

Article

A Comparative Whole-Building Life Cycle Assessment of the Four Framing Systems of the Bakers Place Building Using the Tally LCA Tool

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Abstract: The urgent need for climate change mitigation has increased the focus on reducing embodied carbon and energy, particularly in the construction sector. Utilizing sustainably sourced mass timber products provides a low-carbon alternative to traditional concrete and steel structural systems in buildings. These carbon impacts can be quantified by evaluating the total environmental impact of a building, from material extraction and product manufacturing to construction, operation, and demolition. This study evaluated the environmental impacts of a 14-storey mass timber–steel hybrid building in Madison, USA, through a Whole-Building Life Cycle Assessment (WBLCA) using the Tally LCA tool integrated with Autodesk Revit. The hybrid design was compared to full mass timber, full steel, and post-tensioned concrete structures, which are common structural systems for high-rise buildings, enabling meaningful comparisons of their environmental performance. The results showed that the full mass timber design had the lowest global warming potential (GWP), reducing emissions by 16% compared to the concrete structure. The hybrid design achieved a 14% reduction, with both timber-based systems demonstrating about 30% lower non-renewable energy use. In addition, they provided significant biogenic carbon storage during the building’s lifespan. However, the mass timber and hybrid systems showed higher impacts in categories such as acidification, eutrophication, ozone depletion, and smog formation.



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Keywords: whole-building life cycle assessment; comparative LCA; mass timber; high-rise building; greenhouse gas emissions; global warming potential

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has identified human-driven greenhouse gas (GHG) emissions as the likely dominant cause of global warming observed since the mid-20th century [1]. The building industry plays a significant role in contributing to these GHG emissions, as well as in the consumption of natural resources throughout its life cycle—from construction to demolition. Buildings require energy at all stages, with direct energy used to maintain indoor environments, including heating, cooling, lighting, and appliance operation, referred to as operational carbon, and indirect needs, including the energy necessary for the production and installation of building materials, referred to as embodied carbon [2]. According to Architecture 2030, buildings are responsible for 42% of global CO₂ emissions, with 15% attributed to structural materials and 27% to building operations [3]. As global construction activities continue to rise, many countries

are increasingly committed to achieving the United Nations' Sustainable Development Goals, particularly those focused on reducing the environmental impact of construction. One of the most promising strategies is using green building materials, such as mass timber products (MTPs) from sustainably managed forests. These materials offer a unique benefit: the carbon absorbed during the growth of trees is stored in the harvested wood products for the duration of their service life, which can range from 50 to 80 years [4,5]. This delayed release of sequestered carbon, especially in structural applications, makes mass timber buildings a potential carbon sink over their entire lifespan. This provides a significant advantage over traditional fossil fuel-intensive materials like steel and concrete, positioning mass timber as a key player in sustainable construction.

Understanding a building's embodied energy through a life cycle assessment (LCA) is crucial for identifying opportunities to reduce the embodied energy in new construction. LCA is an internationally accepted, science-based method that assesses the environmental impact of a product or service by quantifying the energy and materials used, as well as the emissions released into the environment at various stages of the product's life cycle [6,7]. Conducting an LCA on functionally equivalent buildings is a widely adopted method for comparing the environmental impacts of traditional building materials versus MTPs.

Numerous studies have utilized LCAs to quantify the reduction in embodied carbon associated with the use of mass timber [8–13]. For instance, Teshnizi et al. conducted a cradle-to-grave LCA on two high-rise student residential buildings at the University of British Columbia, Vancouver, Canada—one built with MTPs and the other with traditional building materials—and found that using MTPs resulted in 25% less global warming potential (GWP) and 18% less fossil fuel depletion compared to traditional materials [9]. Similarly, Chen et al. conducted a comparative Whole-Building LCAs on a high-rise mass timber building, which was designed to be built in the Pacific Northwest of the United States with an aim at quantifying the environmental impacts with the commercial Whole-Building LCA software Athena Impact Estimator [12]. They discovered that around a 20% reduction in GWP for the mass timber construction compared to the concrete design structure [12]. The Nature Conservancy led a research project comparing the mass timber buildings with functional equivalent concrete alternatives on embodied carbon reductions [5,14]. Overall, the mass timber buildings at three different height levels exhibited a reduction in embodied carbon, varying between 22% and 50%.

Stakeholders are increasingly interested in understanding the precise environmental advantages of using MTPs in their specific projects, which could inform decision-making processes. Ideally, this involves comparing the LCA results of a planned mass timber building to those of a concrete or steel version with similar characteristics, such as building profiles, height, and usage patterns. The National Whole-Building Life Cycle Assessment Practitioner's Guide, developed by the National Research Council Canada (NRC), standardizes methodologies for assessing embodied carbon in Canadian buildings. It outlines system boundaries, life cycle stages, and key building elements to ensure accurate compliance with embodied carbon reduction targets [15]. Moreover, the Leadership in Energy and Environmental Design (LEED) certification, provided by the U.S. Green Building Council (USGBC), serves as a widely recognized standard for evaluating the sustainability of building projects. By assessing various environmental performance metrics, LEED certification reflects a project's commitment to reducing CO₂ emissions and promoting a more sustainable environment. This study offered a unique contribution by using the Bakers Place project, a real-world 14-storey mass timber and steel hybrid building located in Madison, WI, USA, as a case study, with four structural designs, including hybrid, full mass timber, steel, and concrete, for comparison. These four designs were developed by the actual structural design team involved in the project using the Revit models. This means

the material quantities and specifications used in the LCA are based on firsthand and actual design data. Using the Tally® LCA tool within Autodesk® Revit®, this study performed a cradle-to-grave Whole-Building Life Cycle Assessment (WBLCA) to compare the environmental impacts of the four structural systems, all based on the same architectural layout. As such, this approach offers a unique realistic comparison that reflects true construction practices, making the results more applicable to real-world decision-making.

2. Materials and Methods

2.1. Goal and Scope of LCA

The goal of this study was to perform a comparative cradle-to-grave Life LCA using the Tally® LCA tool, directly comparing the hybrid (baseline) building to functionally equivalent buildings constructed with post-tensioned concrete, full steel, and full mass timber. The baseline hybrid building was designed by the famous architect Michael Green and developed by The Neutral Project, a sustainability-focused real estate company, serving as a real-world example of sustainable building practices in North America.

The environmental impacts of the four designs were analyzed using Tally®, a LCA tool developed by KT Innovations, which operates as a plug-in for Autodesk® Revit®. Tally® enables users to extract data directly from Revit® models and apply Environmental Product Declarations (EPDs) and Life Cycle Inventory (LCI) data using the Sphera database to calculate embodied impacts. The tool is particularly valuable for architects during the early design phase, supporting informed material choices and promoting sustainability in construction.

The comparison adhered to the ISO 21930 and ISO 21931 standards [16,17]. Tally® generates a comprehensive range of data comparing the environmental impacts across various categories, such as GWP, acidification, eutrophication, smog formation, ozone depletion, and renewable and non-renewable energy demand. In this study, GWP was the primary impact category of interest as it is drawn from all GHG emissions occurring throughout the life cycle of the building components and transfers the emissions to impacts toward global temperature rise. It should be pointed out that this study exclusively focused on the structural frame and did not include materials related to the building's enclosure or architectural elements.

2.1.1. Functional Unit and System Boundary

The functional unit for this study was defined as 1 m² of floor area as it is a well-established standard in building LCAs and is recommended by guidelines such as EN 15978 and ISO 21931. This unit allowed for consistent comparison as all four structural systems were independently engineered by the structural team based on the same architectural layout and were designed to meet equivalent structural performance.

