Lifecycle Impact Assessment for Tall Timber Building: Learning from HAUT

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Abstract. The HAUT building in Amsterdam, the tallest timber structure in the Netherlands, redefines sustainable high-rise construction. This 21-story hybrid design combines mass timber with concrete, offering a benchmark for the Lifecycle Impact Assessment (LCIA) of tall timber buildings. The chapter addresses challenges in embodied carbon, biogenic storage, and end-of-life pathways, using dynamic LCIA modeling to assess environmental impacts. Research shows timber buildings often surpass a 150-year lifespan, exceeding the 50-year evaluation standard in regulations. However, findings suggest timber-only designs lose efficiency above 60 m, requiring hybrid solutions. Lessons from HAUT provide actionable strategies for advancing sustainable timber high-rises.

Keywords: environmental impact · GHG emission · carbon modelling · Cross-Laminated Timber · end-of-life

1 Introduction to the HAUT Building and LCIA

This chapter provides a comprehensive review of Lifecycle Impact Assessment (LCIA) approaches and challenges for tall timber and hybrid buildings, using the HAUT building in Amsterdam as a central case study. HAUT, a 21-story residential tower and the tallest timber building in the Netherlands, combines a concrete core with Cross-Laminated Timber (CLT) floors and walls [1]. By integrating hybrid structural systems and biogenic materials, HAUT exemplifies how design choices affect embodied carbon, service life, and end-of-life scenarios in high-rise timber construction. Through this case, the chapter aims to bridge practice and theory by examining real-world data while generalizing key LCIA considerations for future timber projects aligned with EU climate neutrality targets [2–3].

2 Goal and Scope Definition

Based on ISO 14044 and CEN 15804, the system boundary for HAUT's LCIA includes raw material acquisition (A1), transport (A2), manufacturing (A3), product delivery (A4), and end-of-life scenarios (C1–C4) [12]. Functional units are defined per cubic meter (m^3) of CLT or square meter (m^2) of structural components [4, 5]. This ensures comparability with other LCIA studies in the construction sector.

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Assumptions include regional forestry practices, standard sawmill energy mixes, and typical transportation distances. Challenges arise from wood species variability, preservation treatments, and the hybrid nature of HAUT's structural systems in the Netherlands. In 2024, the Sustainable Building Design Lab conducted a comprehensive study on the lifespan of timber buildings and their components [5]. The study, based on both expert insights and data from historical timber buildings, concluded that timber structures typically exceed an average life expectancy of 150 years, particularly when well-maintained and properly treated. This finding reflects industry perceptions as well as case studies of existing timber buildings that have surpassed this lifespan.

Biogenic Carbon Storage in Timber: Biogenic carbon, captured during tree growth, constitutes approximately 50% of the dry weight of wood, making timber a significant temporary carbon sink. 1 kg of dry wood sequesters about 0.5 kg of carbon, equivalent to 1.83 kg of CO_2-equivalent (CO_2e) when oxidized. The timber used in the HAUT building was sourced from PEFC-certified forests in Austria, managed under sustainable forestry practices with continuous net growth.

End-of-Life Scenarios: Incineration vs. Landfilling: Timber's environmental impact at the end of its life hinges on its disposal method: (1) Incineration with Energy Recovery: Timber's biogenic carbon is released as CO_{2e}, but the process generates energy that offsets fossil fuel use, reducing net emissions. HAUT's prefabricated components, produced by Binderholz and processed by Brüninghoff, minimize waste throughout the lifecycle [6]. (2) Landfilling: Timber decomposition in landfills can release methane (CH4), a potent greenhouse gas.

3 Life Cycle Inventory (LCI) Analysis

The primary challenge in assessing the building's life cycle lies in integrating embodied, operational, and end-of-life GHG emissions calculations across all stages. Figure 1 illustrates the life cycle modules, covering stages such as A1 (raw material supply), A2 (transport), A3 (manufacturing), and A4 (transport to site). For timber products, these stages include forestry operations, sawmill activities, engineered wood processes, and distribution networks. This comprehensive view highlights the complexity of harmonizing emissions data across these interconnected phases for an accurate life cycle assessment.

