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Article

An analysis of comparative studies on embodied carbon and embodied energy assessment of tall building structures

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ABSTRACT

High-rise building construction can lead to a "carbon spike," which refers to excessive carbon emissions resulting from the massive use of structural materials during building production. Furthermore, the embodied carbon (EC) and embodied energy (EE) of buildings are gaining significance, considering the improvement in the operational energy performance of new buildings. Therefore, early design decisions regarding the structural system selection of tall buildings significantly affect the carbon footprint. Previous studies investigated the EC and EE of tall building structures using the life cycle assessment (LCA) approach. The effects of various design parameters on EC and EE are compared. Nevertheless, inconsistencies inherent to the LCA approach and variations in structural design methods used in these studies may lead to incompatibilities in the results. This study examines existing research on the EC and EE of tall building structures through a systematic literature review. The scope, materials, and methodologies employed in the literature are scrutinized to identify current gaps. Results from various scenarios are analyzed regarding specific design parameters, such as building height, structural material use, type of the structural system, and structural components, to identify patterns in reported EC and EE. To enhance the comparability of the findings, further research that adopts a consistent approach is required to explore the EC and EE of tall building structures.

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INTRODUCTION

The urgent need to mitigate the impacts of climate change was most recently addressed at the UN COP26 conference, where countries made commitments to take immediate actions to reduce greenhouse gas emissions. According to the latest report published by the UN Environment, the International Energy Agency (IEA), and the Global Alliance for Buildings and Construction (GABC), 37% of total global energy-related carbon emissions belong to

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the building sector in 2021 (United Nations Environment Programme, 2022). Thus, the construction industry has a substantial potential for mitigating carbon emissions as a major contributor to global emissions. A building is a complex product with a long life, leading to environmental impacts throughout its life. For a comprehensive and systematic environmental impact assessment of a building throughout its lifetime, the life cycle assessment (LCA) is one of the most recognized methodologies (Cabeza et al., 2021). LCA is a method employed to measure the environmental performance of materials, products, and buildings. According to the LCA method, a building's life comprises six main stages: raw material extraction, manufacturing, construction, operation and maintenance, demolition and disposal, reuse, and recycling (Crawford, 2011). In addition, the life cycle stages of buildings are identified in detail in EN 15978 (CEN, 2011) as product stage (A1-A3) including raw material extraction (A1), transportation (A2), and manufacturing (A3), construction stage (A4-A5), use stage (B1-B7), end of life stage (C1-C4), and benefits and loads beyond the system boundary (D). Life cycle methodology is developed within the ISO 14040 framework, and it includes four phases: goal and scope, life cycle inventory, life cycle impact assessment, and interpretation (International Organization for Standardization ISO, 2006). Life cycle inventory analysis (LCI) is one of the most significant processes that involves data compilation incorporating various LCI methods (such as process based, economic input–output, or hybrid), and measuring the inputs and outputs of a product over its entire lifespan.

According to the literature, embodied impacts play a substantial role in the global emissions originating from buildings (Cabeza et al., 2021). Embodied carbon (EC) refers to the cumulative carbon emissions from fuel and process-related sources, whereas embodied energy (EE) denotes the overall primary energy consumption resulting from both direct and indirect processes linked to a product or service within the ICE Database. EE accounts for all energy inputs, regardless of its source, such as renewables. Nevertheless, when quantifying EC, no greenhouse gases are produced through the use of renewable sources. Similarly, net carbon estimations may factor in carbon sequestration, which does not impact the EE of a building.

Although a building uses energy and produces carbon emissions throughout its life, scientific research mainly concentrates on operational energy use and, more recently, related carbon emissions (Röck et al., 2020). Nevertheless, Helal et al. (2018) emphasized that the designers should take action promptly to decrease carbon emissions in the short term, which generally corresponds to a 50-year working life of buildings. Instead, they should directly focus on mitigating carbon emissions starting from the building construction phase. In fact, there is a recent shift in the scientific community toward the embodied impacts of buildings and associated carbon emissions (Azari and Abbasabadi, 2018; Baek et al., 2013; Paya-Zaforteza et al., 2009; Sartori and Hestnes, 2007; Thormark, 2002).