ISO 21930 outlines the life cycle stages of a building enclosed in the Whole-Building LCA study: production, construction, use, and end-of-life stage, as shown in Figure 1 [16]. The system boundary defines which life cycle phases are included in the analysis. The various processes that occur at each stage of a building life cycle are classified and grouped in “modules”, labeled as A1–C4, as shown in Figure 1. For this comparative WBLCA, the system boundary was cradle to grave (A–C, plus D), including Modules A1–A3, A4, B2–B5, C2–C4, and D. The assessment excluded Modules A5 (construction impacts), C1 (demolition; due to Tally's default settings), and B1 (use phase; due to lack of data). Operational energy impacts (B6 and B7) were also excluded from the analyzed system boundary since this study focused on the embodied carbon impacts of buildings and because operational energy use is influenced by factors that remain constant across all four structural scenarios and fall outside the scope of this structural comparison. Additionally,

Tally[®] provides the option to include or exclude biogenic carbon in the analysis. For this study, biogenic carbon was included to accurately consider carbon sequestration by wood-based materials. This inclusion accounts for the carbon dioxide absorbed by trees during growth, which is stored in the wood-based products used in the building. It also considers the eventual release of this stored carbon at the end-of-life stage, depending on the disposal pathway (e.g., landfill, incineration, or recycling). Including biogenic carbon allows for a more comprehensive and realistic evaluation of the environmental benefits of mass timber, particularly in relation to GWP. It highlights both the carbon storage advantage during the production stage and the potential emissions at the end of life, offering a balanced interpretation of the environmental performance of wood.

Product			Construction		Use							End-of-Life				Module D		
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3
Raw Material Supply	Transportation	Manufacturing	Transportation	Construction/ Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operation Water Use	Deconstruction/ Demolition	Transportation	Waste Processing	Disposal	Reuse	Recycling	Energy Recovery

Figure 1. Life cycle stages and modules included (highlighted in green) using the Tally[®] WBLCA modeling in this study [16].

2.1.2. Bakers Place Project Overview

Bakers Place is a mixed-use development project, located in Madison, Wisconsin, USA, with a gross area of 20,850 m² (224,427.53 ft²), and includes 206 residential units. The project is distinguished by its innovative hybrid construction, combining mass timber with steel elements, alongside sustainable features such as passive house principles, LEED certification, and green roofs.

The original design, commissioned in 2020, was developed by Michael Green Architects, in collaboration with Equilibrium Engineers LLC (Equilibrium) structural engineers. The building is a 14-storey structure with a 3-storey concrete podium supporting 11 stories of mass timber–steel hybrid construction. This system integrates steel columns, glulam beams, and cross-laminated timber (CLT) floors. The alternative functionally equivalent structures designed with full mass timber, full steel, and post-tensioned concrete were meticulously designed to align with the architectural floor plan and unit layout of the hybrid baseline (Figure 2). Table 1 provides a detailed comparison of the structural designs for each scheme, highlighting the material usage and their impacts on the building’s podium.

Table 1. Comparative structural aspects of hybrid, full mass timber, concrete, and steel systems.

	Hybrid (Baseline)	Full Mass Timber	Full Steel	Full Concrete
Floor-to-Floor Height	10'–9"	10'–9"	9'–7 ½"	12'–4"
Slab	CLT floors (KLH 180mm), 5/16" sound mat, and 2" gypcrete	Same as the baseline	3½" lightweight concrete on top of 3" 20 ga. steel deck	7.5" post-tensioned concrete

Table 1. Cont.

	Hybrid (Baseline)	Full Mass Timber	Full Steel	Full Concrete
Framing	Steel framing and column with 1" spray fireproofing + glulam beams	Steel framing with 1" spray fireproofing + glulam columns and beams	Steel beams, columns, and braced frames with 1" spray fireproofing	Reinforced concrete columns and shear walls
Fireproofing	2 layers of 5/8" Type X GWB over CLT and 1" spray fireproofing for steel elements	2 layers of 5/8" Type X GWB over CLT	1" spray fireproofing	N/A
Impact to Podium	Foundation as per the podium model in Revit (No impact relative to the baseline)	Foundation as per the podium model in Revit (No impact relative to the baseline)	30% increase in column cross-sectional area and 50% increase in foundation volume	55% increase in column cross-sectional area and 100% increase in foundation volume

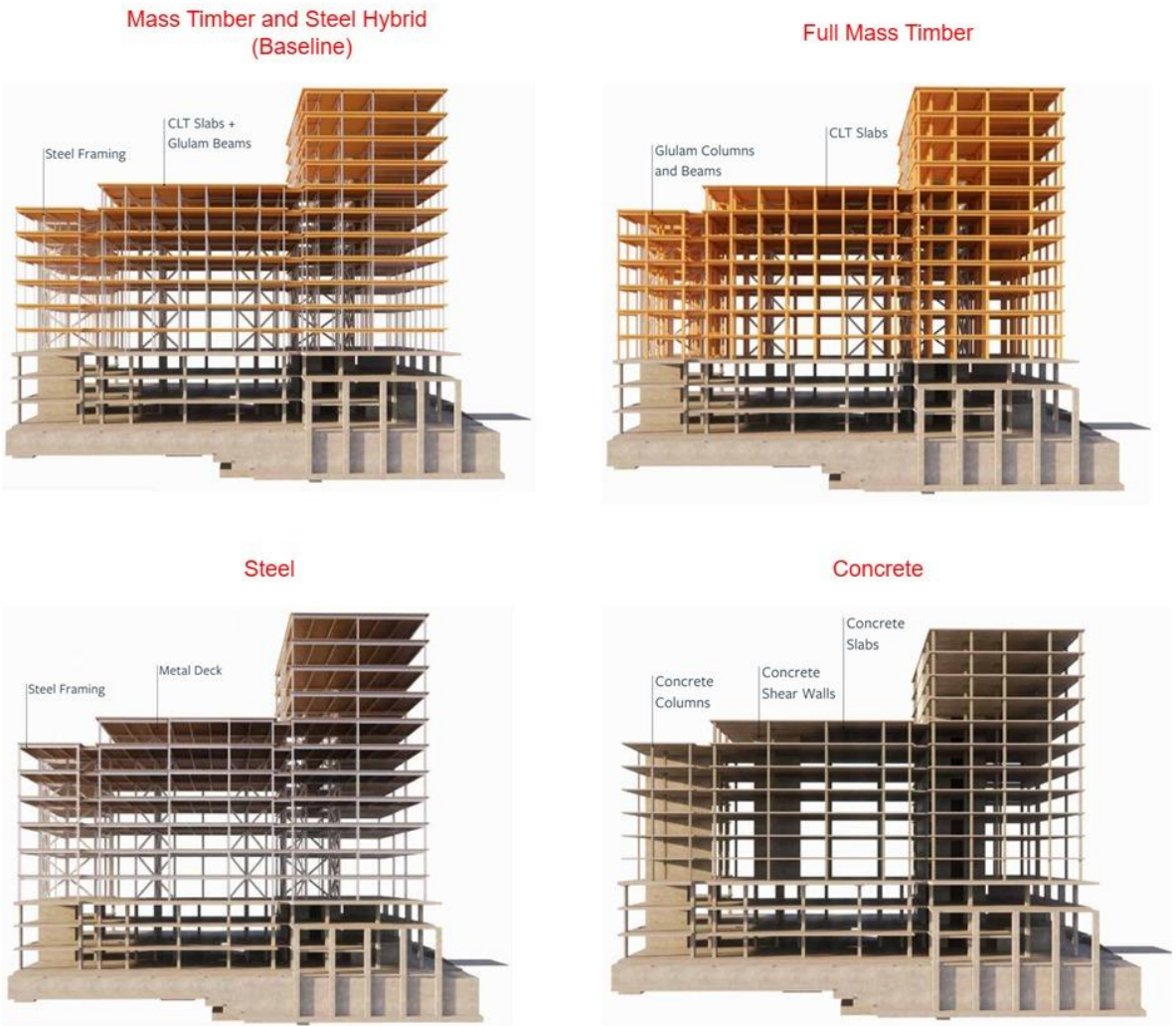


Figure 2. The four structural framing systems designed for Bakers Place: hybrid, full mass timber, steel, and concrete [18].