Data collection prioritizes primary sources supplemented by established LCA databases (Ecoinvent, GaBi). When primary data prove difficult to obtain, validated secondary sources are used to fill information gaps. All data sets undergo consistency checks to align with ISO 14040/44 and are documented to ensure traceability. Primary data were collected from HAUT's project documentation, including mill-level production data, energy consumption records, and transport logistics. Secondary data were sourced from established LCA databases (e.g., ecoinvent, GaBi) to supplement gaps in the inventory.

Key LCI components include the origin of timber (certified forestry vs. non-certified sources), energy inputs for drying and cutting, by-product utilization (e.g., bark, sawdust), and transport logistics. Distinguishing among different product types—solid sawn lumber, cross-laminated timber (CLT), glued laminated timber (glulam)—is crucial, as

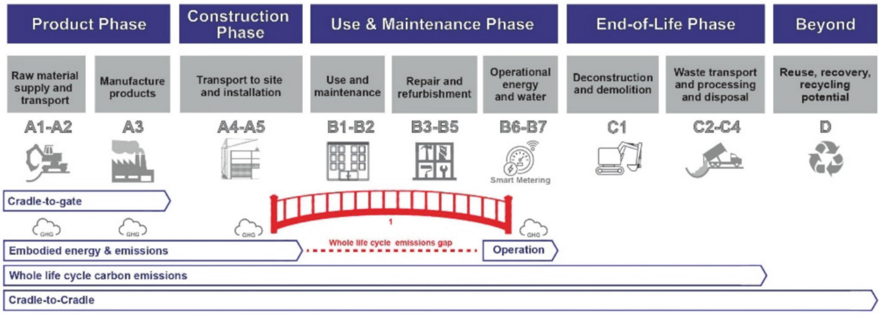

Fig. 1 Building Life Cycle stages and modules and system boundaries [2].

each manufacturing process exhibits unique energy and material flows. Detailed foreground data (e.g., kWh consumed per m^3 of lumber cut) feed into background processes (power generation, fuel production) drawn from recognized databases. HAUT's inventory includes the origin of certified timber, energy inputs for CLT production, and by-product utilization. Transport logistics were modeled to capture emissions from delivering prefabricated components to the construction site.

Service life considerations entail modeling maintenance intervals (e.g., protective coatings every 5–10 years), replacement cycles, and end-of-life scenarios of timber building components and finishes. The chapter specifically addresses how different use conditions (indoor vs. outdoor, high vs. low humidity) affect decay and insect vulnerability [7]. By capturing the frequency of repair or replacement within the 50-year reference period (or another chosen timeframe), the LCI can reflect realistic long-term environmental impacts of timber elements.

4 Life Cycle Impact Assessment (LCIA)

In line with ISO 14044, LCIA emphasizes key categories such as Global Warming Potential (GWP), Acidification, Eutrophication, Photochemical Ozone Creation, and Resource Depletion [4]. Timber's role as a temporary carbon sink is critical for GWP evaluations, as carbon sequestered during tree growth reduces net greenhouse gas emissions—sometimes yielding net-negative results when storage is included. However, common end-of-life scenarios like incineration or landfilling often release this stored carbon, making disposal methods and timeframes pivotal in determining climate benefits. Also, timber's insulation reduces operational energy, though extra layers may offset these gains.

LCIA methods can be categorized based on their impact scope, modeling approach, and geographical relevance. The taxonomy of these are classified by the impact scope including (1) Climate Change Focused (e.g., IPCC 2021, EF 3.0 Climate Change), (2) Midpoint-Oriented (e.g., CML, ReCiPe Midpoint) or (3) Endpoint-Oriented (Damage-Oriented) (e.g., ReCiPe Endpoint, IMPACT World+).