Elnimeiri and Gupta (2008) emphasized the significance of tall building design since tall buildings consume vast resources, especially in the construction and operation stages. Over the last century, energy efficiency in the operational phase of tall buildings has become a prevalent issue owing to their typological evolution (Oldfield et al., 2009). As buildings progressively enhance their energy efficiency, the share of their embodied impacts increases (Gustavsson and Joelsson, 2010; Optis and Wild, 2010; Sartori and Hestnes, 2007). Besides, as the building height increases, the structural material use relatively increases due to the exponential growth of lateral loads. Therefore, the materials used in the structural elements of a building are the major contributors to the overall EC emissions (Moncaster et al., 2018). Due to higher wind sensitivity in tall buildings, the structural material use per unit floor area and the EC become relatively higher than in low-rises (Azari and Abbasabadi, 2018). Treloar et al. (2001) demonstrated that the EC per gross floor area (GFA) of high-rise buildings is almost 60% more than that of low-rise ones.

The number of studies on the LCA of low-rise buildings almost doubled that of high-rise ones (Bahramian and Yetilmezsoy, 2020). Azari and Abbasabadi (2018) also indicated the neglect in the current literature on the embodied impact assessment of tall buildings. Besides, there are incompatibilities in the methods of these studies, which is highlighted by (Trabucco et al., 2015; Bahramian and Yetilmezsoy, 2020; Helal et al., 2020). In this study, the comparative studies on the LCA of tall building structures are critically assessed in terms of their scope, materials and methods, and comparative building design parameters (i.e., building height, the type of the structural system, structural materials, and structural components). Despite the shared similarities in the results, the findings of these studies do not provide a comprehensive framework for the early design stage of a tall building. Helal et al. (2019) also emphasized the necessity of a comprehensive framework for the environmental impact assessment of tall building structural systems. Thus, a consistent approach is required to evaluate the effects of various design parameters for the embodied impact assessment of tall building structures. Table 1 illustrates the nomenclature employed in this paper.

METHODOLOGY

The main objective of this research is to scrutinize the comparative studies on the EC and EE of tall building structures via a systematic literature review. The review is conducted by searching in Web of Science and Scopus

Table 1. Nomenclature used in this paper

ABS	Australian Bureau of Statistics
ACI	American Concrete Institute
AIK	Architectural Institute of Korea
AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
AusLCI	Australian National Life Cycle Inventory Database
CLT	Cross laminated timber
DL	Dead load
EC	Embodied carbon
EE	Embodied energy
EGHG	Embodied greenhouse gas emissions
EL	Earthquake load
EPIC	Environmental Performance in Construction
GABC	Global Alliance for Buildings and Construction
GFA	Gross floor area
GWP	Global warming potential
HKBD	Hong Kong Building Department
HKEPD	Hong Kong Environmental Protection Department
ICE	Inventory of Carbon and Energy
IEA	International Energy Agency
KEITI	Korea Environmental Industry & Technology Institute
LCA	Life cycle assessment
LCI	Life cycle inventory
LL	Live load
NFA	Net floor area
PV	Photovoltaic panel
RC	Reinforced concrete
SEI	Structural Engineering Institute
SRC	Steel reinforced columns
UN	United Nations
UNEP	United Nations Environmental Programme
WL	Wind load

databases using the following keyword combinations: (“embodied energy” or “embodied carbon”) and (“tall buildings” or “high-rise buildings”). In total, twenty-two studies on the LCA of tall buildings are identified by excluding which are not relevant to the scope of this study. Six of them (Bohne et al., 2017; Drew et al., 2014; Helal et al., 2019; Oldfield, 2012; Trabucco, 2011; Zhao and Haojia, 2015) are conference proceedings, and one of them (Trabucco et al., 2015) is a research report. The rest of the studies (Cho et al., 2012; Choi et al., 2016; Fakıoğlu Gedik and Ay, 2023; Foraboschi et al., 2014; Gan, Chan et al., 2017; Gan, Cheng et al., 2017; Helal et al., 2020; Hens et al., 2021; Kofoworola and Gheewala, 2009; Li et al., 2019; Mavrokapnidis et al., 2019; Moussavi Nadoushani and Akbarnezhad, 2015; Resch et al., 2016; Trabucco and Belmonte, 2021; Treloar et al., 2001) are published in peer-reviewed scientific journals.

Firstly, the 22 studies on the LCA of tall buildings are evaluated in terms of their scope. Then, the findings of the seventeen comparative studies on the embodied impact assessment of tall building structures (Treloar et al., 2001; Cho et al., 2012; Drew et al., 2014; Foraboschi et al., 2014; Moussavi Nadoushani and Akbarnezhad, 2015; Trabucco et al., 2015; Zhao and Haojia 2015; Choi et al., 2016; Bohne et al., 2017; Gan, Chan et al., 2017; Helal et al., 2019; Li et al., 2019; Mavrokapnidis et al., 2019; Helal et al., 2020; Hens et al., 2021; Trabucco and Belmonte, 2021; Fakıoğlu Gedik & Ay, 2023) are examined according to their materials and methods and building design parameters. The methodology of the paper is demonstrated in Figure 1.