2.2. Building Material Inventory

Four schematic-level structural scenarios, focusing solely on the major structural members for Bakers Place, were developed by the architects and engineers at Equilibrium

LLC using Revit® 2025 software. To build material inventories of the four designs for LCA, Tally®, an application built in Revit®, converted material quantities into volumes and areas, facilitating the accurate assignment of the EPD and Life Cycle Inventory (LCI) data for all building elements. Tally® utilizes the Sphera database, the standard for reporting stages A1–A3 in EPDs for building products. For later life cycle stages, Tally® primarily relies on North American averages from its database, allowing adjustments only for the transportation stage (A4) based on specific project data. Additionally, Tally® accounts for the materials not explicitly modeled in Revit®, such as rebar within concrete assemblies, ensuring a comprehensive representation of the building’s material composition. Table 2 lists all the materials extracted by Tally® that were used in the analysis of each structural framing system of the Bakers Place building.

Table 2. Tally of building material quantities of each structural framing system of the Bakers Place building.

Materials Used in Different Assemblies		Unit	Hybrid Building (Baseline)	Mass Timber	Steel	Concrete
Floor and Roof	Concrete	m ³	4648.11	4648.11	5188.65	8283.98
	Lightweight Concrete	m ³	605.82	605.82	1209.57	
	Steel Reinforcement Rebar	kg	196,951.11	196,951.11	210,313.54	426,484.33
	Steel Welded Wire Mesh Reinforcement	kg	44,105.29	44,105.29	84,355.89	43,128.89
	Steel Deck	kg	3222.00	3222.00	136,064.00	
	Cross-Laminated Timber (CLT)	m ³	2,335.23	2335.23		
	Steel Plate Connection	kg	12,653.00	12,653.00	19,930.00	
	Gypsum Wall Board (GWB)	kg	347,796.00	347,796.00		
Foundation	Concrete	m ³	758.82	758.82	1138.23	1517.64
	Steel Reinforcement Rebar	kg	18,972.56	18,972.56	28,457.92	37,944.01
Column and Beam	Concrete	m ³	219.28	219.28	285.05	492.80
	Steel Reinforcement Rebar	kg	39,030.10	39,030.10	50,859.37	87,730.05
	Cold-Formed Hollow Structural Steel	kg	236,946.70	155,195.90	160,134.90	1043.00
	Hot-Rolled Structural Steel	kg	291,561.23	111,535.38	541,687.58	65.69
	Spray Fireproofing	kg	162,485.00	58,853.84	214,223.74	322.60
	Glue-Laminated Timber (GLT)	m ³	171.75	941.29		
	Steel Plate Connection	kg		30,296.00		
Wall	Concrete	m ³	997.31	997.31	997.31	1458.16
	Steel Reinforcement Rebar	kg	118,671.80	118,671.80	118,671.80	173,493.80

2.3. Building Material Specifications and Assumptions

The following building material specifications and assumptions were used in this study:

- The transportation distance for concrete was assumed to be 40 km, while mass timber components (CLT and glulam) were sourced from Austria, requiring transport by truck, boat, and train over distances of 799 km, 6482 km, and 1127 km, respectively. For other materials, including steel, Tally® used default industry-average values.
- All materials were assumed to have the same lifespan as the building, which was set to 60 years.
- Regarding connections, the structural designer specified an assumption of 0.2 pounds per square foot (psf) of A36 steel for the hybrid (baseline) model. For the steel scheme, they assumed 0.15 psf of headed studs for the connections. However, since the Tally® database lacked an EPD for headed studs, it was recommended, in consultation with structural engineers, to use 0.3 psf of A36 steel plate as a substitute. These quantities were added as an accessory material to the floor system of each building scenario.
- The only EPD available for GLT in Tally® was from the EPD published by the American Wood Council for North American glulam products, with a moisture content of 14%. However, the Wiehag GLT used in the project has a lower density of 466 kg/m³ than the GLT EPD available in the Tally® database (534 kg/m³), as well as a lower moisture content of 11%. To ensure accuracy in the analysis, the material take-off in Tally® was adjusted to reflect the Wiehag GLT density, rather than the default North American glulam density.
- Most concrete elements in the project, including columns, foundation, slabs on grade, and mat slabs, were located in the podium and reported as cast-in-place with 30–50% supplementary cementitious material (SCM). The National Ready Mixed Concrete Association's (NRMCA) industry-wide EPDs for cast-in-place concrete, based on the Great Lakes Midwest regional average for SCM, were used in this analysis. Since Tally® does not offer a specific 30–50% SCM option, the regional average was selected. Reinforcement for concrete was defined using the Concrete Reinforcing Steel Institute's (CRSI) EPD. In the columns above the podium, concrete strength varied by height: 10,000 psi for floors 4–7, 7000 psi for floors 7–10, and 5000 psi for floors 10–roof, with an assumed reinforcement of 178 kg/m³. The podium columns had similar reinforcement but with a concrete strength of 6000 psi. The foundation and wall elements were designed with 4000 psi concrete, reinforced with 25 kg/m³ and 119 kg/m³ of rebar, respectively. The slab on grade also used 4000 psi concrete with welded wire mesh reinforcement at 20.3 kg/m², while the mat slab had a concrete strength of 6000 psi, reinforced with 25 kg/m³ of rebar, similar to the foundation elements.
- As there is no North American industry-average EPD available for acoustic underlayment mats within the Tally® database, this material was excluded from the LCA for the CLT floor systems in both the hybrid and mass timber schemes, assuming the quantity of this material would not have significant impacts on the final result [19].
- For the post-tensioned concrete used in the podium and the overall concrete design, structural engineers specified reinforcement with rebars at 1.75 kg per square foot and pre-stressed steel tendons at 0.8 kg per square foot. However, Tally® does not have EPD data for tendons; so, an adjustment was required. The GWP of tendons, based on the Suncoast Post-Tensioning System Manufacturer-Specific EPD [20], is approximately 1.7 times higher per metric tonne than that of rebars, according to the Concrete Reinforcing Steel Institute's (CRSI) EPD [21]. To account for this difference, the quantity of tendons per cubic meter of concrete was calculated and then multiplied

by 1.7 to reflect the higher GWP. This adjusted figure was then used in Tally® instead of the tendon data.

- A Type IV-B building requires that mass timber be protected with non-combustible material, typically Type X Gypsum Wall Board (GWB), except where it is exposed. The structural engineers specified that the exposed area of the CLT floor and attached beams must not exceed 20% of the CLT floor area in any residential unit. In Tally®, GWB was specified as an accessory material to the CLT floor, with the take-off method based on area and only the thickness of the GWB layer being adjustable. To meet the fire rating requirement of covering 80% of the CLT floor area, the required GWB volume was manually calculated by multiplying 80% of the CLT area by two layers of GWB (31.8 mm). Since Tally® does not allow assigning the required thickness to a specific portion of the area, the GWB thickness was adjusted from 31.8 mm (two layers of 5/8") to 25.4 (80% of 31.8) mm to achieve the same overall volume designed to comply the fire rating requirement. The take-off method for the GWB used the modeled area, an adjusted thickness of 25.4 mm, and a density of 1092 kg/m³ to obtain the total mass (kg) of the GWB required in the designs for the LCA analysis.

Key specifications for each major material category, as defined by Equilibrium, the structural engineering company, and their Tally® database equivalents are summarized in Table 3.

Table 3. Materials specified by the architectural designs and their equivalents found in the Tally® material database.

