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Environmental impact assessment of mass timber, structural steel, and reinforced concrete buildings based on the 2021 international building code provisions

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A B S T R A C T

Building construction and operation accounts for over a third of global anthropogenic greenhouse gas (GHG) emissions and energy consumption. To determine whether more prevalent use of mass timber (MT) construction could significantly reduce environmental impacts of construction, we performed whole building life cycle assessment (WBLCA), using Athena Impact Estimator for Buildings (IE4B) software, on a series of nine multi-story residential buildings of three varying materials and heights. Three MT buildings of 18-, 12-, and 8-story heights, respectively represent IV-A, -B, and –C occupancies of the 2021 and 2024 editions of the International Building Code (IBC), which facilitate regulatory approval of tall wood buildings. When benchmarked with six functionally equivalent structural steel (SS) and reinforced concrete (RC) buildings and accounting for cradle-to-grave (A-C) system boundaries pertinent to embodied energy, MT buildings lowered global warming potential (GWP) by an estimated range of 39–51% and 28–34% compared to functionally equivalent RC and SSbuildings, respectively. Extending system boundaries to consider module D to account for biogenic carbon of mass timber and recyclability of steel and concrete, the GWP reduction of MT buildings further reduced to ranges of 81–94% and 76–91%, respective to RC and SS buildings. Reducing the reference study period (RSP) to 60 years generally lessened GWP 11–21% relative to the standard RSP of 75 years. Finally, greater exposure of MT components permitted in the 2024 IBC further reduced GWP up to 1.05% by using less structural fire encapsulation material (e.g., gypsum wallboard) than previously prescribed.

1. Introduction

The built environment accounts for approximately 37% of annual global CO_2 emissions, with contributions of 27% and 10 %, respectively attributable to building operational energy and embodied carbon emissions [1]. Thus, accounting for over a third of the world's primary energy usage, international efforts aim to reduce the environmental impacts of construction to net zero carbon emissions [2]. A comprehensive set of strategies has been mapped to enhance energy efficiency, use renewable energy, and build with low-embodied carbon materials [1–3]. To enact these strategies, several countries may implement building code initiatives that primarily target operational energy consumption. Although building with greener construction materials is conjointly critical to reduce net carbon emissions of the whole building life cycle, voluntary sustainability standards primarily guide materials selection while most building codes overlook embodied carbon [4].

Mass timber (MT), a family of engineered wood products that assembles high volumes of timber into composite structural components that rival precast concrete in size, has garnered global popularity in recent years as a sustainable construction material [5–10]. MT construction mostly utilizes cross-laminated timber (CLT) and glued laminated timber (glulam) framing [11] that can be used in place of traditional tall building materials such as structural steel (SS) and reinforced concrete (RC). Made primarily from standard lumber or veneers, MT offers several advantages that lessen environmental impacts via renewability of trees, carbon sequestration with wood, and low

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levels of embodied carbon [6]. Additionally, the prefabrication of MT components off-site can reduce waste and improve construction efficiency. The use of MT in construction is also beneficial for indoor air quality because wood products emit fewer harmful volatile organic compounds (VOCs) compared to other building materials [12,13]. Additionally, wood furnishings and architecture may evoke physiological relaxation, characterized by reduced brain activity, increased parasympathetic nervous system activity, decreased sympathetic nervous system activity, as well as lowered blood pressure, heart rate, and stress hormone levels [13]. MT construction has become increasingly popular worldwide due to its ease with onsite erection, aesthetic appeal, and eco friendliness [14]. As concerns about sustainability and environmental impacts continue to grow, MT is becoming an attractive option for designers and builders who want to create sustainable buildings [15]. In fact, there has been a recent surge in the number of tall buildings made of MT in North America and around the world [16]. With the benefits of MT, it is likely that this material will continue to gain code adoption and popularity in the construction industry as a sustainable alternative to traditional building materials [17].

The International Code Council (ICC) develops the International Building Code (IBC) as a model building code for constructing tall wood buildings that outline safety requirements and performance standards [18]. IBC contains guidelines to ensure the safety of building occupants, firefighters, and emergency responders by specifying requirements for fire resistance, structural integrity, and durability of tall wood buildings. The guidelines address various factors, including fire safety, structural design, moisture management, acoustics, seismic performance, and wind resistance [19]. With the increasing demand for sustainable building materials and construction methods, the IBC guidelines for tall wood buildings are expected to play a vital role in the continued growth of MT construction in the coming years. Development of prescriptive building code provisions for MT construction will further expedite its mainstream use. Building codes commonly prioritize minimum safety requirements over sustainability. The combustibility of wood and the tall heights that MT structures may achieve, make fire the top safety concern. Based on research and proven applications around the world, the ICC has approved proposals to include tall wood buildings as part of the 2021 IBC, which encourage use of MT as a construction material in U.S. states that adopt new editions of the IBC [19–21]. The 2021 IBC includes three new construction types, Type IV-A, IV-B, and IV-C, which address the use of MT materials [20]. The code also provides prescriptive provisions for up to 18 stories of Type IV-A construction for both business (B) and residential occupancies (R2) if the structural elements are encapsulated with noncombustible materials (e.g., gypsum board) to mitigate fire risks. The adoption of these new code provisions by the ICC facilitates the safe construction of tall wood buildings and continued growth of MT construction in the United States and around the world [20].

A whole building life cycle assessment (WBLCA) is a method for evaluating the environmental impact of various building types [22] and construction materials [23] over the course of their entire life cycle [24–26]. WBLCA can provide insights on the life cycle environmental impacts of a building including impacts from raw materials extraction, their transport to manufacturing facilities, processing materials into products, their transport to building construction sites, installation, maintenance/use, demolition after the service life, and various end-of-life options such as landfilling, recycling, or burning for energy recovery. A key factor impacting the environmental performance of any building is fossil energy usage, which is generally classified into embodied energy and operational energy, both of which are crucial for reducing the overall environmental impact of the building. Embodied energy refers to the total energy required to manufacture, transport, and ultimately dispose of a building material throughout its entire life cycle. It includes the energy used in the extraction of raw materials, processing and manufacturing, transportation, construction, maintenance, and the eventual demolition or disposal of the product or material [27]. Operational energy, on the other hand, refers to the energy consumed by a building or a product during its normal day-to-day use or operation, such as the energy needed for heating, cooling, lighting, and powering appliances. Although operational energy tends to dominate the energy consumption of buildings over their lifetime, assessments of embodied energy are most useful in the decision process of structural systems selection [28], along with the long-term trends of operational energy reduction compared to embodied energy [29–31]. When selecting structural systems, operational energy is typically not considered because several past studies have assumed or suggested that the day-to-day energy need for functionally equivalent buildings are similar [32–34]. Embodied energy comparisons, however, are critical to distinguishing the differences among structural materials and minimizing net carbon impacts beyond the limits of efficient mechanical and building envelope systems. The findings of Amiri et al. [35] indicate that 20–30% of the total energy consumed can be embodied energy in the pre-use stages, and the percentage is likely to increase as operational energy use is reduced by enhancements to insulation, renewable energy production, and efficiency of equipment. Studies [27,32–34,36–40] demonstrated that the embodied emissions of a building are mainly influenced by the choice of building materials and design decisions.

Using WBLCA, several past studies compared the environmental impacts of MT buildings to that of traditional RC and SS buildings [27,33,34,36–46]. These studies suggest that MT buildings typically have lower environmental impacts (e.g., reduce GHG emissions), than SS and RC buildings. Among the most distinctive sustainability advantages, wood comes from a renewable natural resource and when used for MT, can store carbon for a long-term. A comprehensive overview of the past WBLCA studies conducted in the United States and worldwide, which is the main jurisdiction of IBC building codes, is presented in Table 1. For example, Milaj et al. [37] assessed the environmental effects of using MT in place of RC and SS in commercial construction and renovation in Oregon, United States and found that using MT as a structural material can lower the global warming (GW) impact by about 60%, demonstrating the viability of MT as a sustainable and eco-friendly substitute in commercial construction. Pierobon et al. [42] analyzed the environmental impacts of a hybrid, 8-story, mid-rise commercial building constructed with CLT and compared it to a functionally equivalent building constructed with RC. For the hybrid CLT building's fire protection, two alternative designs were considered: 1) a "fireproofing design," in which gypsum wallboard was applied to the structural wood; and 2) a "charring design," in which two additional layers of CLT were added to the panel. Their findings demonstrated that the hybrid CLT building had an average 26.5% lower GWP than the concrete building, excluding biogenic carbon emissions. Using the inherent, insulative charring of wood to mitigate fire, instead of fireproofing encapsulation, was advantageous for all impact categories, except for minor differences in ozone depletion. Their embodied energy assessment of the various building types indicated that the total primary energy in hybrid CLT buildings and RC buildings was generally comparable. However, their findings showed that the hybrid CLT building used 8% less fossil-based energy compared to an RC building. In the scenarios with fireproofing and charring, more than 1,556 tCO_2e and 2,567 tCO_2e, respectively were stored in the wood components of the building (biogenic carbon) compared to the RC structure. Chen et al. [34] compared the environmental impacts of a 12-story mixed-use (residential and commercial) building made of CLT and a functionally equivalent RC building designed by Lever Architecture for Portland, Oregon, USA. They estimated that the total mass of CLT buildings was 33.2% lower than RC buildings, suggesting higher resource efficiency of MT buildings. Excluding operational energy use, their WBLCA results showed that the embodied carbon emissions for the CLT building were 20.6% lower than those for RC buildings. The estimated embodied carbon emissions were much lower (69.5%), when biogenic carbon stored in MT materials were considered.