ANALYSIS OF THE FINDINGS REGARDING SCOPE, MATERIALS AND METHODS, AND BUILDING DESIGN PARAMETERS

In this section, the existing studies on the LCA of tall building structures are examined according to their scope, materials and methods, and building design parameters. The materials and methods of these studies are categorized based on their LCA and structural design approaches, whereas the building design parameters incorporate the relationships between the building height, structural material, structural system types, and structural components with respect to the EC and EE.

Scope

There are differences in the scope of the existing studies on the LCA of tall building structures. Most of the existing studies (17 comparative studies) focused on comparing specific building design parameters such as building height, structural materials, and structural components (Tables 1-3). For example, Oldfield (2012) and Kofoworola and Gheewala (2009) compared the share of buildings’ operational and embodied energy and carbon, respectively. On the other hand, Trabucco (2011), Gan, Chan et al.

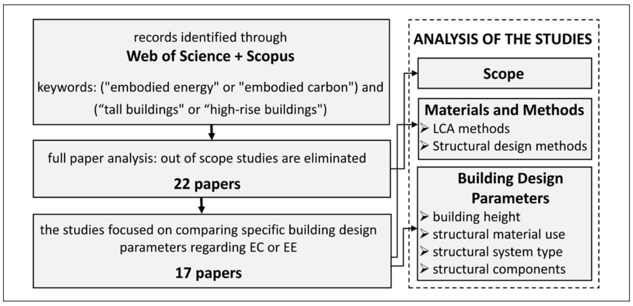

Figure 1. Flowchart of the methodology: the systematic review and the analysis of the selected studies.

(2017), and Helal et al. (2019) focused on the methods used for the LCA of tall building structures. Unlike the others, Resch et al. (2016) focused on the urban scale and investigated the environmental impacts of building height at an urban scale, considering the transportation and road infrastructure energy.

The seventeen comparative studies on the LCA of tall buildings are focused on EC, EE, or both. Trabucco (2011), Kofoworola and Gheewala (2009), Foraboschi et al. (2014), Resch et al. (2016), and Treloar et al. (2001) focused on only the EE of buildings. In contrast, Drew et al. (2014), Zhao and Haojia (2015), Choi et al. (2016), Gan, Cheng et al. (2017), Gan, Chan et al. (2017), Helal et al. (2019), Helal et al. (2020), and Hens et al. (2021) focused on only the EC. Cho et al. (2012), Moussavi Nadoushani and Akbarnezhad (2015), Trabucco et al. (2015), Li et al. (2019), and Mavrokapnidis et al. (2019) examined both EC and EE of tall buildings.

The majority of the reference buildings used in the selected studies are existing buildings (Treloar et al., 2001; Trabucco et al., 2015; Zhao and Haojia, 2015; Oldfield 2012; Kofoworola and Gheewala, 2009; Cho et al., 2012; Drew et al., 2014; Foraboschi et al., 2014; Helal et al., 2019; Moussavi Nadoushani and Akbarnezhad, 2015; Gan, Cheng et al., 2017; Mavrokapnidis et al., 2019; Bohne et al., 2017; Choi et al., 2016). The rest of the eight studies used hypothetical building models. Another difference among the existing studies is the functional use of buildings. For example, four studies used residential building examples (Cho et al., 2012; Drew et al., 2014; Resch et al., 2016; Trabucco and Belmonte, 2021), and in eight of these studies, buildings with office functions are used (Fakıoğlu Gedik and Ay, 2023; Helal et al., 2020; Kofoworola and Gheewala, 2009; Oldfield, 2012; Trabucco et al. 2015; Trabucco and Belmonte, 2021; Treloar et al., 2001; Zhao and Haojia, 2015). The functional use of the buildings is not indicated in ten studies (Bohne et al., 2017; Choi et al., 2016; Foraboschi et al., 2014; Gan, Chan et al., 2017; Gan, Cheng et al., 2017; Helal et al., 2019; Hens et al., 2021; Li et al., 2019; Mavrokapnidis et al., 2019; Moussavi Nadoushani and Akbarnezhad, 2015).