Category	Material Specifications	Tally® Database Equivalent
Steel	Hollow structural steel (HSS) section	Cold-formed HSS section + Spray fireproofing (cementitious)
	Hot-rolled steel: W and L sections	Hot-rolled structural steel (AISC-EPD) + Spray fireproofing (cementitious)
Wood	Wiehag GLT	GLT(AWC-EPD), no finish, 534 kg/m ³ density
Concrete	Type	Cast-in-place (NRMCA-EPD)
	SCM 30-50%	Great Lakes Midwest regional average
	Strength	5000–10,000 psi
	Reinforcement	Concrete reinforcement varies in quantity per volume in different structural concrete elements
Floor Materials	Steel floor assembly 3 1/2" Concrete over 3VLI floor deck	Lightweight, cast-in-place concrete, 3000 psi, Great Lakes Midwest regional-average SCM (NRMCA-EPD)
		Welded wire mesh reinforcement, pre-defined value (4 × 4, 6 ga), 3.03 kg/m ²
		Steel roof and floor deck, Steel Deck Institute (SDI-EPD), 10 kg/m ²
	Mass timber floor assembly 5-PLY CLT (7 1/16")	CLT: generic LCI data set by Tally® LCA
	2" Gypcrete	3000 psi, lightweight concrete, 0% SCM (NRMCA-EPD), with no reinforcement
	5/16" Acoustic mat	No acoustic mat in the Tally® database
	Post-tensioned concrete slab	Cast-in-place concrete, 5000 psi, 0% SCM (NRMCA-EPD)
	Reinforcement: 1.75 psf (rebar) and 0.8 psf (tendon)	Rebar (CRSI- EPD)

3. Results and Discussion

3.1. Comparison of Building Material Mass and Relative GWP

The total mass of the major structural materials for the hybrid building, including foundations, was about 19.2 million kg, similar to the full mass timber building designed. However, the concrete and steel buildings were much heavier. The concrete building weighed around 28 million kg in total, approximately 46% more than the mass timber building, and the steel building weighed about 21.5 million kg, or roughly 12% heavier than the mass timber building. Figure 3 illustrates the mass quantities for different assemblies across the four building designs. Floors contributed most to the mass in each scenario, accounting for about 70% of the total. Notably, the floor mass in the concrete design is approximately 33% higher than the steel design and 44% more than both the hybrid and full mass timber designs. The mass timber and hybrid design generally had the lowest mass across all structural elements, except for columns and beams. The mass of columns and beams in the hybrid and mass timber designs is slightly higher than the concrete building but still lower than the steel design. Although the concrete design increased the cross-sectional area of columns in the podium by about 55%, compared to a 30% increase in the steel design, it utilized reinforced concrete shear walls for lateral support instead of beams. This choice eliminated the need for additional beam mass, resulting in a lower combined mass for columns and beams compared to the steel design, which had the highest total mass of these components. However, when considering all structural elements, including foundations, columns, and beams, the concrete design still had the highest overall mass.

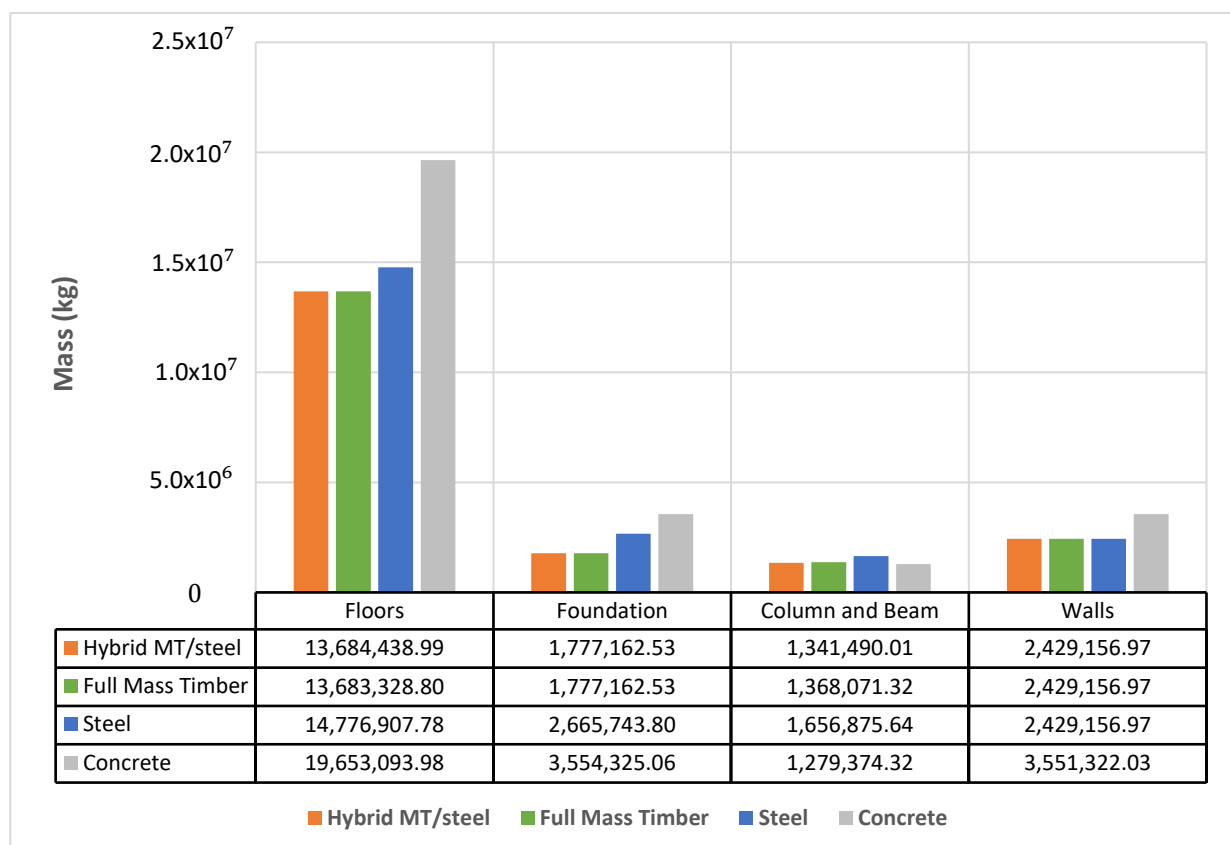


Figure 3. Mass of different assemblies for the four different structural framing system designs.

When analyzing the relative mass of each structural material and their corresponding GWP impact across all building systems (Figure 4), concrete consistently stood out as the largest contributor to carbon emissions, regardless of the structural design. This is mainly

because all four structural framing system designs require a substantial amount of concrete, especially in the concrete and steel scenarios. To support their heavier superstructures, these two designs required larger foundation volumes and column sizes in the podium, which further increased the overall concrete mass. In contrast, the lighter mass timber and hybrid systems imposed lower structural loads, allowing for smaller and less heavily reinforced foundations, and ultimately used nearly 40% less concrete than the concrete design. This reduction in concrete use played a key role in lowering the overall GWP of the hybrid and mass timber buildings as concrete has a high carbon footprint due to the fossil fuel-intensive processes involved in its production. Since concrete was the dominant contributor to total GWP across all designs (Figure 4), reducing its volume directly resulted in significant GWP savings in the mass timber-based systems.