Liang et al. [33] conducted WBLCA and life cycle cost analysis

Table 1
Summary of the few past Whole Building Life Cycle Assessment (WBLCA) studies conducted in the United States and Europe.

Author	Region	Construction material	Building stories	Occupancy	Reference study period (years)	Software	Database	Standard/ Framework/ Impact Method	LCA system boundary
Milaj et al. [37]	Oregon, USA	MT, RC, SS	2 1, 1.5 2-story+2mezzanines 5 1 1	Office Exercise facility Sport center Residential Medical Warehouse	100	IE4B	Athena LCI database [53]	ISO 14040; EN15978 TRACI v2.1	A1-A5, B2, B4, C, D
Pierobon et al. [42]	Pacific Northwest, USA	RC, Hybrid CLT-RC	8	Commercial	100	SimaPro 8	USLCI [54]e coinvent [40] Athena 5.2 [52]	ISO 14040, ISO14044 TRACI v2.1	A1-A5
Chen et al. [34]	Portland, Oregon, USA	MT, RC	12	Mixed-use (residential and commercial)	60	IE4B	Athena LCI database [53], USLCI [54]	EN15978, TRACI	A1-A5, B2, B4, B6, C1-C4, D
Liang et al. [33]	PNW, USA	MT, RC	12	Mixed-use (residential and commercial)	60	SimaPro 9.0	DATASMART [55]	ISO 14040, ISO14044, ISO 21930, EN15978 TRACI 2.1	A1-A5, B2-B4, B6-B7, C1, C3, D
Puettmann et al. [41]	PNW, NE, SE, (USA)	MT, RC	8, 12, and 18	Mixed-use (residential and commercial)	–	SimaPro 9.1	USLCI [54], ecoinvent [56], DATASMART 2019 [55] Athena LCI database [53]	ISO 14044, EN15978, ISO 21930 TRACI	A1-A5
Allan and Phillips [40]	North America	SS, MT	5, and 12	Business Residential	60	IE4B	Athena LCI database [53]	EN15978; TRACI	A1-A5, C1-C4, D
Hellmeister [32]	Baltimore, Boston, USA	MT, RC, SS	8	Mixed-use (nonresidential)	60	IE4B	Athena LCI database [53]	ISO 14040; IBC 2021, TRACI v2.1; EN15978	A-D
Greene et al. [39]	Fort Collins, CO, USA	SS, MT	4	Commercial	30	N/A	ecoinvent 3.7 [56], SCLI [54], WARM	ISO 14040, ISO 14044, IPCC 6th Report	A1-A5, B6, C1-C4, D
Andersen et al. [47]	Trondheim, Norway	RC, CLT	5, 8	Residential	100	SimaPro 9.0.0.35	ecoinvent v3.5	ILCD LCA	A-D
Dodoo et al. [48]	Växjö, Sweden	CLT, RC	8	Residential	100		ecoinvent v3.7.1	EN 15978, ISO/TS 14067	A1-A5, B2-B4, C1-C3, D
Dolezal et al. [49]	Vienna, Austria	RC, MT	8	Mixed-use (residential and commercial)	100	Eco2soft building LCA	ecoinvent v2.2 for materials ecoinvent v3.5 for energy	ISO 14040, ISO 21930, EN 15978, and EN15804	A-D
Skullestad et al. [50]	USA, Trondheim, Norway	MT, RC	3,7,12, and 21	Hotel	60	Sima Pro v7	ecoinvent v.3.2	ISO	A1-A3, D
Present work	USA	MT, SS, RC	8, 12, and 18	Residential	75	IE4B	Athena LCI database [53]	ISO 14040, ISO 21930, ASTM E2921-22, EN15978; IBC 2021	A1-A5, B2, B4, C, D

Notes.
PNW= Pacific Northwest; NE = Northeast; SE = Southeast.
MT = Mass timber; RC = Reinforced Concrete; SS = Structural Steel.
IE4B = Impact Estimator for Buildings (software) [52].
ISO = International Organization for Standardization [57,58]; TRACI = Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts [59]; ASTM = American Society for Testing and Materials [24]; ELCD = European reference Life Cycle Database; WARM= Waste Reduction Model.

(LCCA) to analyze the environmental and economic performance of a 12-story high-rise MT building with mixed-use (residential and commercial) occupancies in the Pacific Northwest of the United States, designed by Lever Architecture. They indicated that MT building had lower total energy (embodied and operational) of 3,153 $kgCO_2e/m^2$, compared to conventional RC buildings value of 3,203 $kgCO_2e/m^2$. In their 60-year reference study period (RSP), over 90% of GHG emissions were estimated to occur during the operational stage. They also suggested that the end-of-life recycling could provide carbon offsets of up to 364 $kgCO_2e/m^2$, lowering overall GHG emissions by 12%. Puettmann et al. [41] compared the environmental impacts of 8-, 12-, and 18-story MT buildings with mixed-use occupancies (residential and commercial) with functional equivalent RC buildings in the Pacific Northwest, Northeast, and Southeast regions of the United States. When compared to RC buildings across a range of regions and building heights, they found that MT buildings showed an embodied carbon reduction ranging from 22% to 50% for life cycle stages of A1-A5 (raw material extraction to construction), depending on building height and region. Allan and Phillips [40] found that MT structures were 31–41% better for the environment in terms of GWP, eutrophication potential, and particulate matter for human health, compared to SS structures. However, they also found that SS buildings had lower impacts in the other three environmental impact categories, including smog, acidification, and ozone depletion potential, with reported reductions in these impacts ranging from 48% to 58%, compared to MT buildings. Hellmeister [32] quantified the environmental impacts of an 8-story building for mixed-use (residential and commercial) with 6-stories of residential and 2-stories of commercial use, with a 10,220 m^2 floor area classified as Type IV-C construction in the IBC 2021. Their findings indicated that the MT building design had 52% less mass and 53% less embodied carbon from production to end-of-life (A-C).

Greene et al. [39] quantified the environmental impacts of a 10,000 m^2, 4-story office building made of MT and a functionally equivalent SS building with concrete foundation. In their three end-of-life scenarios for MT products (e.g., (i) 100% MT products sent to landfill, (ii) 95% of MT products used for particleboard manufacturing along with the remaining 5% sent to landfill, and (iii) direct reuse of 95% of glulam beams and 75% of CLT panels), the MT alternative offered an 80–99% reduction in embodied carbon with estimated values of 50–795 tCO_2e (5–79 $kgCO_2e/m^2$) and 3,999 tCO_2e (398.5 $kgCO_2e/m^2$), respectively for MT and SS buildings. They also found that direct reusing of 95% glulam and 75% CLT was the most sustainable end-of-life practice, resulting in successful long-term storage of 74.2% and 81%, respectively, of biogenic carbon stored initially in wood. Andersen et al. [47] studied the use of cross-laminated timber (CLT) and its potential environmental implications compared to conventional materials such as RC. They conducted a consequential life cycle assessment (LCA) on two mid-rise apartment buildings in Trondheim, Norway, one using CLT and the other using concrete as the main structural material. They evaluated the importance of different approaches for handling biogenic carbon in a building LCA and how this would affect the overall conclusions drawn from the study. They also evaluated the potential increased wood demand on forests and the forest area needed for future wood construction demand by extrapolating the case study results. Their study provided specific material quantities and ecoinvent unit processes used for modeling different building parts and gave a complete overview of the life cycle inventory for both buildings.