Materials and Methods

There are variations and inconsistencies between the LCA and structural design methods of the existing studies on EC and EE of tall building structures. Bahramian and Yetilmezsoy (2020) presented a detailed review of the LCA of high-rise buildings by introducing the differences in the life cycle inventory (LCI) compilation methods (either process-based, economic input–output, or hybrid). In addition, Helal et al. (2020) also identified five comparative studies on the existing literature on LCA of tall building structural systems and underlined the discrepancies and incompleteness in the approaches to both structural design and the LCA. The following sections present the disparities in LCA and structural design approaches.

LCA Methods

Many studies underlined the inconsistencies and variations in the literature related to EC calculation methods in buildings (Abd Rashid and Yusoff, 2015; Azari and Abbasabadi, 2018; Chau et al., 2012; Dixit et al., 2010, 2012; Shadram et al., 2016; Simonen et al., 2017). Some of the common reasons for the variation of EE calculations presented in these studies are the broad variation in system boundaries, using different LCI compilation methods (process-based LC, input-output LCA, or hybrid LCA), differences in the geographic location of a study, and variation in the data sources and low data quality. The inconsistencies inherent to the LCA method also exist in the studies on the embodied impact assessment of tall building structures as presented in Table 2. In fact, the system boundaries are not even indicated in some of the studies. Furthermore, there is no consensus on the functional units either, which can impede the comparability of the results (Table 2). According to Table 2, almost all studies except Cho et al. (2012) utilized databases rather than software tools for the embodied impact assessment. The UK-based Inventory of Carbon and Energy (ICE) database is the most frequently used database, followed by the Environmental Performance in Construction (EPIC) database from Australia.

Structural Design Methods

In this study, the structural design methods refer to the structural design loads, related specifications, and structural software tools used in the selected studies, as presented in Table 3. Treloar et al. (2001) investigated the existing buildings, so structural analysis was not performed. The structural design methods are not transparent in some studies (Drew et al., 2014; Trabucco et al., 2015; Trabucco and Belmonte, 2021) since no detailed information is given regarding the structural design and analysis.

Depending on the geographic location, buildings taller than 30–40 storeys are more sensitive to wind-induced loads (Momtaz et al., 2017). All of the studies in Table 3 considered the effects of wind loads on the structural design except Moussavi Nadoushani and Akbarnezhad (2015). However, the wind load can be insignificant since the maximum height of the alternative buildings is only 15 storeys. Unlike the wind loads, most of the studies in Table 3 neglected the effects of seismic loads (Cho et al., 2012; Foraboschi et al., 2014; Bohne et al., 2017; Gan, Chan et al., 2017; Hens et al., 2021; Mavrokapnidis et al., 2019). Nevertheless, the structural models should be analyzed and checked considering all the load combinations described in the codes and specifications rather than the most demanding scenario.

Helal et al. (2020) investigated the effects of static wind, static earthquake, and dynamic earthquake on the carbon emissions of tall building structures. The research indicates

Table 2. Inconsistencies in the LCA methods

Authors/year of the study	Life-cycle stages	Functional unit	LCA databases and software tools	Geographic location
Treloar et al. (2001)	not indicated	GJ/m^2 (GFA)	based on Treloar (1997) (hybrid LCI)	Australia
Cho et al. (2012)	not indicated	kgCO$_{2eq}$/m^2 (GFA)	SBTool (process-based LCI)	Korea
Drew et al. (2014)	A1-A3	tCO$_2$	ICE Database, Athena Institute (process-based LCI)	Chicago, USA
Foraboschi et al. (2014)	A1-A3	MJ/m^2 (NRA)	ICE Database (process-based LCI)	Australia
Moussavi Nadoushani and Akbarnezhad (2015)	A1-A3, A4, A5	kgCO$_{2eq}$/m^2	ICE Database (process-based LCI)	Atlanta, USA
Trabucco et al. (2015)	A1-D	tCO$_{2eq}$	EcoInvent, Wordsteel databases, BETIE and various US EPDs (process-based LCI)	Chicago, USA
Zhao and Haojia, (2015)	A1-A3	tCO$_2$	ICE Database (process-based LCI)	China
Choi et al. (2016)	not indicated	kgCO$_2$/m (m denotes the unit length of the column)	KEITI 2016 (process-based LCI)	Korea
Bohne et al. (2017)	A1-A3	kgCO$_{2eq}$/m^2	based on Kaspersen et al. (2016) (SimaPro, EPDs)	not indicated
Gan, Chan et al. (2017)	A1-A3, A4	kgCO$_{2eq}$/m^2 GFA	A1-A3: The formula proposed by Gan, Cheng et al. (2017) is used. 4: HKEPD 2008 (process-based)	Hong Kong
Helal et al. (2019)	not indicated	kgCO$_2$-e/m^2 GFA kgCO$_2$-e per capita	AusLCI - process data ABS – input–output tables Australian National Greenhouse Gas Inventory (DEE 2015) - GHG emission data (hybrid LCA)	South Korea
Li et al. (2019)	A1-A3 (the carbon in the atmosphere absorbed by trees included)	tCO$_2$	AusLCI, EPDs of Structurlam (from North America)	Australia