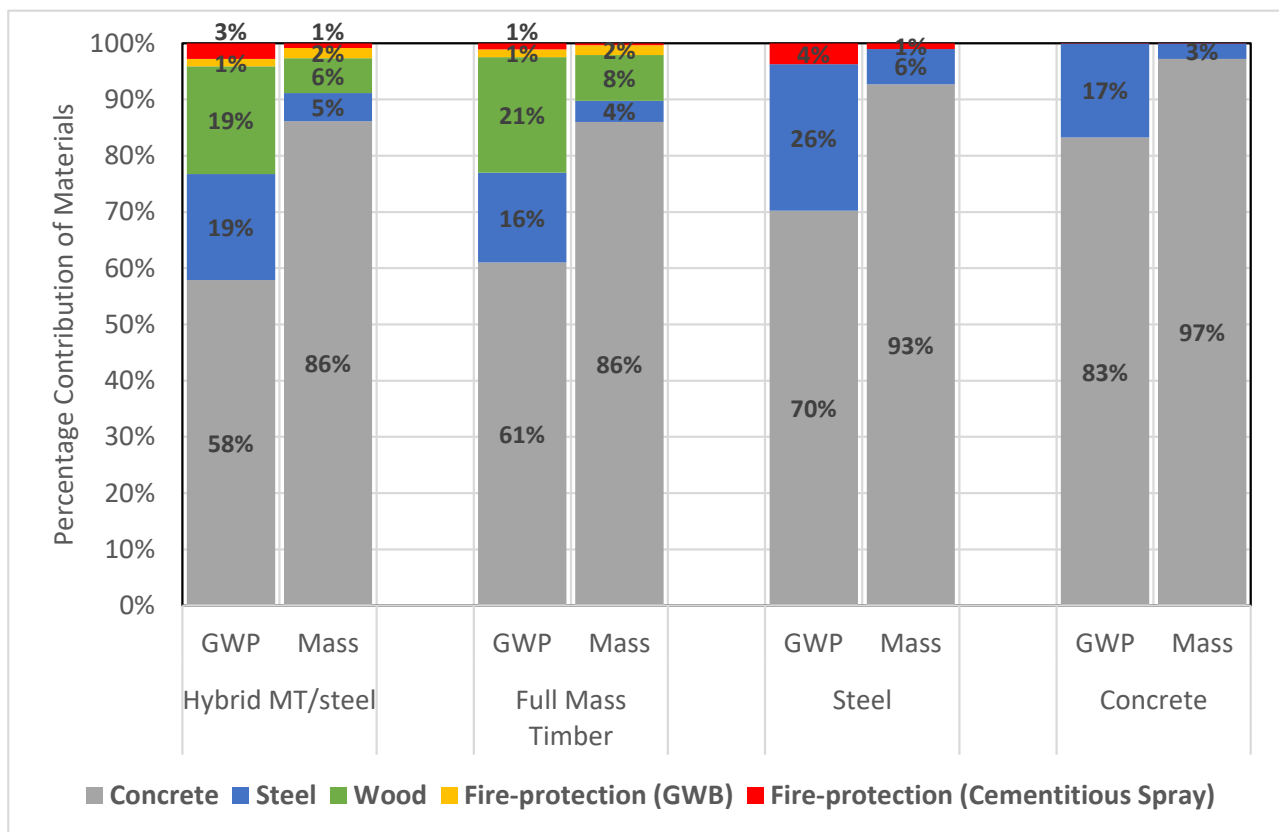


Figure 4. Contribution of materials to total building mass and GWPs of each structural framing system.

3.2. Life Cycle Assessment Comparison for Environmental Impacts

The cradle-to-grave LCA results of the four structural framing systems based on the functional unit of 1 m² floor area are summarized, primarily focusing on GWP due to its significant impact on global temperature rise, compared to the other impact categories assessed by Tally[®]. All calculated environmental impact categories and contributions are summarized in Table 4. The full mass timber system outperformed the hybrid system and steel and concrete alternatives in both GWP and renewable energy use, with GWP values being 1.2% lower than the hybrid system, 4.5% lower than the steel system, and 19.7% lower than the concrete system. The hybrid design showed that it had a higher GWP by 1% than the steel design but showed a 12% lower GWP compared to the concrete design. The small difference between the hybrid and steel structures is mainly due to transportation emissions, end-of-life assumptions, and the continued use of steel in the hybrid system. Although the hybrid structure used mass timber, which has much lower emissions during the production stage and stores carbon, it also included steel components such as steel

decking. These steel elements contribute to high emissions during the manufacturing stage, which adds to the overall GWP of the hybrid system. In addition, the timber was imported from Austria, resulting in much higher transportation emissions compared to the locally sourced steel. At the end-of-life stage, the steel structure also received a large credit because it was assumed that 98 percent of the steel would be recycled. The hybrid structure, on the other hand, included timber components assumed to go to landfill, where the stored carbon would eventually be released. These combined factors, especially the CO₂ emissions released during the steel production stage, reduced the environmental advantage of using timber in the hybrid design. As a result, the hybrid structure ended up with a slightly higher GWP than the steel structure. However, the timber components can be repurposed instead of going to landfills. By taking this into account, the difference in GWP between hybrid and steel structures would become much smaller. This is a topic for future research.

Table 4. Cradle-to-grave environmental impacts of each framing system.

Impact Category	Unit	Hybrid	Mass Timber	Steel	Concrete
Global Warming	kgCO ₂ eq/m ²	330.27	313.43	327.52	375.19
Acidification	kg SO ₂ eq/m ²	1.53	1.64	1.12	0.99
Eutrophication	kgNeq/m ²	0.13	0.16	0.05	0.063
Smog Formation	kgO ₃ eq/m ²	25.54	27.63	17.60	20.12
Ozone Depletion	CFC-11eq/m ²	1.48×10^{-6}	2.37×10^{-6}	7.49×10^{-7}	-1.74×10^{-7}
Primary Energy Demand	MJ/m ²	3290.80	3376.50	3102.37	3265.98
Non-Renewable Energy Demand	MJ/m ²	2110.10	2028.60	2915.78	3064.89
Renewable Energy Demand	MJ/m ²	1173.94	1340.95	186.36	200.43

Although the mass timber and hybrid systems required more total primary energy, they relied significantly on renewable energy compared to the steel and concrete systems, which used only 6% renewable energy. This difference is largely due to the use of mill residues as an alternative heating source and for on-site electricity generation in wood product manufacturing, particularly for drying lumber to make CLT and glulam products. However, the steel and concrete systems outperformed the hybrid and mass timber systems in several other impact categories. This result differs from previous U.S. studies [8,12], which compared the mass timber structures to structures made using traditional materials. These two studies found that mass timber systems not only had better performance in GWP and renewable energy use but also showed better outcomes in eutrophication and ozone depletion impacts. These differences could be attributed to the different material LCI databases and tools used in the WBLCA analysis.

Since the focus of this study was only on the materials in the building, no operational energy during the building's occupancy was considered or modeled. Moreover, in this analysis, no impacts were observed in Modules B2–B5 (i.e., maintenance, repair, replacement, and refurbishment), despite their inclusion. This is because all materials were assumed to have a lifespan equal to the building's 60-year life, eliminating the need for maintenance or replacement. However, if finishing materials or paint had been defined for CLT or glulam components in Tally[®], their impacts would have been evident in these stages, such as in repair or replacement activities. Moreover, factors such as fire resistance and durability can also influence maintenance requirements and service life. Engineered wood products like CLT and glulam are typically designed with fire safety considerations, relying on charring behavior and insulation layers to meet fire code requirements. However, actual fire performance and long-term durability during the service life can vary depending on

the specific design and maintenance practices, which was beyond the scope of this study but will be a good topic for future research.

The reported environmental impacts and energy use across different life cycle stages for each building design showed a major contribution at the production stage (see Figures 5 and 6). Exceptions are the impacts of eutrophication in the full mass timber and hybrid designs that exhibit the highest contribution from the building end-of-life stage (C2–C4 stages). As shown in Figure 5, more than 50% of the eutrophication potential in the mass timber and hybrid designs occurred at the end-of-life stage, while nearly 90% and 84% of the eutrophication impacts in the steel and concrete designs, respectively, were attributed to the production stage. As noted by Chen, the higher eutrophication potential is largely due to wood decomposition in landfills, which produces harmful leachates that affect aquatic systems [22]. Since Tally[®] assumes that over 50% of wood is landfilled, with a significant amount of wood used in the hybrid and mass timber building scenarios, this resulted in higher eutrophication impacts at the end-of-life cycle stage.