Dodoo et al. [48] estimated environmental impacts for an 8-story multi-family building made of CLT in Växjö, Sweden. The building had a total heated floor area of 3,374 m^2 and had 33 apartments. They integrated knowledge from optimized CLT utilization, connections in CLT assemblies, risk management in building service life, and life cycle analysis to improve the competitiveness of CLT-based building systems and to reduce climate impact. Connecting structural engineering aspects of CLT with life cycle analysis is a multi-disciplinary way to reduce the life cycle carbon footprint. It was highlighted that there was a potential for more efficient assembly through pre-fabrication, such as reducing assembly time and improving the quality of connections. Dolezal et al. [49] quantified environmental impacts for a multi-story MT building with up to eight stories in Vienna, Austria, and compared it with a functionally equivalent RC building. A comparison of the total mass and embodied carbon of the timber building with the concrete building showed 47% lower mass and 18% less embodied carbon in the timber building. They highlighted the need for comprehensive methods to calculate temporary carbon sequestration in order to accurately assess the GWP impact of MT. By applying LCA to compare the climate change impact of RC benchmark structures to alternative MT structures for buildings ranging from 3 to 21 stories in USA and Trondheim, Norway, Skullestad et al. [50] discussed how to account for biogenic CO_2 emissions in LCA and highlighted the underestimation of the benefit of storing carbon in long-lived products. Analyzing the outcomes of their WBLCA via a weighted sum method, Ahmed et al. [44], concluded that MT buildings were preferred choice over SS buildings when cost was a low priority and environmental concerns were a moderate to high priority. Their study also indicated that SS buildings were preferred choice when addressing global warming was not a top priority. However, when both the cost and global warming criteria were given a moderate weight, both materials roughly equaled scores, so neither was strongly preferred. In contrast, their finding indicated that a hybrid solution that combined elements of both materials, such as replacing concrete floors and decks with lightweight CLT flooring, was the best choice in every situation because it could maximize the benefits and minimize the drawbacks. Internationally, there have been over 60 documented LCA studies that have identified a trend of lower global warming potential and life cycle primary energy than prevalent RC and SS systems [51].

In the present work, a WBLCA was carried out to compare the environmental impacts of multi-story MT buildings designed according to recently enacted 2021 International Building Code (IBC) guidelines for tall wood buildings [20] and their functionally equivalent SS and RC structures in the United States. Buildings in categories IVA-18 stories, IVB-12 stories, and IVC-8 stories were studied, with the maximum floor area being specified according to the IBC 2021 provisions [20]. To assess the environmental impacts of the buildings, the study utilized the Athena's Impact Estimator for Buildings (IE4B) software tool [52], which utilizes the Athena Life Cycle Inventory database [53] to simulate the bill of materials. This study considered a cradle-to-grave (modules A-C) system boundary while including module D but excluding operating energy (module B6) and water (module B7), based on the assumption that structural materials have negligible effects on operations but profound effects on embodied carbon and energy.

While this study is similar to past WBLCA studies in evaluating the life cycle environmental impacts of MT buildings compared to their functionally equivalent counterparts, it differs in the following respects. First, unlike these past studies, the current WBLCA is based mainly on building designs guided by the 2021 IBC guidelines, while also conducting a sensitivity analysis based on the changes in the 2024 IBC guidelines. Second, it provides a detailed and context specific WBLCA for MT, SS, and RC multistory residential occupancy building projects in one place, capturing realistic and practical construction practices associated with each structural material in the United States. To our best knowledge, few published works have quantified the environmental impacts of MT, SS, and RC together to illustrate the full implications of structural systems selection, such as differing floor-to-floor heights and fireproofing details only for single-family and low-rise multifamily buildings. Past studies had focused mainly on mixed use and non-residential buildings without considering the more recent IBC guidelines. Finally, past studies used different reference study period (RSP), for instance 60 years, based on Leadership in Energy and Environmental Design (LEED) guidelines. The current study used RSP of 75 years adhering to the guidelines outlined in ASTM E2921-22 [24] and EN 15978 [25] for conducting comparative analyses, while also conducting a sensitivity analysis with RSP of 60 years. It is important to note here that the estimated environmental impacts are generally sensitive to the chosen RSP and therefore it is important to consider a RSP that is consistent with the existing standards [24,25].

2. Material and methods

The objective of this study was to assess the life cycle environmental implications of constructing multistory residential occupancy buildings using three different structural materials: MT, SS, and RC, in alignment with the tall wood building provisions specified in the 2021 and the 2024 IBC editions for further comparison. The analysis encompassed a total of nine buildings categorized as IV-A (18 stories), IV-B (12 stories), and IV-C (8 stories). To ensure equitable comparisons, the buildings were kept identical in terms of building footprints, floor-to-floor heights, overall heights, gross floor areas, and general floor plan layouts. However, certain factors, such as beam span and column grid layout, were allowed to vary, reflecting realistic and practical construction practices for each specific structural material. The assessment of the buildings' environmental performance in this study adheres to the guidelines outlined in ASTM E2921-22 [24] and EN 15978 [25] for conducting comparative analyses. A detailed description of the methodological approach utilized to achieve the study objective is provided below including the system boundary and functional units, reference study period, and building designs.

2.1. System boundary and functional units

The system boundary of the WBLCA considered in this study is depicted in Fig. 1, which employed a cradle-to-grave (stages A-C) system boundary. Module D was included in the assessment, while operating energy (module B6) and water (module B7) were excluded. This exclusion was based on the past studies that assumed or identified that the choice of structural materials had minimal impact on building operations but significantly affected embodied carbon and energy [31–33]. The functional unit adopted for this analysis was one square meter (m^2) of occupiable residential floor area in a multi-story building for 75 years. The only common constraint on the functional unit is that all structural systems must comply with minimum building code requirements. Each building type, therefore, provides only the same gross occupiable residential floor area. Because of the assumed building assemblies, other performance parameters, such as lateral stiffness, span length and depth constraints on the floor structure, and thermal efficiency, were not imposed on the functional units. Despite the lack of additional performance constraints, each building used the same RC shear walls as the spine of the lateral system and building envelope assemblies to facilitate equitable comparisons. Lateral stiffness and thermal efficiency, therefore, would be similar [32–34].

2.2. Reference study period

The RSP represents the timeframe used to analyze changes in the evaluated object, such as a building. The chosen RSP is highly sensitive, because various factors contribute differently to a building's environmental impacts over its lifetime, including operational energy and water use, maintenance, repair, replacement, and refurbishment. Determining the appropriate RSP for buildings is challenging due to non-technical considerations like occupant behaviors, environmental factors, climate severity, and maintenance schedules. Different frameworks and methodologies define different RSPs; for example, LEED suggests a RSP of 60 years. The current work follows guidelines from ASTM E2921-22 [24] and EN15978 [25], setting the RSP at 75 years for the comparative analysis purpose. Because of the different RSP specified among standards, both values are analyzed for comparison.

2.3. Building design

The building design utilized in this assessment is derived from the Timber Tower research project, which reflects multi-residence construction preferences found in cities across the United States [60]. To optimize the floor area within the categories of IBC 2021 for R-2 residential occupancies (IV-A-18-, IV-B-12-, and IV-C-8 stories), the dimensions and fire ratings of the hypothetical buildings were specifically redesigned for this study. Detailed information on these modifications is provided in Table 2 and Table S1. For example, a Type IV-A building has dimensions of 37.19 m × 25.60 m (122 ft × 84 ft) and a floor area of 17,137.27 m^2 (184,464 ft^2). Each floor was designed to accommodate a total of 11 residential units. The original hypothetical MT buildings (known as Timber Tower [60]) were initially designed for a generic location in Chicago, Illinois. However, for the purposes of this study, no specific site was considered; we used the default location of USA

Table 2
Building characteristics for the comparative whole building environmental impact assessment of R-2 residential occupancy buildings considered in this study.