that the static linear analysis of seismic loads results in the overestimation of structural materials compared to that of dynamic linear analysis. Nevertheless, further investigation is required for buildings over 30 storeys to verify this statement. Another statement is that static wind and dynamic earthquake loads can result in up to a 22% increase in EC emissions per NFA for a 50-storey building. Thus, the variation in design loads can substantially impact the EC emissions of high-rise buildings.

Building Design Parameters

The main contributions of the comparative studies on the EE or EC of tall building structures are presented in Table 4. In these studies, the parameters regarding building design, such as the building height, structural systems, structural materials, structural components, and structural loads, are investigated in terms of their effect on the EE or EC.

Building Height

The current literature evaluates a wide range of building heights regarding the EC and EE of tall building structures. As indicated in Figure 2, the number of studied buildings decreases as the building height increases, except for the buildings with 60–70-storey height. Only five buildings are studied that are taller than 120 storeys. Furthermore, there are only nine supertall buildings (+300m).

Table 3. Inconsistencies in the structural design methods

Authors/year of the study	Structural software tool	Structural design loads	Related specifications on structural design
Treloar et al. (2001)	not indicated	not applicable	not applicable
Cho et al. (2012)	not indicated	DL: 3.8 kN/m^2, LL: 1.7 kN/m^2, WL: applied, EL: not applied	not indicated (but the buildings are assumed to be in Korea)
Drew et al. (2014)	Neither the structural method nor the loads are indicated by stating that structural engineers identify the dimensions of structural components.		
Foraboschi et al. (2014)	not indicated	DL: 2.5 kN/m^2, LL: 3 kN/m^2, Façade load: 4kN/m, WL: applied, EL: not applied	Eurocode 1
Moussavi Nadoushani and Akbarnezhad (2015)	ETABS	DL: 2.1 kN/m^2 for composite and 2.8 kN/m^2 for concrete floors, LL: 1.7 kN/m^2, Super-imposed DL: 3.6 kN/m^2, EL: applied, WL: not applied	AISC Seismic Provisions ASCE7-05, AISC360-10, ACI 318-08
Trabucco et al. (2015)	Neither the structural method nor the loads are indicated by stating that structural engineers identify the dimensions of structural components.		
Zhao and Haojia (2015)	not indicated	not indicated	not indicated
Choi et al. (2016)	not indicated	WL: applied but not indicated, EL: applied but not indicated	ACI 2008, AISC 201, AIK 2010
Bohne et al. (2017)	not indicated	DL: not indicated, LL: 2.4 kN/m^2, WL: applied, EL: not applied	Norwegian engineering consultancy company
Gan, Chan et al. (2017)	ETABS	DL: 4.55 kN/m^2, LL: 4 kN/m^2, Façade load: 8 kN/m, WL: applied, EL: not applied	The codes and standards for high-rise buildings in Hong Kong are used (HKDB 2011, 2004a; HKDB, 2004b; HKBD 2013)
Helal et al. (2019)	not indicated	WL: applied but not indicated, EL: applied but not indicated	not indicated
Li et al. (2019)	Space Gass 12.6	DL: applied but not indicated, LL: applied but not indicated, WL: applied (dynamic load), EL: applied (equivalent static analysis)	AS1170.0 (Australian Standards) AS3600-2009 (RC standards)
Mavrokapnidis et al. (2019)	ETABS	DL: applied but not indicated, LL: applied but not indicated, Super-imposed DL: applied but not indicated, WL: applied but not indicated, EL: not applied	Eurocode 1

Table 3. Inconsistencies in the structural design methods (Cont.)