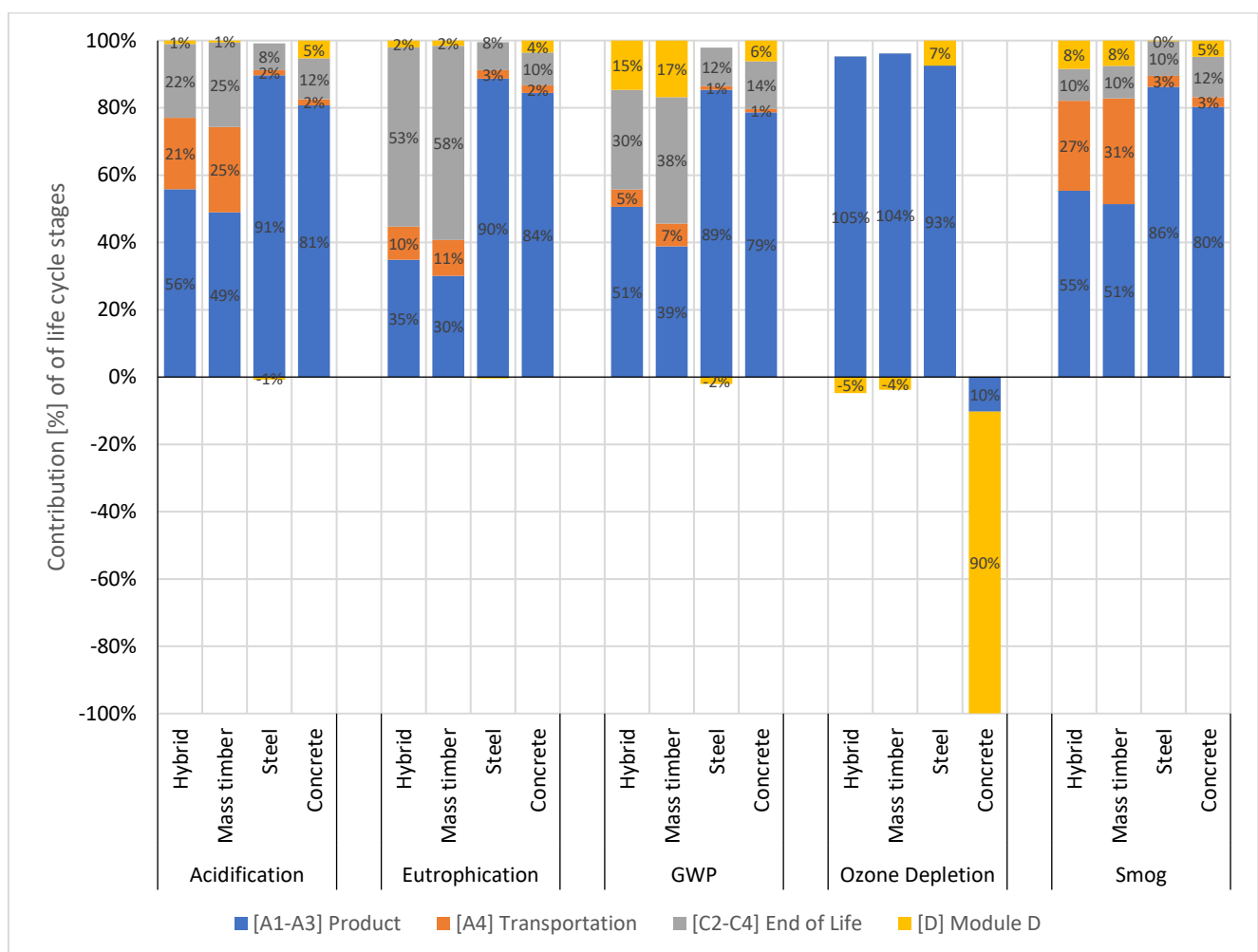


Figure 5. Contribution of life cycle stages to the environmental impacts, including acidification, eutrophication, GWP, ozone depletion, and smog, across hybrid, full mass timber, steel, and concrete building designs.

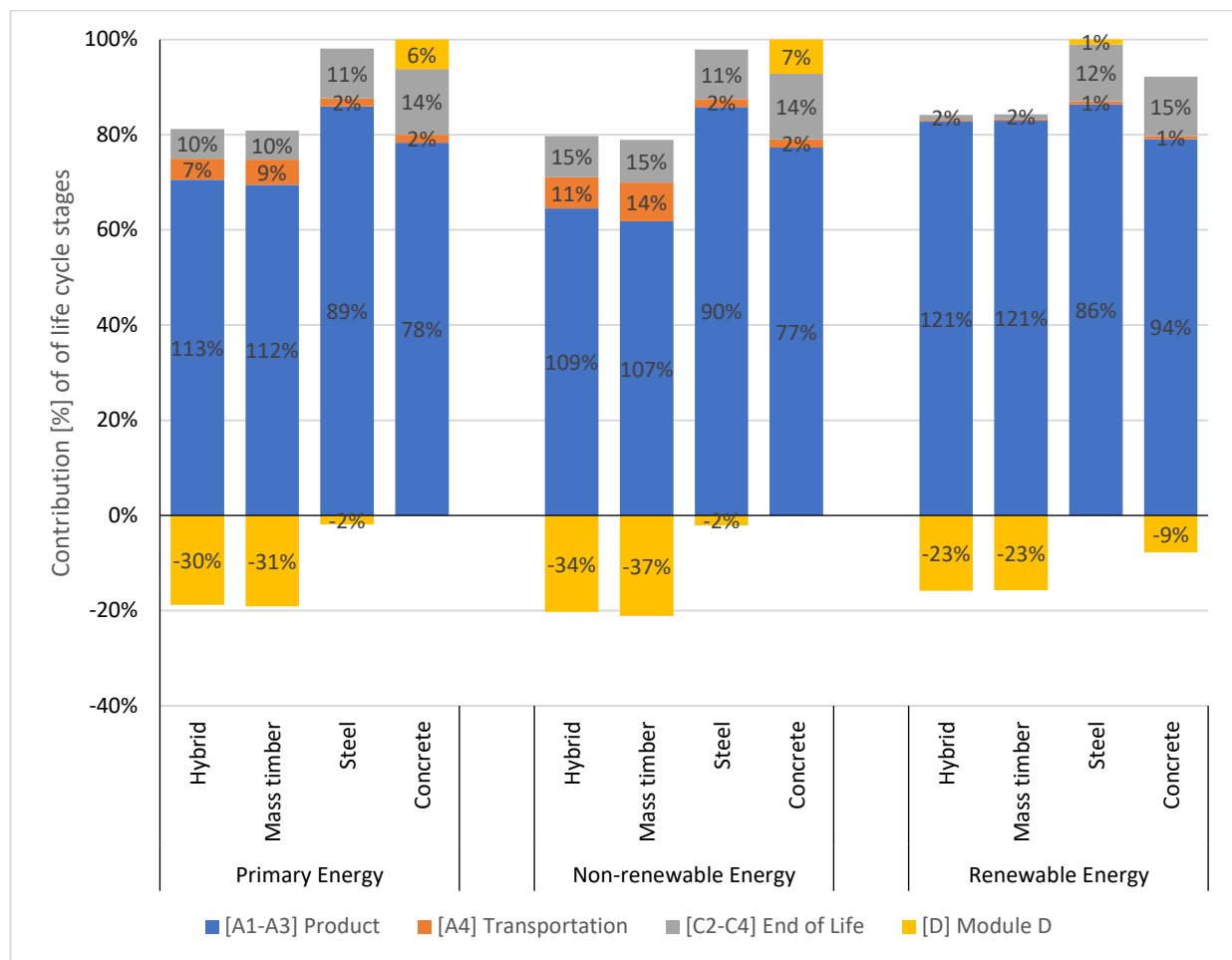


Figure 6. Contribution of life cycle stages to the energy use, including primary, non-renewable, and renewable energy, across hybrid, full mass timber, steel, and concrete building designs.

Additionally, the concrete system in this LCA study exhibited a net negative impact on ozone depletion, with 90% of this contribution occurring in Module D. This outcome could be primarily due to Tally's assumptions for steel-fabricated reinforcement in stage D, which include 100% scrap input. The remaining 10% of the negative value was attributed to the production stage, primarily due to the use of welded wire mesh as reinforcement in the slab-on-grade components within the building's podium. Although all building designs featured slab-on-grade components with welded wire mesh reinforcement in the podium, the steel, mass timber, and hybrid designs showed higher ozone depletion contributions in the production stage. The use of other materials with higher ozone depletion impacts, such as steel decking in the steel design and wood components in the mass timber and hybrid designs, contributed to this increase. Their high ozone depletion impacts during the production stage effectively offset the negative ozone depletion contribution from the welded wire mesh in these designs.

Moreover, the GWP contribution from the production stage was significantly lower for the mass timber and hybrid designs compared to the steel and concrete designs. The hybrid design showed 38% and 28% lower GWP than the steel and concrete designs, respectively. The full mass timber design demonstrated even greater reductions, with 50% and 40% lower GWP than the steel and concrete designs, respectively, at the production stage alone, which will be discussed in detail.

The increased transportation distance for mass timber products at stage 4 significantly influenced acidification and smog formation, with these impacts being approximately

10 times higher in the full mass timber and hybrid designs compared to the locally sourced steel and concrete designs. Eutrophication also increased substantially, with impacts around five times higher in the mass timber and hybrid designs than in steel and concrete. Similarly, a study by Gu et al. examined the environmental impacts of transporting mass timber products for a mid-rise institutional building in New Brunswick, Canada [23]. Their study conducted a comparative cradle-to-gate LCA using SimaPro software and the TRACI impact assessment method to compare a steel-frame building to an alternative mass timber design. They found that the mass timber design had higher impacts on smog formation, acidification, and eutrophication due to the longer transportation distance and increased diesel fuel consumption associated with transporting mass timber components to New Brunswick, Canada [23].