MT buildings category as per IBC 2021	Stories	Building height m (ft)	Total Floor area m^2 (ft^2)	Dimensions m x m (ft x ft)
IV-C	8	25.6 (84)	7717.1 (76,608)	34.75 × 25.6 (114 × 84)
IV-B	12	38.4 (126)	11,424.8 (122,976)	37.19 × 25.6 (122 × 84)
IV-A	18	57.6 (189)	17,137.3 (184,464)	37.19 × 25.6 (122 × 84)

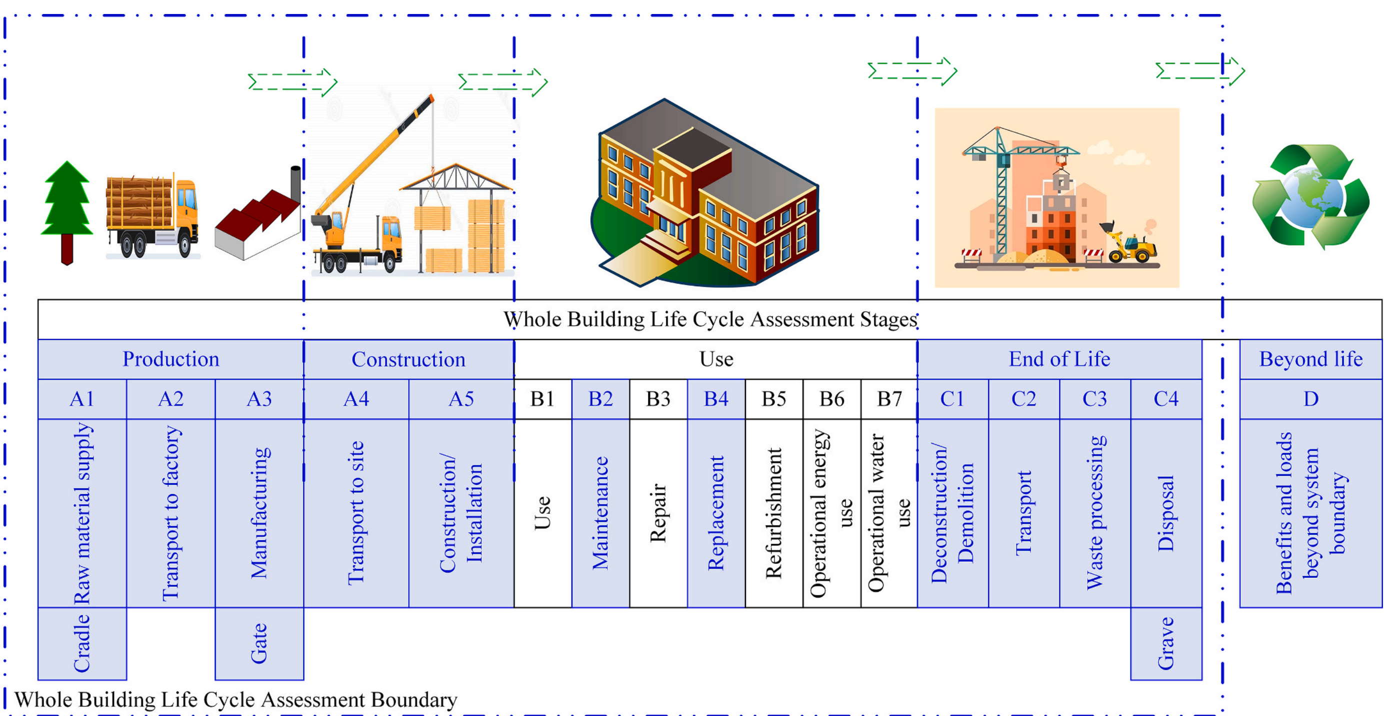

Fig. 1. System boundary considered for Whole Building Life Cycle Assessment (WBLCA) in the present work (modules highlighted in blue are considered for the evaluation): adopted from ISO 21930 [57].

provided in the IE4B, the Athena Impact Estimator for Building Software. The layouts of the 8-, 12-, and 18-story structures are depicted in Figs. S1a (MT) and S1b (SS and RC). Gridlines are represented by capital letters and dimensions are represented by small letters. In this study, the buildings were also redesigned to meet fire resistance requirements outlined in the tall wood building provisions of IBC 2021. For instance, a Type IV-A primary structural frame constructed with MT and requiring a 3-h fire rating would necessitate the use of five layers of 5/8″ Type X gypsum wallboard. The fire ratings for the different assembly groups are provided in Supplementary Tables S3 and S4. The IBC21's approved dimensions for tall wood buildings are listed in Table S2.

2.3.1. Building assembly information

For comparisons of functional equivalence between MT buildings (Fig. S1a) and buildings constructed with SS and RC (Fig. S1b), the red-highlighted columns, beams, and foundation pillars along gridlines C and E were eliminated for the SS and RC framing systems that are capable of spanning longer distances. For all structural systems, however, demising walls were retained because the division of residential units provides a logical location for shear walls or lateral bracing components that typically resist lateral wind or seismically induced forces. In general, a consistent post-and-beam structural archetype was consistently applied for each structural configuration, to reflect urban construction practices. The mass timber configurations were based on glulam column and beam framing with cross-laminated timber decks serving as the horizontal diaphragms. Steel configurations used wide flange beam and column framing with composite steel and concrete decks as diaphragms. The concrete configurations used reinforced concrete columns and post-tensioned flat slab decks of uniform thickness that eliminated the need for beams and minimized the volumes of concrete and mild steel reinforcement needed in the structure. Floor-to-floor heights ranged between 3.7 m (12 ft) and 3.0 m (10 ft) to accommodate structural depths, which are greatest for mass timber and least for concrete structures. This resulted in slightly taller columns and greater height of interior and exterior partitions needed at each floor. While differences in height are less consequential at heights of 8 and 12 stories, concrete flat slab buildings can nearly fit 19 stories of occupancy within the same height as an 18-story post-and-beam mass timber structure.

2.3.1.1. Columns and beams. Columns and beams in the building serve as part of the primary structural frame, with a 3-h fire rating for IV-A and a 2-h fire rating for IV-B and IV-C categories. As a result, the MT building requires 5 layers of 5/8″ Type X gypsum wallboard for fire protection in IV-A areas and 3 layers for IV-B and IV-C areas. In the MT building layout (Fig. S1a), there are 18 columns designed for each floor. However, due to the removal of 4 columns from the MT layout, the RC and SS buildings (Fig. S1b) have 14 columns designed per floor.

2.3.1.2. Primary structural wall. The primary structural wall, highlighted along gridlines B and F in Fig. S1, has a 3-h fire rating for IV-A and a 2-h fire rating for IV-B and IV-C. Additionally, the primary structural wall encompasses the core, which is indicated in green. For the lateral systems, the core and stiffening walls were assumed to be made of reinforced concrete, which would provide consistent stiffness of the lateral system for all buildings. Average wind and seismic risks were assumed to avoid comparisons based on local geographic conditions.

2.3.1.3. Demising/separation wall. Primary structural walls, as described in the preceding paragraph, also function as demising walls in this scheme. Nonstructural demising or separation walls, shown in Fig. S1 along gridlines highlighted in blue and red, were included in the LCA to account for materials that may contribute significantly to the embodied energy and emissions of the building. Although nonstructural demising walls may conceal structural components, such as columns, the primary function is visual, sound, and fire separation. These walls have an 80-min fire rating for IV-A and IV-B, while IV-C does not require a fire rating. For mass timber (MT) buildings, 2 layers of 5/8″ Type X gypsum wallboard are needed. Steel buildings require 3 layers of ½" fire-rated gypsum wallboard [19], RC buildings only need ample concrete cover for an 80-min fire rating. Although typically not necessary for fire protection, at least one layer of gypsum commonly covers concrete wall surfaces as an architectural finish. Therefore, this layer has been included in the floor and wall assemblies of the RC system.

2.3.1.4. Exterior wall. Regarding the exterior wall, the opaque versus transparent portions were calculated using a predesign methodology since the LCA model did not include exterior facades. The percentage of the exterior façade consisting of opaque areas was determined based on the draft design. Opaque areas that were considered uniform for all building types were those with different wall assemblies and thermal (U- or R-value) ratings. The R-values for the opaque area in the comparative models were determined from specific wall assemblies and detailed material takeoffs for each building. A typical transparent assembly of the façade includes glass fenestration with extruded aluminum alloy frames. The opaque portions of the wall include interior gypsum, insulation such as extruded polystyrene (XPS), moisture control barriers, and exterior cladding, namely brick.

2.3.1.5. Floors. For floors, MT structures require three layers of 5/8″ Type X gypsum wallboard due to the 2-h fire rating for IV-A, IV-B, and IV-C. Steel structures necessitate four layers of ½" fire-rated gypsum wallboard based on fire resistance calculations [19]. RC buildings, on the other hand, only need a specified minimum concrete cover to achieve the minimum 1 layer of 5/8″ Type X gypsum wallboard for an 80-min fire rating [19].

2.3.1.6. Roofs. Roofs in IV-A require an 80-min fire rating, while roofs in IV-B and IV-C need a 60-min fire rating. Thus, MT structures would require 2 layers of 5/8″ Type X gypsum wallboard for the roof.