Comprehensive (Multi-Impact) (e.g., EF 3.0, ReCiPe, IMPACT 2002+). It is recommended for timber buildings LCIA to use the IPCC 2021 method because it incorporates biogenic carbon storage, delayed emissions, and cascading use scenarios. Sensitivity analysis evaluates the influence of transport distances, material substitutions, and hybrid designs on overall results. This approach often includes additional modeling steps for delayed emissions, allowing dynamic LCIA models to track carbon storage over a 50-year service life or beyond while considering end-of-life pathways, such as recycling into secondary wood products or energy recovery through incineration [8].

Moreover, a Material Flow Analysis (MFA) has to be conducted for timber buildings to track biogenic carbon uptake, storage, and emissions across the life cycle (A1–C4). At end-of-life (C1–C4), MFA differentiates between reuse in secondary applications (e.g., furniture, particleboard), incineration with energy recovery, or landfill disposal, each influencing carbon fluxes differently. This approach enhances Global Warming Potential (GWP) calculations by integrating cascading material use and disposal scenarios in LCIA.

Finally, sensitivity analysis is essential, as variations in local waste management practices, forestry conditions, and energy mixes can significantly affect outcomes. System boundaries must be clearly defined. Some studies focus on cradle-to-gate impacts (A1–A3 in CEN 15804 terminology) (CEN 15804 + A2), while others adopt cradle-to-grave or cradle-to-cradle perspectives for more comprehensive insights into disposal or reuse scenarios. The functional unit—typically one cubic meter of sawn timber—must align with the system boundary to ensure transparency and comparability across different timber products or building components.

Timber's service life can dramatically influence overall environmental impacts since more frequent replacements raise the total embodied carbon attributable to manufacturing, transport, and construction. Balancing these concerns, proper detailing and careful selection of protective layers can reduce the likelihood of structural damage and allow timber components to remain in use beyond the assumed standard lifespan.

LCIA results often reveal that the initial increase in certain impact categories (e.g., chemical production for treatments) can be more than offset by the avoided manufacturing and transport involved in multiple replacements. These practical implications underscore the importance of accurate service-life data within an LCIA model.

5 Results

Figures 2 and 3 illustrate the percentage increase in greenhouse gas (GHG) emissions between biobased-only and hybrid constructions (A1-A3, excluding under ground) over 50, 100, and 150 years. At 50 years, emissions rise from 5 kg CO_2e/m^3 (biobased) to 8 kg CO_2e/m^3 (hybrid), representing a 60% increase. At 100 years, emissions increase from 4 kg CO_2e/m^3 (biobased) to 5 kg CO_2e/m^3 (hybrid), a 25% rise. By 150 years, emissions grow from 3.4 kg CO_2e/m^3 (biobased) to 5.4 kg CO_2e/m^3 (hybrid), reflecting a 59% increase. These trends demonstrate that hybrid constructions consistently result in higher GHG emissions compared to biobased-only designs over the entire lifespan.

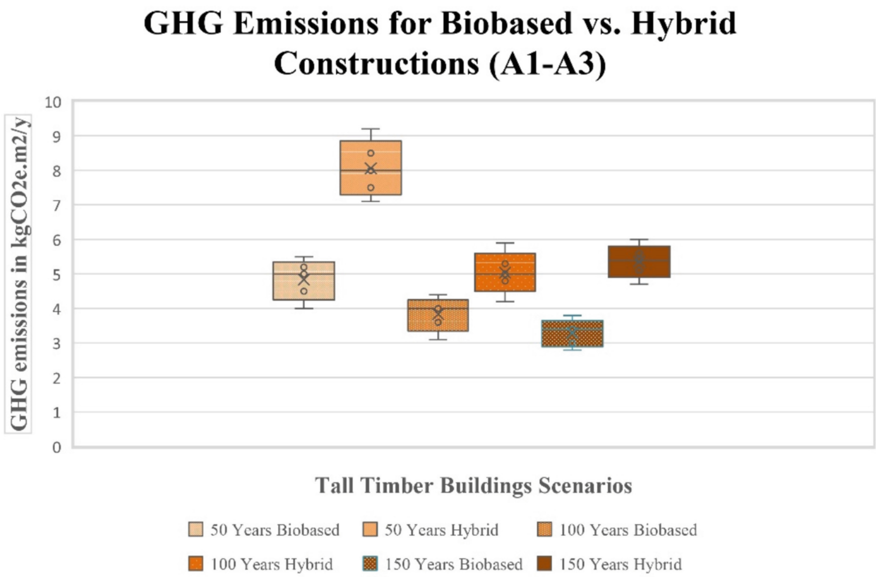

Fig. 2 Comparative bar chart illustrating the greenhouse gas (GHG) emissions for biobased-only construction versus hybrid construction with steel and concrete consolidation over 50, 100, and 150 years