3.3. Comparison of GWP Impact on Different Life Cycle Stages

Figure 7 highlights the GWP impacts of different building types across various life cycle stages. The production stage (A1–A3) had the highest GWP impact, particularly for concrete and steel buildings. The concrete and steel structures demonstrated similar GWPs within stage A, including modules A1–A3, with 295 and 292 CO₂ eq emissions per m² floor area, respectively. They were about 77% and 142% higher than that of the hybrid (167 CO₂ eq) and full mass timber (122 CO₂ eq) building designs, respectively. The hybrid and full mass timber configurations demonstrated significantly lower GWP impacts in the production stage, reflecting the biogenic carbon in wood products flowing into the system as a negative carbon sink. This highlights the contribution of mass timber construction to positive environmental impacts since wood can store more carbon than it emits throughout the building's production stage. Tally[®] accounted for this benefit by incorporating it into the system at stage A. However, this initial credit was partially offset at the end-of-life stage (Stage C) as well as stage D, where the release of stored carbon during the demolition of wood products was considered. This explains why the hybrid and mass timber designs showed higher impacts in the end-of-life stage and Module D, whereas the steel building exhibited a lower impact in the end-of-life stage and achieved a net negative GWP of −7.12 kg CO₂ eq/m² in Module D, primarily due to Tally's assumption of a 98% recyclability rate for steel materials. Tally's method assumes that 63.5% of wood ends up in landfills, 22% is incinerated, and only 14.5% is recycled. However, the end-of-life scenarios for mass timber are likely to involve various pathways and can differ significantly across LCA software due to the uncertainties in predicting future conditions. With mass timber construction being relatively new and no buildings having reached the end-of-life phase yet, real-world data are lacking. Thus, various assumptions and scenarios in this stage can influence the results. Tally[®] estimates 32% of permanent biogenic carbon storage in landfills, a conservative figure compared to the Athena Impact Estimator's 64% and the upper range of 80% suggested in other products' EPDs [24,25]. Some studies in Australia indicated even lower decomposition rates, with softwoods and hardwoods losing only 18% and 17% of their carbon content over 46 years, respectively [26]. These differing assumptions and uncertainties limited many studies to cradle-to-site boundaries or led them to explore multiple end-of-life scenarios, such as 100% landfill, incineration, or recycling of timber products, to assess their different environmental performances. Feitel et al. analyzed the GWP released at stage D for different end-of-life pathways of CLT panels. They revealed that both the baseline scenario, which follows Tally's default database, and the 100% landfill scenario produced nearly identical GWP levels. However, 100% incineration emerged as the most effective option, with a GWP about 36% lower than the baseline. Conversely, 100% recycling had the highest GWP, roughly 38% higher than the baseline. They also suggested that if 100% direct reuse of CLT panels in another building cycle could happen, it could

keep nearly all the stored biogenic carbon sequestered, significantly reducing the net GWP impact and enhancing carbon sequestration [19].

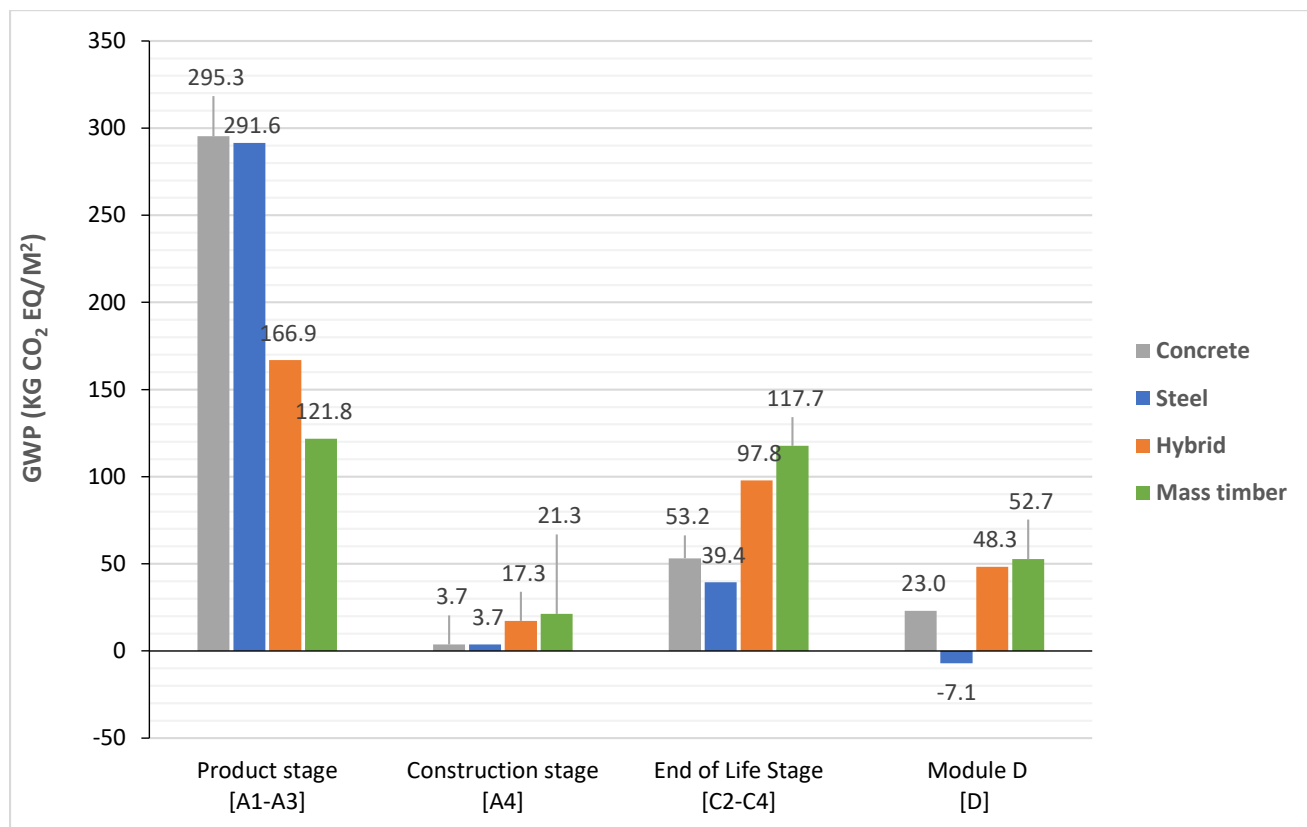


Figure 7. Comparison of GWP (functional unit) impacts over different life cycle stages of the four building system designs.

Moreover, it is important to note that the construction (A5) and deconstruction (C1) stages were excluded due to Tally's default settings. However, Chen et al. [12] and Jolly et al. [27] examined these stages separately and confirmed a higher GWP impact for concrete compared to the mass timber structure. Despite this, in this study, when considering broader stage groupings, such as A4 and A5 or C1–C4, mass timber still showed an overall higher GWP impact (Figures 5–7) than concrete due to significant contributions from transportation (A4) and waste processing and disposal (C3 and C4) assumptions for mass timber products. This is because, while most materials used the Tally® LCA's default U.S. average transportation data, the hybrid and mass timber systems required adjustments to reflect the actual modes and distances used to deliver MTPs to the construction site. Unlike locally sourced materials like concrete and steel, the MTPs are normally transported over longer distances using multiple modes (e.g., boats, trains, and trucks), thus resulting in a higher GWP impact for these systems, emphasizing the environmental considerations of transporting materials from distant locations. Transportation impacts were minimal for the steel and concrete systems, contributing less than 1% to the total building GWP. However, for the hybrid and mass timber systems, transportation accounted for 5% and 7% of their GWP, respectively. This suggests that the establishment of regional facilities for producing MTPs should be considered, with the aim of reducing transportation impacts on GWP, for example.