2.4. Biogenic carbon sequestration in Athena ***Impact Estimator***

As reported on the WoodWorks website [61], biogenic carbon is automatically taken into account by Athena IE4B, but the precise biogenic carbon flows at each stage of the life cycle are not specified. The amount of permanently stored biogenic carbon (i.e., carbon after a life cycle stored in a landfill) is reported in module D of Athena's IE4B. Athena explains the following biogenic carbon flows in the distance: Biogenic carbon enters the system through A1, and A3, where some of it exits. More biogenic carbon leaves the system when Athena applies a waste factor based on the material and product type in module A5. In modules C2-C4, Athena includes three end-of-life scenarios. There are a few presumptions that IE4B makes that the user cannot alter. In this range of potential end-of-life scenarios, 38.4% of the biogenic carbon is released as biogenic carbon emissions, while 61.6% of the biogenic carbon is permanently stored. Although the end-of-life stage (modules C1–C4) is where this 61.6% permanent biogenic carbon storage occurs, Athena displays this value in Module D, at point "h" in Fig. 2. The effects of module D take place outside the system boundary, so it will not be included in the reported global warming potential if a user only runs stages A–C.

2.5. Results interpretations

The results were obtained per square foot from Athena IE4B and then converted to per square meter for a consistent comparison with existing literature. The primary metrics reported were embodied carbon, represented as global warming potential (GWP) in kilograms of carbon dioxide equivalents per square meter (kgCO_2e/m^2), and embodied energy,

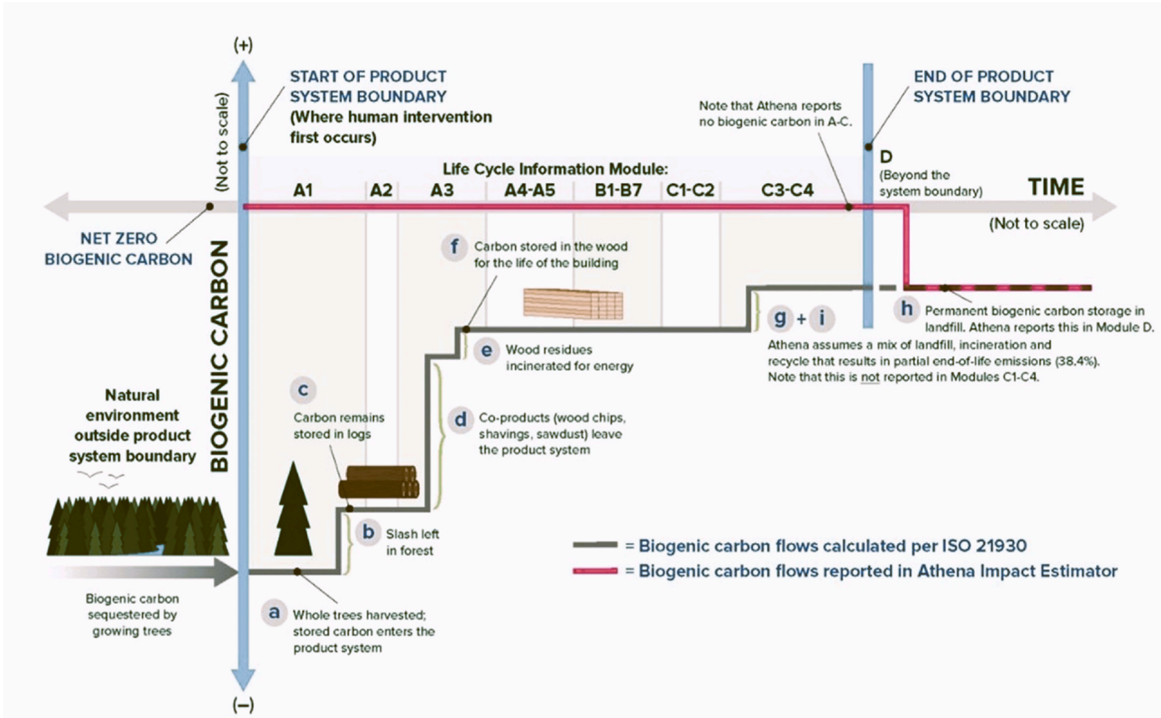

Fig. 2. Biogenic carbon flows in Athena's IE4B as reported on WoodWorks website [61].

measured in megajoules per square meter (MJ/m^2). In addition to these metrics, other environmental impact indicators including stratospheric ozone depletion, land and water acidification, eutrophication, tropospheric ozone formation, and the depletion of non-renewable energy resources were also reported. The GWP was reported for all the following life cycle modules (A1–A5, B2, B4, C1–C4, and D) to account for the impact of biogenic carbon. However, other results were reported for life cycle stages (A1–A5, B2, B4, and C1–C4), but excluded module D.

To assess the impact of the building's service life, a sensitivity analysis was conducted comparing a RSP of 75 years (EN 15978 [25] and ASTM E2921-22 [24]) with the RSP of 60 years (defined in LEED). Additionally, the study explored the GWP resulting from one of the approved changes in IBC 24 for tall wood buildings, specifically for type IVB-12 Stories [21,62].

3. Results

The bills of materials generated through the IE4B software tool are provided in Supplementary Table S8 for different building systems (MT, SS and RC) and building heights (IV-C-8-story, IV-B-12-story, and IV-A-18-story). A brief explanation and definition of the LCA metrics can also be found in the supplementary material.

3.1. Global warming potential (GWP) by life cycle stages

Table 3 presents the estimated GWP associated with the life cycle stages (A1–A5, B2, B4, C1–C4, and D) for all three building systems. MT buildings is estimated to show the lowest embodied carbon per unit area, compared to functionally equivalent RC buildings, consistent with findings in Liang et al. [33] and Puettmann et al. [41] and SS buildings, consistent with findings in Allan and Phillips [40]. The total estimated GWPs normalized in terms of building floor area for MT buildings for life cycle stages (A-D) are 27.47, 59.32, and 86.13 $kgCO_2e/m^2$ for 8-, 12-, and 18-story buildings, respectively, which includes biogenic carbon contained in MT materials of −222.09, −221.45 and −193.9 $kgCO_2e/m^2$ for 8, 12, and 18 stories, respectively reported in module D. Similarly, the estimated GWP for SS buildings ranges from 319.97, 341.73 and 358.98 $kgCO_2e/m^2$ for 8-, 12-, and 18-story buildings, which is 76–91% higher than MT buildings. Our estimated GWP for SS building is consistent with the findings of Allan and Phillips [40]. Like MT buildings, SS buildings also have some Module D carbon benefits that results from reuse/recycling of some SS materials. These benefits are estimated as −60.91, −56.60, and −30.41 $kgCO_2e/m^2$ for 8-, 12-, and 18-story SS buildings, respectively. Likewise, the estimated total GWP for A-D stages for RC buildings are 477.4, 459.15, and 457.56 $kgCO_2e/m^2$ for 8-, 12-, and 18-story buildings, respectively, which are 81–94% higher than

Table 3
Estimated global warming potential associated with life cycle stages (A1-A5, B2, B4, C1-C4 to D) in $kgCO_2e/m^2$.

Building System		Life Cycle Stages					
		Production (A1-A3)	Construction Process (A4-A5)	Use (B2-B4)	End of Life (C1-C4)	Beyond Building Life (D)	Total (A-D)
IVC-8-story	MT	142.86	42.90	49.55	14.24	−222.09	27.47
	RC	382.71	36.16	69.50	19.55	−30.53	477.40
	SS	274.37	29.40	64.36	12.75	−60.91	319.97
IVB-12-story	MT	164.14	44.83	57.33	14.48	−221.45	59.32
	RC	367.19	34.40	67.13	18.66	−28.24	459.15
	SS	290.18	32.51	62.26	13.37	−56.60	341.73
IVA-18-story	MT	165.07	44.20	56.92	13.84	−193.90	86.13
	RC	352.55	33.79	55.89	17.99	−2.66	457.56
	SS	282.69	32.02	62.31	12.36	−30.41	358.98

their functionally equivalent MT buildings and 21–33% higher than SS buildings. The RC results for 8-story building is consistent with the findings of Cai et al. [63] and Pierobon et al. [42]. The GWP for all buildings is shown to increase with building heights, consistent with the findings of Allan and Phillips [40]. In general, for GWP, our results indicates that MT buildings fare better than both SS and RC buildings, whereas SS buildings fare better than their functionally equivalent RC buildings across all building categories. Looking at the GWP by life cycle stages (Fig. 3), we find that the major share of the total life cycle GWP is associated with product life cycle stages (A1-A3) across all building types (MT, SS, and RC) and height categories (8-, 12-, and 18-story), which is consistent with the literature [32–34,41].