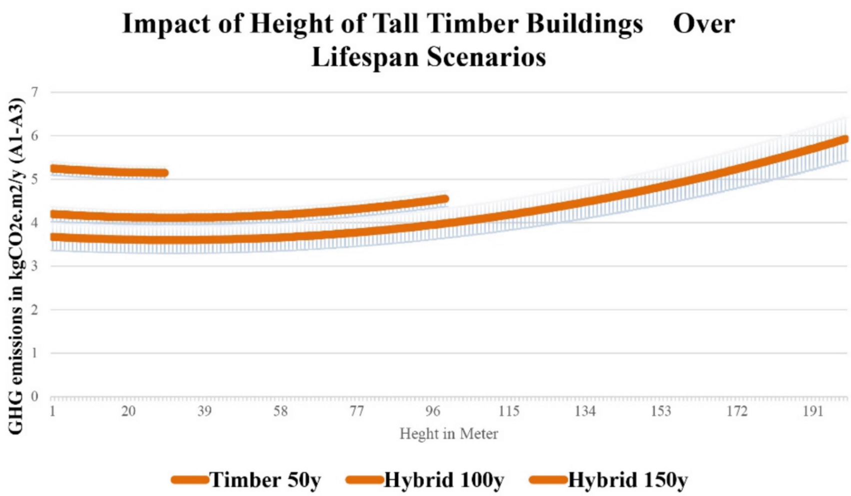

Fig. 3 The impact of GHG emissions across building heights in tall hybrid timber building, emphasizing the relationship between building height and emissions over lifespan scenarios.

6 Conclusions

The HAUT building serves as a benchmark for sustainable tall timber construction, illustrating the synergies between biogenic carbon storage, hybrid systems, and sustainable sourcing. By adopting dynamic LCA methods and prioritizing end-of-life management, HAUT sets a precedent for leveraging timber's environmental benefits while addressing its challenges [10]. As the construction industry strives toward net-zero emissions, projects like HAUT underscore the transformative potential of timber when used thoughtfully and responsibly.

6.1 Key Insights for LCIA in High-Rise Timber Buildings

- Impact Characterization: The IPCC 2021 method improves the accuracy of biogenic carbon accounting.
- System Integration: Hybrid systems, such as HAUT's concrete core and CLT walls, balance structural demands with sustainability goals.
- Lifecycle Durability: Maintenance schedules and protective measures significantly influence long-term environmental impacts.
- Cascading Use: Promoting reuse and recycling of components enhances the sustainability profile.

6.2 Specialized LCIA Considerations for Timber

When dealing with high-rise or complex timber applications, certain characteristics must be captured in the LCIA to avoid underestimating or overestimating impacts. Timber's dimensional changes, load-bearing requirements, fire safety rules, and end-of-life realities can each shift the environmental balance.

- **Material Properties and Biogenic Carbon Storage:** Timber sequesters carbon over its growth phase. However, if over 70% of used timber in Europe is incinerated or landfilled at the end of its life, the ultimate GWP profile can worsen. Shrinkage and deformation also introduce the need for additional connectors, raising resource depletion and embodied carbon, while necessary protective layers may temper any natural insulation benefit.
- **Structural Stability, Foundations, and Underground Features:** Excavation for underground parking or mechanical spaces further inflates environmental burdens, particularly regarding global warming and resource depletion.
- **Fire Safety and Protection:** Fire safety measures in high-rise timber can include chemical treatments or additional layers like gypsum board or concrete cladding, all of which boost embodied impacts and can complicate end-of-life recycling. Regulatory compliance tends to be stricter for timber, often necessitating more conservative design margins or redundant protective systems.
- **Hybrid and Composite Designs:** Many tall or complex buildings employ hybrid solutions: concrete cores for stiffness and elevator shafts, steel frames in critical load-bearing zones, and timber infills or façade elements for reduced weight. This mixing of materials makes LCIA more complex since each material has its own

