is measured through annual net-availability, an indicator ensuring that forest regeneration rates remain intact, a core principle of sustainable forestry. The supply–demand balance is a factor of 2 in the Continental region and up to 9 and 15 in the Nordic and Northern Continental regions. Even if all building types and elements were included, potential supply shortages pertain primarily to the Continental geocluster. Overall, timber availability does not appear to constrain an extreme scenario where Denmark and neighboring countries shift completely to wood-based construction.

Despite the simplifications, this study provides support for policymakers aiming to reduce GHG emissions in Denmark's building sector. Multi family homes and office buildings are highlighted as major contributors to non-renewable resource use and GHGe, with single family houses also contributing significantly. To achieve meaningful environmental reductions, targeted mitigation strategies must focus on these building typologies. Recent policy developments in Denmark, such as the 2024 climate agreement for new construction (Ministry of Social Affairs and Housing, 2024), represent a significant step forward. By introducing stricter climate limit values for buildings (Ministry of Social Affairs and Housing, 2024), this agreement incentivises carbon-mitigating designs and materials. This shift has also amplified the focus on biobased, low-impact solutions, aligning with broader global initiatives. Five of the eight buildings comply with their climate limit value when changing to wooden constructions. It emphasises it as a capable climate reduction strategy remain within the limit values in most situations. In this pursuit, it important to mitigate impacts on POCP, AP, and ADPF, through acquisition of materials for suppliers having focus on these impacts.

The United Nations Environment Programme (UNEP) highlight the potential of biobased solutions in reducing the climate impact of the construction sector. UNEP envisions increasing the global share of biobased building materials from approximately 11% in 2020 to 50% by 2060 (UNEP, 2023). However, UNEP also stresses that biobased materials alone cannot fully address the sector's environmental challenges. A more comprehensive approach is necessary to achieve meaningful change. UNEP's three-fold strategy - *avoid, shift, and improve* - underscores the importance of such an approach (UNEP, 2023). The most effective measure is to *avoid* unnecessary construction and limit material consumption by adopting circular economy principles and prioritizing renovation over new construction (UNEP, 2023). The next step is to *shift* toward regenerative materials like wood wherever possible. Finally, efforts to *improve* the emissions profile of conventional materials, such as concrete, must continue (UNEP, 2023). Although renewable materials are highlighted as a key mitigation strategy, their sustainability relies on specific conditions. This entails ensuring that harvesting maintains or increases the biogenic carbon stock by matching or exceeding the natural increment (Plassmann, 2017). Additionally, sourcing these materials must account for factors such as biodiversity preservation and land use changes (Plassmann, 2017).

Despite this study demonstrating several benefits of wood-based construction for most building typologies, relying solely on bio-based solutions has notable limitations. Under the wood-based pathway, total emissions reach 1.04 Mt CO₂ eq annually, compared to 2.03 Mt CO₂ eq in the conventional pathway. When compared to Denmark's allocated share of the global carbon budget - estimated at 2.1 Mt CO₂ eq annually, based on the Planetary Boundaries framework and varying with allocation principles (Häyhä et al., 2016; E. Hoxha et al., 2024) – the building covered in this study account for 49% and 96% of the budget under the wood-based and conventional pathways, respectively. However, this 2.1 Mt CO₂ eq budget represents Denmark's total national allowance, which must cover all consumption, including clothing, food, buildings, energy, and more. Given that the building sector currently accounts for 30% of Denmark's GHGe, the emissions from the buildings analysed in this study far exceed the share they can reasonably allocate within the national carbon budget. Thus, this underscores that substituting

conventional materials with biobased alternatives, while important, is not sufficient on its own. Achieving Denmark's climate targets and contributing to global sustainability requires systemic changes across the construction industry. A balanced strategy that integrates innovative materials, robust policies, and increased renovation rates is essential. These findings highlight the need for holistic solutions that address emissions at every stage of the building lifecycle, paving the way for a sustainable and climate-resilient future.

4 Conclusion

This study highlights the critical role and trade-offs of material choice in shaping the environmental impact of Denmark's building sector. By analyzing material flows and environmental impacts, it provides a strategic roadmap for promoting sustainable construction practices both in Denmark and globally. Single family houses, multi family homes, and office buildings are identified as the primary contributors to future material consumption and emissions, underscoring their pivotal role in achieving significant emissions reductions across the sector. The five other building typologies in the wood-based and conventional pathways constitute 18% and 13%, respectively, of the impact on global warming potential.

The wood-based pathway demonstrates the potential to nearly halve GHG emissions compared to conventional methods of the full life cycle, showcasing its effectiveness in reducing GHGe and other environmental impacts. However, it also shows trade-offs with other impact categories, such as POCP, AP, and ADPF, that must be considered. While wood-based construction offers substantial benefits, it alone cannot achieve the required emissions reductions to meet climate targets. The findings reveal that annual emissions under both pathways cover 49% and 96% of Denmark's allocated share of the global carbon budget (wood-based and conventional pathway, respectively), emphasizing the urgent need for systemic changes within the construction industry.

To address these challenges, the study advocates for a balanced approach that integrates robust policies, technological innovation in material use, and a shift toward renovation over new construction. Achieving decarbonization in the building sector will require collaborative efforts among stakeholders to align industry practices with global sustainability goals and build resilience against climate change.

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Authorship contribution statement

Camilla Ernst Andersen: Writing – reviewing & editing, Writing – original draft, Visualisation, Validation, Methodology, Data curation, Conceptualisation

Rasmus Nøddegaard Hansen: Writing – reviewing & editing, Methodology, Conceptualisation

Endrit Hoxha: Writing – reviewing & editing, Supervision, Methodology, Conceptualization

Harpa Birgisdóttir: Writing – reviewing & editing, Supervision, Conceptualisation

Declaration of competing interests

The authors declare that they no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT and Grammarly in order to review the manuscript for language accuracy and correctness. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication

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