3.2. Global warming potential (GWP) by assembly group

The GWP for the assembly groups for all three building systems (MT, SS, and RC; IV-C, IV-B, and IV-A) covering life cycle stages A-C is shown in Fig. 4 and these values, broken down by each life cycle stage, are shown in Table 4. The majority of the total A-C stage GWP for MT buildings is associated with the wall and floor components across all three MT height categories (8-, 12-, and 18-story), which is consistent with the findings of Pierobon et al. [42]. Therefore, among all assembly groups, walls, and floors have the best opportunity to reduce the amount of embodied carbon via innovative designs.

3.3. Embodied energy associated with life cycle stages

Embodied energy refers to the energy required to produce, process, and deliver the materials and components that make up a product and the energy used during its assembly and maintenance, but not operational energy. The embodied energy results associated with life cycle modules (A1-A5, B2, B4, C1-C4) for all building systems (MT, SS, and RC; 8-, 12-, and 18-story) are presented in Table 5, while. Fig. 5 compares renewable vs nonrenewable energy usage associated with those building systems and heights. For IV-C-8-story, embodied energy for MT buildings is lower than functionally equivalent RC buildings but similar to SS buildings, which aligns with the finding of Allan and Phillips [40]. This is probably because SS in North America are made with cleaner processes (e.g., less mining) that primarily use recycled scrap steel. MT has higher total embodied energy in IV-B and IV-A, categories compared to RC buildings; however, MT has lower embodied carbon because it uses more renewable energy, therefore having lower embodied carbon.

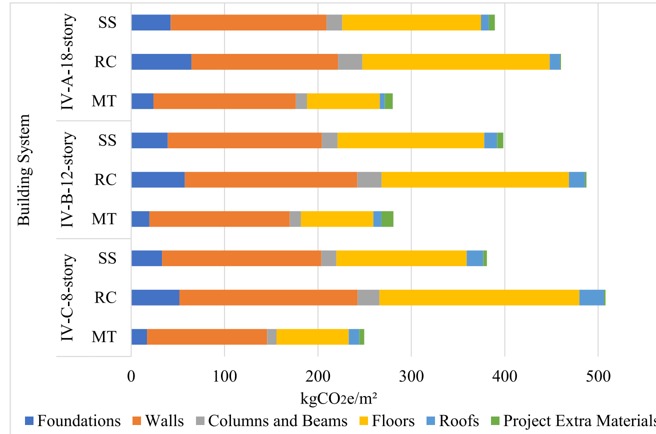

Fig. 4. Comparison of Embodied Carbon (GWP) associated with life cycle stages (A1-A5, B2, B4, C1-C4) for different assembly groups.

The estimated embodied energies for MT buildings are 4,404.61, 4,728.07, and 4,610.59 MJ/m^2 for 8-, 12-, and 18-story buildings, respectively. MT buildings show equivalent total embodied energy to SS buildings; however, they have lower embodied carbon as they use more renewable energy (around 24%) than functionally equivalent SS buildings, which use only 1.2–1.9% renewable energy in total (Fig. 5; Table 5). Similarly, RC buildings use only 1.7–2.3% renewable energy in total across all building systems.

3.3.1. Life cycle environmental impact metrics: RC and MT buildings

The results for the environmental impact metrics presented here covers life cycle stages A1-A5, B2, B4, and C1-C4. With RC as a reference, MT buildings outperform RC buildings in all six LCA impact categories (Fig. 6), with score differences ranging from 50.87% for GWP, 44.37% for stratospheric ozone depletion, 19.23% for land and water acidification, 62.24% for eutrophication, 11.02% for tropospheric ozone formation, and 30.3% for depletion of non-renewable energy resources for 8-story buildings. Similarly, for 12, MT buildings perform better in all six categories of LCA metrics, as shown in Fig. 6. Except for tropospheric ozone formation, MT performs better for an 18-story building in the other five impact categories. Supplementary Table S6 reports all life cycle environmental impacts for all building systems.

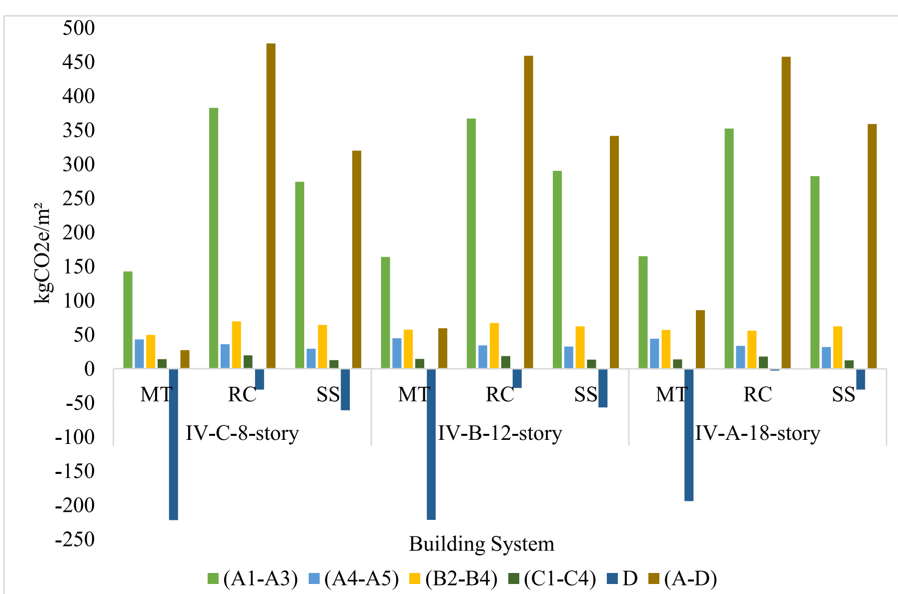

Fig. 3. Global warming potential (embodied carbon in kgCO$_2$e/m^2) associated with life cycle stages (A1-A5, B2, B4, C1-C4, and D).

Table 4
Estimated global warming potential associated with life cycle stages (A1-A5, B2, B4 to C1-C4) by assembly group in $kgCO_2e/m^2$.

Building System		Foundations	Walls	Columns and Beams	Floors	Roofs	Project Extra Materials	Total
IVC-8-story	MT	17.01	128.66	9.97	77.27	11.33	5.31	249.56
	RC	51.73	190.85	23.22	214.05	26.31	1.77	507.92
	SS	33.11	170.54	16.07	139.55	17.61	4.01	380.88
IVB-12-story	MT	19.53	150.43	11.91	77.49	8.64	12.77	280.77
	RC	57.47	184.70	26.01	200.43	17.23	1.56	487.39
	SS	39.21	165.06	16.79	156.88	13.88	6.51	398.33
IVA-18-story	MT	24.02	152.44	11.91	77.78	5.35	8.54	280.03
	RC	64.56	156.94	26.09	200.54	11.04	1.04	460.21
	SS	42.43	166.79	16.79	148.58	8.53	6.26	389.38

3.3.2. Life cycle environmental impact metrics: SS and MT buildings

With SS as a reference, 8-story MT buildings outperform SS buildings in four impact categories, including GWP (34.48%), land and water acidification (7.43%), eutrophication (26.62%), and depletion of non-renewable energy resources (25.36%) (Fig. 7). In contrast, SS fare better in the two other impact categories of stratospheric ozone depletion (−17.32%) and tropospheric ozone formation (−10.17%) (Fig. 7). Likewise, for 12- and 18-story categories, MT buildings outperform SS in four impact categories including GWP, land and water acidification, eutrophication, and depletion of non-renewable energy sources (Fig. 7). For instance, these heights categories of MT structure show 29.51% and 28.08% lower GWP than their functionally equivalent SS counterparts (Fig. 7). The estimated life cycle environmental impacts for all building systems are reported in Supplementary Table S6.

3.3.3. Life cycle environmental impact metrics: SS and RC buildings

With RC as a reference, SS buildings perform better than RC buildings in all six environmental impact categories (Fig. 8), with percentage differences for 8-story buildings of 25.01% for GWP, 52.59% for stratospheric ozone depletion, 12.75% for land and water acidification, 48.54% for eutrophication, 19.23% for tropospheric ozone formation, and 6.61% for depletion of non-renewable energy resources. However, for 12 and 18- stories, height category SS buildings perform better in only five impact categories (except depletion of non-renewable energy resources), as shown in Fig. 8 and Table S6.

3.4. Sensitivity analysis: lower reference study period

A sensitivity analysis was conducted in accordance with ISO 14040 to simulate the effect on the results of changes in the input parameters. Out of all the input variables, the building RSP had the greatest effect on the estimated GWP. Lowering the current RSP of 75 years to 60 years (as defined in LEED) results in MT GWP values of 24.52, 51.44, and 67.90 $kgCO_2e/m^2$ that are 11–21% lower than those estimated with an RSP of 75 years. However, the GWP values for RC structures show a reduction of upto 3.22%. The GWP values for SS structures dropped by as much as 5.5%. These results suggest that past studies overestimated the GWP reduction effects of MT buildings by considering lower RSPs than suggested by ASTM E2921-22 [24] and EN 15978 [25] for conducting comparative analyses. The results of this sensitivity analysis are shown in Supplementary Table S7.