production processes, maintenance needs, and EoL pathways. Dynamic or seismic loads can also push toward heavier or reinforced assemblies, thereby increasing the share of high-impact materials like steel or concrete. The use of a concrete core in HAUT (73 m) was crucial to ensure the structural integrity required for a building of its height, particularly for wind and seismic resistance. The need for concrete in cores and steel reinforcements increases the embodied carbon footprint. CLT can be effective for buildings up to 60 m, beyond this height, it becomes less efficient or sustainable to rely solely on timber [9]. This is due to the increased material intensity required to meet structural and fire safety standards at greater heights and the growing need for hybrid systems.

- **Lifecycle Durability, Maintenance, and Cascading Use:** Cascading uses strategies—reuse, recycling, or repurposing before disposal—can defer carbon release and reduce reliance on virgin resources. Prefabrication improves quality control and lowers on-site emissions but may raise transport impacts, especially with packaging or long-distance shipping. Tall structures often require significant steel reinforcement, increasing overall embodied emissions.
- **End-of-Life Scenarios and LCIA Adjustments:** If timber is disposed of via incineration or landfilling, biogenic carbon is eventually released. Cascading use offers an alternative: secondary products like panel boards, particleboard, or even new cross-laminated timber (CLT) layers can extend the timeframe over which carbon remains stored. By adopting dynamic LCIA models, practitioners can better capture the net effect of multiple use cycles on overall GWP. Aligning with circular economy policies that incentivize reuse, and recycling can further improve timber's environmental profile.
- **Transportation and Construction Logistics**: Prefabricated components can streamline on-site construction and reduce local emissions, yet greater protective packaging or specialized transport requirements can erode these benefits. Hybrid structures involving many different materials can increase overall transport demands if coordination is poor. Consequently, the net effect on GWP and resource depletion depends on an interplay of factors such as shipping distances, on-site waste management, the ability to integrate deconstruction-ready designs.

6.3 Recommendations for Future Projects

While timber is gaining traction in the construction industry, experts caution against its overuse in high-rise buildings due to technical limitations such as strength and combustibility. Nevertheless, HAUT demonstrates that these challenges can be addressed effectively with thoughtful design and the use of sustainably sourced timber. PEFC certification ensures responsible forest management, aligning with EU policies on sustainable construction. The project highlights timber's potential to reduce embodied carbon in urban densification strategies, aligning with the goals of the European Green Deal. Future LCIA studies should adopt dynamic modeling approaches, prioritize IPCC 2021 for characterization, and incorporate detailed service life data to capture the full environmental benefits of timber high-rise buildings. Studies from the Dutch Environmental Database emphasize the importance of accounting for biogenic carbon in lifecycle assessments [11]. For instance, temporary carbon storage in timber can provide measurable Global Warming Potential (GWP) benefits. However, these benefits must be credited appropriately to avoid double counting, particularly when materials are recycled or reused.

6.4 Limitations of Current LCIA Approaches

Finally, while LCIA methods provide a robust framework for assessing environmental impacts, they still face significant limitations. Most notably, standard LCIA models—particularly midpoint methods like ReCiPe or CML—tend to overlook local ecological impacts, such as biodiversity loss, soil degradation, or changes to local hydrology, especially relevant in forestry-based materials like timber. Current indicators often fail to distinguish between sourcing wood from monoculture plantations versus ecologically diverse forests, leading to an underestimation of ecosystem-level trade-offs. Additionally, social aspects such as labor practices in forestry, land use conflicts, or the displacement of communities are not typically captured in conventional LCA tools. These limitations underscore the need for more holistic, next-generation LCIA frameworks that integrate regionalized biodiversity metrics and social life cycle assessment (S-LCA) into mainstream building assessment workflows.

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