Authors/year of the study	Structural software tool	Structural design loads	Related specifications on structural design
Helal et al. (2020)	ETABS	LL: 2 kN/m^2, Super-imposed DL: 1 kN/m^2, Facade loads: 3.5 kN/m, WL: applied, EL: applied (both static and dynamic linear analyses are performed)	Australian Standard AS1170.1:2002 Structural design actions
Hens et al. (2021)	Karamba3D in Grasshopper and Python code	Super-imposed DL: 2.06 kN/m^2, Facade load: 0.57 kN/m^2, LL: 3.83 kN/m^2, WL: 1.92 kN/m^2, EL: not applied	ASCE 7-10
Trabucco and Belmonte (2021)	Neither the structural method nor the loads are indicated by stating that structural engineers identify the dimensions of structural components.		
Fakıoğlu Gedik and Ay (2023)	ETABS	DL: applied but not indicated Super-imposed DL: 3.5 kN/m^2, LL: 2.4 kN/m^2, WL: applied, EL: applied (equivalent static analysis)	ASCE/SEI 7-16

Considering the growing concerns about the environmental impact of tall buildings, determining the optimal building height regarding carbon emissions becomes a prevalent research question. Treloar et al. (2001), Drew et al. (2014), Foraboschi et al. (2014), Bohne et al. (2017), and Gan, Chan et al. (2017) investigated premium building height in terms of carbon savings. According to Bohne et al. (2017), the optimum building height is between 10 and 20 storeys for reinforced concrete (RC), steel, and timber structures in terms of mitigated EC. Yet, buildings over 21 storeys are not investigated in the study. Foraboschi et al. (2014) stated that there is an upward trend in the EE per NFA of tall buildings as the building height increases. In contrast, there is a convex trend in EC per GFA of tall buildings according to the study of Gan, Chan et al. (2017), demonstrating a premium for height in terms of EC for various structural systems ranging between 50 and 90 storeys. Drew et al. (2014) have a broad perspective and evaluated the carbon emissions of buildings based on their height on the urban scale. According to the research, 34 and 58-storey buildings perform best in terms of carbon saving where the land saved for electricity generation from PV panels is concerned. Resch et al. (2016) conducted a similar study focusing on the environmental impacts of high-rise developments in cities regarding EE and lifetime energy. The height of the buildings range between 3 and 60 storeys, and the unitary EC emissions of materials are obtained from previous literature. The results showed that the optimum building height is between 7 and 27 storeys, depending on the city's population and the building's lifetime. Thus, the optimum building height depends on the scope of the research, system boundaries, and various other parameters. There is no consensus in the existing literature on the optimum building height considering the embodied impacts.

Structural Material Use

Mainly four structural materials are examined in the existing literature regarding EE or EC: RC, steel, composite (steel and RC), and timber. Due to its relatively low carbon footprint, timber became a popular structural material for tall buildings as an alternative to RC and steel. Bohne et al. (2017) stated that the EE of timber structures is considerably lower than the RC and steel structures: the EE of a 20-storey timber building is approximately 25% that of the RC and the steel buildings, even if the net carbon storage of the timber is excluded. However, if carbon storage is included, negative emissions (approximately 600 kgCO2 per square meter of a building) can be gained from timber buildings. Li et al. (2019) investigated the embodied impacts of structural timber for a 43-storey building. The results are interestingly different from the study of Bohne et al. (2017); although the timber alternative has the lowest EC, the EE of the timber alternative is greater than the RC alternative.