3.5. Sensitivity analysis: potential changes to the upcoming IBC 2024

The 2021 IBC guideline allowed (IV-B-12-story MT buildings to have an exposed ceiling area no larger than 20% of the floor area as long as it was covered with gypsum wallboard. However, the 2024 IBC will permit Type IV-B-12-story buildings to have 100% exposed MT ceilings [21]. The new requirement will reduce construction costs as well as the carbon footprint of MT construction by doing away with the requirement for drywall for ceilings, which consumes substantial amount of energy. Therefore, another sensitivity analysis was conducted to understand the potential GWP reductions resulting from modifications to MT construction's fire rating, based on upcoming 2024 IBC guideline (Fig. S2). The analysis indicates that 12-story MT residential structure could reduce GWP by 1.05%, with SS and RC building showing no effects, compared to the 2021 IBC guidelines.

4. Discussion

The findings indicated a lower GWP for all building heights and floor areas considered, even without biogenic carbon sequestration benefit included, with MT buildings demonstrating a GWP reduction in the range of 39–51% compared to functional equivalent RC building, which is consistent with the past studies [47,64]. However, it should be worth noting that when biogenic carbon sequestration was included, the overall results for MT improved substantially, in the range of 81–94% reduction in GWP, which is slightly higher than past studies [47,50].

MT buildings demonstrated a GWP reduction in the range of 28–34% compared to functional equivalent SS buildings, without considering biogenic carbon sequestration, which further improved to 76–91%, when biogenic carbon sequestration was considered.

Also, the findings indicated that MT buildings outperformed other construction materials in terms of GWP (by 81–94% compared to RC buildings and 76–91% compared to SS buildings across all building categories), while SS buildings demonstrate better performance in certain impact categories compared to MT structures and in five impact categories compared to RC buildings. Our research showed that SS performed better in the United States than RC for production stages A1–A3. This is most likely due to the fact that SS is produced in North America using cleaner methods (e.g., less mining) that primarily use recycled scrap steel [40], while RC performs better in other regions (as reported in Dodoo et al. [48]). MT buildings showed equivalent embodied energy, but lower embodied carbon compared to SS buildings, as they utilize more renewable energy compared to SS buildings. In contrast, RC buildings showed the highest embodied energy and embodied carbon than MT and SS buildings for IV-C-8-story buildings, while for higher stories, RC buildings had lower embodied energy, which is in line with the reported literature [49]. Additionally, RC buildings used less renewable energy across all systems, which is also consistent with the literature [49]. The sensitivity analysis showed that lower RSPs, contrary to 75 years suggested by ASTM E2921-22 [24] and EN 15978 [25], would overestimate the GWP reduction benefits of MT buildings. Additional sensitivity analysis on higher allowable MT exposure area, as suggested in [21] and described in the 2024 IBC guidelines [65–67], indicated 1.05 % lower GWP of IV-B-12-story MT buildings compared to those estimated based on 2021 IBC guidelines.

Our results reaffirm the general conclusions in the existing literature [14,33,40,41,44] that MT buildings can contribute substantially to climate mitigation goals by replacing conventional high-rise SS and RC structures in the United States. Our results also suggest that SS buildings would be preferred choice over RC buildings in terms of their environmental impacts as they performed better than their functional equivalents RC buildings across five environmental impact categories in the United States.

We need to discuss a few more analysis-related limitations and how

Table 5
Estimated embodied energy associated with life cycle stages (A1-A5, B2, B4 to C1-C4) in MJ/m^2.

Building System		Product (A1 to A3)		Construction Process (A4 & A5)		Use (B2 & B4)		End of Life (C1 to C4)		Total (A-C)		Total
		Renewable	Non-renewable	Renewable	Non-renewable	Renewable	Non-renewable	Renewable	Non-renewable	Renewable	Non-renewable	
IVC-8-story	MT	1,084.65	1,886.00	12.03	617.32	21.40	578.99	0.53	203.70	1,118.60	3,286.01	4,404.61
	RC	85.83	3,272.18	3.82	422.89	22.48	738.41	0.60	280.91	112.73	4,714.39	4,827.12
	SS	58.85	3,162.04	2.98	396.57	22.48	664.02	0.56	179.94	84.87	4,402.57	4,487.44
IVB-12-story	MT	1,081.23	2,119.86	12.01	645.37	20.35	641.42	0.51	207.32	1,114.10	3,613.97	4,728.07
	RC	81.43	3,177.08	3.62	403.17	21.38	712.60	0.58	268.14	107.01	4,561.00	4,668.00
	SS	58.26	3,449.39	2.99	441.56	21.38	639.09	0.55	189.24	83.17	4,719.28	4,802.46
IVA-18-story	MT	1,050.21	2,093.75	11.83	634.54	2.88	617.59	0.42	199.36	1,065.34	3,545.25	4,610.59
	RC	69.92	3,025.79	3.67	393.76	2.90	593.56	0.49	259.63	76.97	4,272.75	4,349.72
	SS	45.23	3,347.89	2.94	435.75	2.90	634.24	0.45	175.84	51.52	4,593.72	4,645.25

they might affect the quantified outcomes. Modules A1-A5, B2, B4, C1-C4, and D of the WBLCA were used to estimate carbon emissions. Typically, embodied carbon emission does not include operational energy (B6) and water use (B7) modules. For this analysis, B1, B3, and B5 modules were also not included mainly because the IE4B does not support use (B1), repair (B3), and refurbishment (B5) modules [68]. While many studies [32–34] assume that MT and functionally equivalent alternative buildings use the same operational energy (B6), a few others [38] suggest that energy consumption is lower in MT buildings due to better thermal properties, which is an important research topic that needs further investigation. Whether the thermal resistivity of MT may be used effectively to conserve operational energy primarily depends on the structural configuration or function in the architectural building envelope. Exterior load-bearing wall systems or buildings clad in architectural precast concrete, for example, may be able to use the thermal properties of mass timber to achieve more efficient alternatives. The post-and-beam archetypes used in this study, however, do not substantially benefit from the thermal resistivity characteristics of MT only because the framing scheme used interchangeable building envelope systems.

Our analysis evaluated the end-of-life and beyond-life (stage C and module D) options provided in IE4B. The amount of permanently stored biogenic carbon (i.e., carbon after a life cycle stored in a landfill) is reported in module D of Athena's IE4B. The study can be improved by using alternative WBLCA tools [69,70] by evaluating different end-of-life options such as increased recycling [71] or reuse of demolished wood materials from construction [72,73] or burning discarded wood to replace fossil fuels. However, the actual magnitude and levels of alternative end-of-life options of MT buildings have not been yet measured as their building stock is quite young compared to SS and RC.

For RC construction, calcination, which is a chemical process used in cement production that emits CO_2. When calcium carbonate (limestone) is heated, CO_2 is produced as a byproduct. The CO_2 emissions for concrete due to calcination are included in the GWP results, per ISO 21930:2017 [68]. However, carbonation which is a process that occurs when concrete is exposed to air and removes CO_2 from the air. Calcium carbonate is formed when calcium hydroxide in cement reacts with atmospheric CO_2 (in the presence of water). Due to a lack of data and methods applicable to this tool, the IE4B does not account for CO_2 uptake by concrete [68]. Carbonation options were not considered in the present work due mainly to the lack of such options in the IE4B, which can be investigated in future research.

In the present work, we have considered only the conceptual design of the building with 11 units per floor; however, detailed design, which includes analysis of interior architectural finishes, such as internal partitions within the units, kitchen, and washroom fixtures, internal doors, etc., could be designed and analyzed to get more comprehensive estimates of the life cycle assessment.