Several studies have highlighted the benefits of locally sourced timber to reduce CO₂ emissions [12,28]. Jolly et al. conducted a cradle-to-grave LCA study on the mid-rise mass timber construction and traditional concrete buildings in Australia and examined the trans-

portation impacts of concrete and CLT, both locally sourced and imported from Austria. They found that the concrete building had the lowest GWP for transportation, while locally sourced timber had five times, and imported timber materials had 15 times the GWP [27]. Moreover, in a cradle-to-site comparative LCA, Liang et al. analyzed the environmental impact of transporting CLT for a 12-storey mixed-use building in Portland, OR, USA, primarily constructed from mass timber. They examined various transportation distances, ranging from local production (320 km) to overseas sourcing from Europe (21,333 km). They found that the GWP for locally produced CLT was 3.4 kg CO₂ eq/m², which increased significantly with longer transport distances—reaching up to 47 kg CO₂ eq/m² for European sources [29]. This underscored the substantial impact that transportation could have on the overall environmental footprint of mass timber buildings.

3.4. Biogenic Carbon in the Buildings

Negative GWP impacts from timber products shown in the production stage (A1–A3) of LCAs represent the biogenic carbon sequestered by trees that become part of the wood-based product pool. Trees absorb carbon dioxide from the atmosphere through photosynthesis, storing approximately 50% of their dry mass as elemental carbon [30]. When a tree is harvested (Stage A1), this sequestered carbon enters the LCA system and is considered a negative emission because it reflects carbon that was previously removed from the atmosphere and is now temporarily locked out of the carbon cycle. It remains stored until the end of its service life, which, in this study, is aligned with the 60-year lifespan of the Bakers Place building. This biogenic carbon storage is credited in the Production stage (A1–A3) as a negative GWP impact, which significantly lowers the overall GWP of the hybrid and full mass timber designs during this phase.

Both the hybrid and full mass timber buildings in this study utilized 2335.23 m³ of CLT panels, while the hybrid design incorporated 171.75 m³ of glulam beams and columns, and the full mass timber design included 941.29 m³ of glulam beams and columns. The stored carbon potential of these timber components was calculated based on the biogenic CO₂ content (kg CO₂/m³) derived from the timber products' Environmental Product Declaration (EPD).

The glulam product's EPD showed that the biogenic carbon content of glulam is 763 kg CO₂ eq/m³. Using this value, the total CO₂ stored in glulam beams and columns in the hybrid design was calculated as follows:

$$763 \text{ kg CO}_2 \text{ eq/m}^3 \times 171.75 \text{ m}^3 = 131,045.25 \text{ kg CO}_2$$

The CLT product's EPD provided a biogenic carbon content of 762 kg CO₂ eq/m³. According to that, the total CO₂ stored in CLT floors in the hybrid design was calculated as follows:

$$762 \text{ kg CO}_2 \text{ eq/m}^3 \times 2335.23 \text{ m}^3 = 1,779,445.26 \text{ kg CO}_2$$

Thus, the total stored biogenic carbon in the hybrid design was calculated at approximately 1,910,490.5 kg CO₂, while the total stored biogenic carbon in the full mass timber design was approximately 2,497,649.5 kg CO₂.

Figure 8 illustrates the stored biogenic carbon of each mass timber component (at stage A) per square meter for both the hybrid and full mass timber designs, highlighting the significant carbon storage potential and environmental advantages of utilizing wood products.

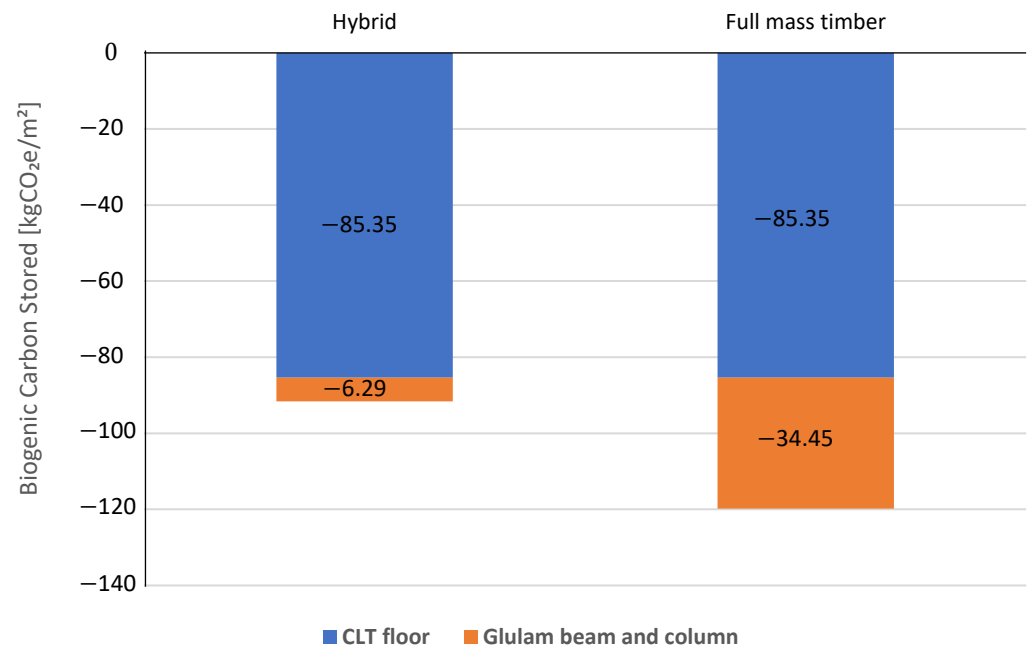


Figure 8. Biogenic carbon stored in the hybrid and full mass timber building designs.

4. Conclusions

A cradle-to-grave LCA was conducted for four high-rise building designs, namely, hybrid (mass timber with steel), full mass timber, steel, and concrete, based on Bakers Place in Madison, WI, USA. The following conclusions were drawn from this study:

- Mass timber and hybrid designs weighed 33% and 12% less than the concrete and steel designs, respectively, significantly reducing the reliance on concrete, a major contributor to GWP.
- The hybrid design exhibited a slightly higher GWP (1%) than the steel design but showed a 12% lower GWP compared to the concrete design. The full mass timber design performed the best, with 5%, 4%, and 16% lower GWP than the hybrid, steel, and concrete designs, respectively.
- Full mass timber and hybrid designs had higher eutrophication impacts at the end-of-life stage, primarily due to wood decomposition in landfills. In contrast, the steel and concrete designs saw most of their eutrophication impacts occur in the production stage.
- Full mass timber and hybrid designs experienced significantly higher acidification and smog impacts, mainly due to longer transportation distances for imported timber. Conversely, steel and concrete systems benefited from local sourcing of materials.
- Mass timber and hybrid designs relied more on renewable energy sources, while steel and concrete systems heavily depended on non-renewable energy sources.

These findings provide valuable guidance for sustainable material choices in high-rise buildings to address climate change and highlight the environmental benefits of mass timber systems, especially in reducing embodied carbon. However, they also reveal important trade-offs that must be considered in design and policy decisions.

It is recommended that the use of mass timber products be prioritized in building designs to reduce GWP. However, to minimize transportation-related emissions and enhance the environmental performance of mass timber buildings, policymakers and developers should also prioritize local sourcing and support the development of regional manufacturing facilities. Further regional studies are also needed to explore practical and effective end-of-life strategies for wood-based products and to identify the most suitable options for

policy development. Enhanced reuse, recycling, or alternative disposal methods could help reduce environmental impacts from wood decomposition and improve overall sustainability. The limitations of the LCA tool used in this study (Tally), including restricted user adjustments and limited regional end-of-life data, prevented the inclusion of alternative scenarios. Therefore, it is strongly recommended that more region-specific research be conducted to improve waste management data for wood-based products, which can help expand and update LCA tool databases for more accurate results.

Overall, for mass timber-based building designs, sustainability can be significantly improved by prioritizing local material sourcing, implementing effective end-of-life policies for wood products, and reducing reliance on concrete in non-critical structural areas.

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Conflicts of Interest: The authors declare no conflicts of interest.

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