Despite the increasing popularity of timber as a structural

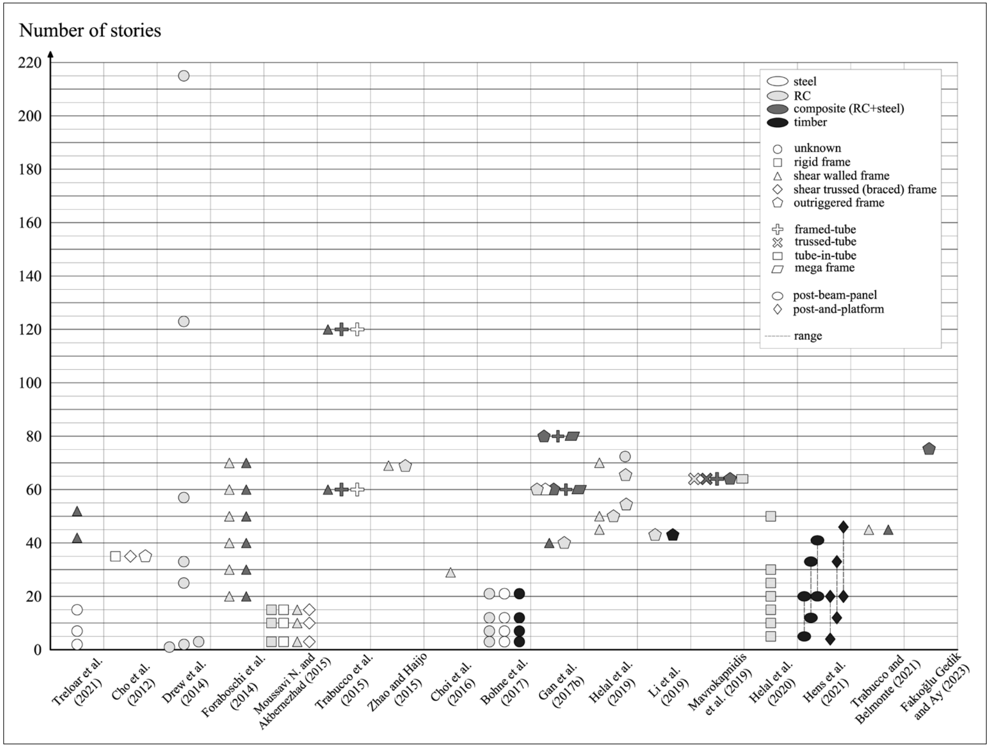

Figure 2. Building models according to their height, structural system, and material.

material, RC and steel still dominate the building industry and scientific research. According to the literature review of Bahramian and Yetilmezsoy (2020) on EE of high-rise buildings, only 3 of the 28 studies investigated timber as a structural material. Many of the studies compared the effects of RC and steel structures in terms of EC or EE depending on the building height and the type of the structural system (Foraboschi et al., 2014; Gan, Chan et al., 2017; Mavrokapnidis et al., 2019; Moussavi Nadoushani and Akbarnezhad, 2015; Trabucco et al., 2015; Trabucco and Belmonte, 2021; Zhao and Haojia, 2015). According to these studies, RC buildings consume less EC and EE per GFA than steel buildings for various structural systems whose height ranges between 3 and 60 storeys. However, Trabucco et al. (2015) indicated that a composite diagrid building is better than RC alternatives in terms of global warming potential for a 120-storey building. More research is required for buildings ranging from 60 to 120 storeys to clarify the effects of RC and steel on EC.

The amount of recycled content, manufacturing technologies, and material strengths are critical parameters when comparing the EC and EE of RC and steel structures. Although RC structures are commonly accepted as less carbon-intensive when compared to steel structures, the amount of recycled content can change the results (Zhao and Haojia, 2015; Gan, Chan et al., 2017; Mavrokapnidis et al., 2019). For instance, according to Gan, Chan et al. (2017), a 60-storey steel building is less carbon-intensive than the RC alternative when the recycled content of steel is <70% and 100% Portland cement is used. Similarly, Zhao and Haojia (2015) indicated that when the recycling rate of steel is above 70%, and 15% fly ash concrete is used, the 69-storey building with two outrigger levels becomes less carbon-intensive than the RC alternative. Although the system boundaries of both studies and data sources are different, as indicated in Table 2, there is a critical point in the recycled content percentage of steel where steel buildings produce less EC than RC alternatives, depending on the recycled content of concrete and building height.

The manufacturing processes of steel are an essential factor that has a substantial impact on both the quantity of recycled scrap and the associated EC emissions (IEA, 2007). For example, the amount of recycled steel scrap is limited to 30% for blast furnace-basic oxygen furnace, whereas steel containing 100% scrap can be produced with an electric arc furnace (Gan, Chan et al. 2017). Zhao and Haojia (2015) contributed that as the recycling content of steel increases, in addition to the developments of steel-making techniques, steel buildings with high recycled contents will be more common due to increasing economic and environmental advantages.

Using high-strength materials substantially reduces EC emissions of tall buildings (Choi et al. 2016; ASCE Carbon Task Group 2017). For example, Choi et al. (2016) proposed that choosing composite columns, namely the steel-reinforced concrete (SRC) columns rather than conventional RC columns, substantially decreases the