5. Conclusions

Despite the lack of direct attention to embodied carbon, building code acceptance of new timber structural systems may lead to greener construction. This article demonstrated through comparative building lifecycle analysis how recent changes to building codes in the United States enable specification of MT structures that may effectively reduce the carbon footprint of construction relative to prevalent SS and RC building systems. Based on a better understanding of fire safety, the most recent building code standard permits greater exposed area of MT structural components in taller construction. The main objective of this comparative WBLCA was to demonstrate a range of embodied carbon reductions currently achievable with MT structures in conformance with prescriptive building code provisions. Illustrated with US-specific design requirements, this comparison of WBLCA's generally addresses nuances of structural materials selection and a balance of fire safety and sustainability considerations reflected in the latest prescriptive

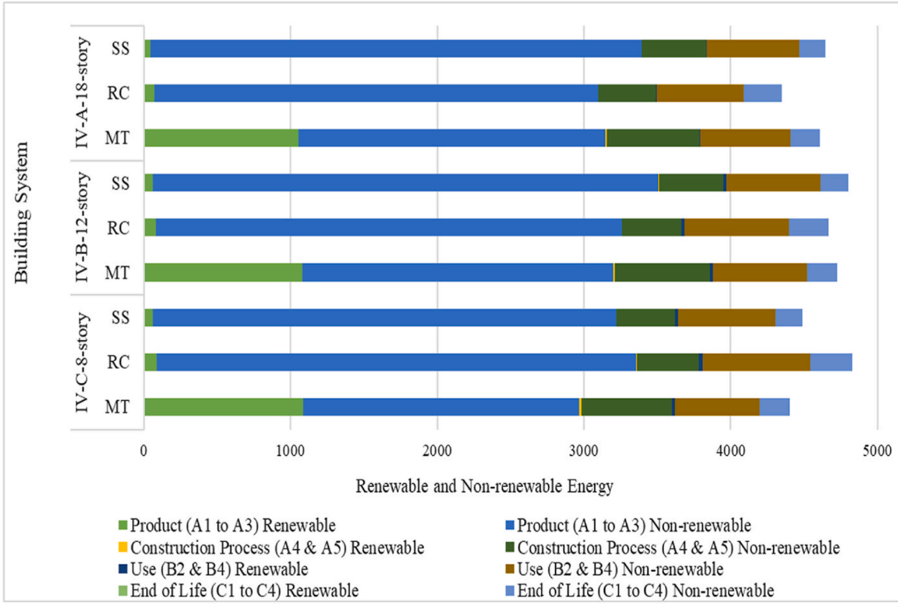

Fig. 5. Embodied energy in percentage of renewable vs. non-renewable energy for building systems (MT, SS, and RC; 8-, 12-, and 18-story buildings) associated with life cycle stages (A1-A5, B2, B4, C1-C4).

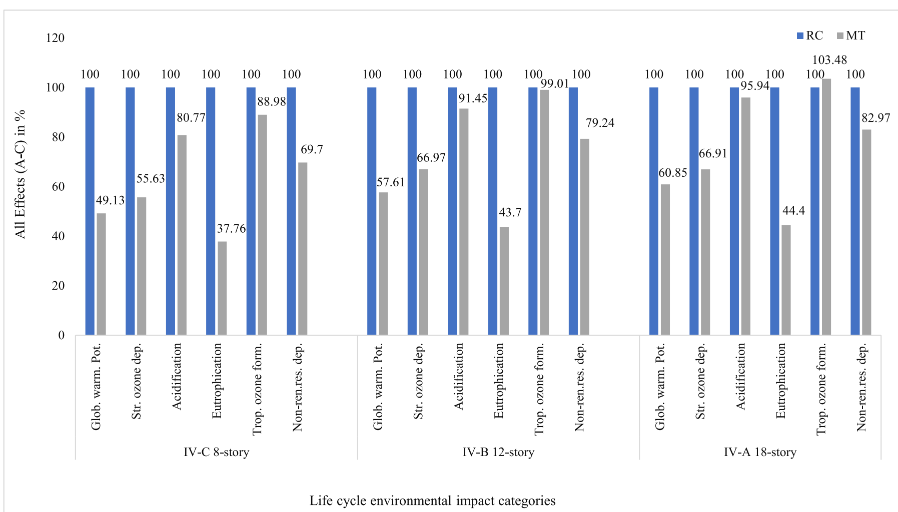

Fig. 6. Estimated environmental impacts associated with life cycle stages (A1-A5, B2, B4, and C1-C4) having RC as a reference and MT as the designed building for IV-C-8-story, IV-B-12-story, and IV-A-18-story.

requirements for MT buildings. The building designs and WBLCAs of this study were conducted using conventional methods to be indicative of results that could be routinely achieved in practice, rather than optimum performance that could otherwise be determined by advanced procedures. Results were organized to convey the sustainability implications of materials selection for various structural components.

In addition to fire safety, these building code provisions impact sustainability of MT buildings, because gypsum wallboard is most often used to satisfy prescriptive encapsulation requirements. The embodied energy and GHG emissions of gypsum wallboard, therefore, offsets reductions otherwise achieved by opting for MT structural systems. Encapsulation of MT, moreover, limits appeal as an aesthetic feature of the architecture. Since the groundbreaking introduction to the 2021 IBC, new prescriptive requirements have been approved in 2024 IBC, which permit greater exposure of MT for architectural view. To assess the implications of these prescriptive provisions on sustainability and how MT may reduce the environmental impacts of Type IV occupancies, WBLCA provides a general state-of-the-art tool.

Compliance with ethics guidelines

Vaibhav Kumar, Marco Lo Ricco, Richard D. Bergman, Prakash Nepal, Neelam C. Poudyal declare that they have no conflict of interest or financial conflicts to disclose.

CRediT authorship contribution statement

Vaibhav Kumar: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Marco Lo Ricco:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Richard D. Bergman:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Data curation. **Prakash Nepal:** Writing – review & editing, Visualization, Validation,

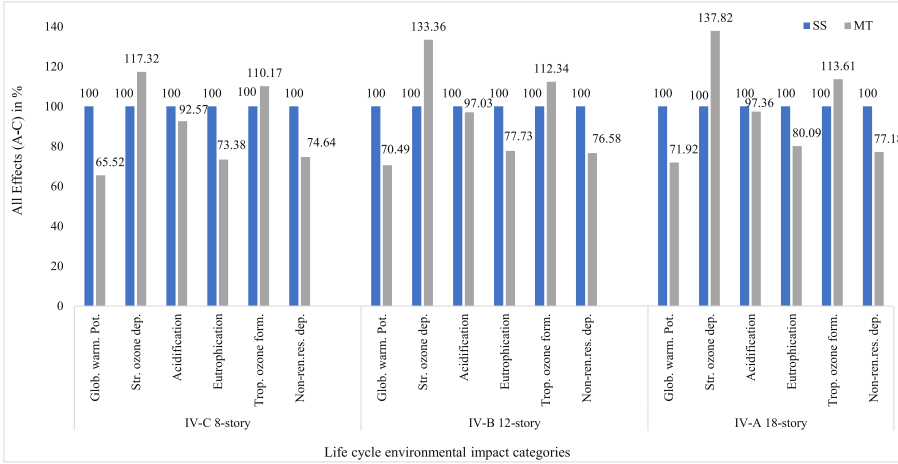

Fig. 7. Estimated environmental impacts associated with life cycle stages (A1-A5, B2, B4, and C1-C4) having SS as a reference and MT as the designed building for IV-C-8-story, IV-B-12-story, and IV-A-18-story.

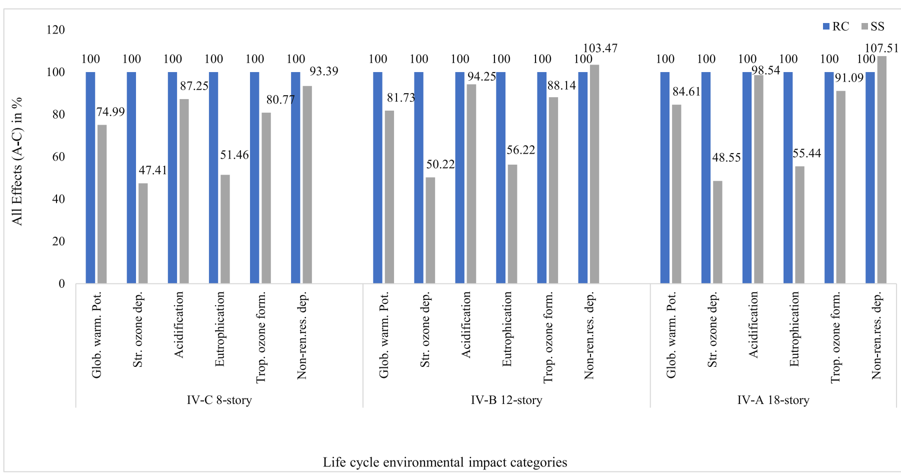

Fig. 8. Estimated environmental impacts associated with life cycle stages (A1-A5, B2, B4, and C1-C4) having RC as a reference and SS as the designed building for IV-C-8-story, IV-B-12-story, and IV-A-18-story.

Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Neelam C. Poudyal:** Writing – review & editing, Project administration.

Declaration of competing interest

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

Data availability

The data used in the work is shared online via supplementary data files.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111195.

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