Table 4. The main findings of the existing studies

Authors/year of the study	**Main contributions**
Treloar et al. (2001)	The EE per unit GFA of 42 and 52-storey buildings is 60% more than the others.
Cho et al. (2012)	The least amount of EE and associated EC emissions per unit area belongs to chevron bracing, followed by X bracing, outriggered frame, and rigid frame system, respectively.
Drew et al. (2014)	34 and 58-storey buildings perform best in terms of carbon saving by using the land saved for electricity generation from PV panels.
Foraboschi et al. (2014)	1. Reinforced concrete (RC) frames consume less EE than steel frames.
	2. The majority of the EE almost always belongs to the floors compared to other structural components.
	3. The lowest EE is consumed by RC slabs and followed by lightweight floor systems and steel-concrete floors.
Moussavi Nadoushani and Akbarnezhad (2015)	When only the EC at A1-A3, A4, and A5 stages are considered, RC structures are less carbon-intensive; however, when life-cycle carbon emissions are considered, steel structures are less carbon-intensive.
Trabucco et al. (2015)	1. 60-storey RC buildings have the highest GWP and cradle-to-grave EE among the other 60-storey alternatives with no recycled content.
	2. 120-storey composite diagrid building has the lowest GWP and cradle-to-grave EE among the other 120-storey alternatives with no recycled content.
Zhao and Haojia (2015)	RC shear frame system has the least EC compared to outriggered frame systems because of the limited steel recycling rates in China.
Choi et al. (2016)	1. SRC columns are more advantageous in carbon emissions than RC columns.
	2. Increasing material strength and cross-sectional area of steel shape rather than concrete is a better strategy in a composite structure for reducing carbon emissions.
Bohne et al. (2017)	1. Timber structures have far less EE than steel and concrete, even the carbon capture is not included.
	2. Optimum building height is 10–20 storeys for each alternative.
Gan, Chan et al. (2017)	1. Among the 60-storey buildings with RC, composite, and steel structures, the RC alternative is less carbon-intensive (EC/GFA) when no recycling content is included. However, the EC of alternative models changes as the ratio of the recycled content of steel and RC increases.
	2. Optimal building height in terms of minimum EC ranges between 50 and 90 storeys for the compared structural systems.
Helal et al. (2019)	1. Triangular floor plan configuration has lower embodied greenhouse gas (EGHG) per GFA than the rectangular configuration.
	2. A new functional unit is introduced: EGHG per capita (person).
	3. Steel reinforcement constitutes most of the EGHGE despite its relatively smaller volume.
Li et al. (2019)	1. EE of CLT is much higher than concrete; thus, all timber alternatives (except the RC core) have the highest EE among the three alternatives.
	2. Unlike EE, EC of the all-timber alternative is the lowest (indeed has negative carbon emissions) among the others.
Mavrokapnidis et al. (2019)	The EC emissions of the five structural systems are sorted from lowest to highest as RC trussed tube, RC tube-in-tube, steel diagrid, steel trussed tube, and steel outriggered frame.
Helal et al. (2020)	The EGHGE of structural systems can be influenced by as much as 22% due to the structural design techniques and the magnitude of structural loads.
Hens et al. (2021)	The post-beam-panel system exhibits a greater EC compared to the post-and-platform system, and this gap widens as the building height increases.
Trabucco and Belmonte (2021)	RC alternatives are the best regarding EE, EC, and cost, whereas the steel alternatives have the highest EE, EC, and cost.
Fakıoğlu Gedik and Ay (2023)	Reducing the structural core increases the cumulative EC, whereas surrounding outriggers with belt trusses increases the structural efficiency, and less EC can be obtained compared to a relatively larger structural core.

EC of columns (43% EC reduction) for a 29-storey core-frame building. Tall building construction requires high-performance materials such as composite materials, high-strength concrete, and pre-stress tendons, which are not commonly required for conventional building design (Gan, Cheng et al. 2017). The EC factors of these high-performance materials differ from conventional structural materials, yet they are commonly overlooked in the current literature. Gan, Cheng et al. (2017) investigated the EC factors of commonly used structural materials in tall building design.

Gan, Cheng et al. (2017) investigated the share of EC (A1-A3 and A4 phases) produced by concrete (%35 fly ash), structural steel, and steel reinforcement (no recycled content in structural steel and rebar) in a 60-storey high-rise building with outriggered frame system. The results show that although the mass of concrete, structural steel, and reinforcement are 82%, 12%, and 6%, the EC of those materials is 17%, 54%, and 27%, respectively. Thus, the EC of reinforcing bars is much greater than the concrete in contrast to its relatively small weight. Zhao and Haojia (2015) also analyzed the amount of EC produced by rebar, structural steel, and concrete for three different structural systems for a 69-storey building. The EC share of concrete, structural steel, and reinforcement in RC shear frame structural systems is approximately 52%, 12%, and 36%, respectively. On the other hand, in outriggered frame systems, their respective contributions are around 28%, 54%, and 18%. In the study by Gan, Cheng et al. (2017), the EC share of rebar in outriggered frame systems is higher than Zhao and Haojia (2015). Nevertheless, the variation can be clarified by the usage of recycled scrap (38%) in rebars and also the lower amount of recycled content (15% fly ash) in concrete by Zhao and Haojia (2015). Unlike the EC contribution of reinforcing bars, the EC share in structural steel is quite similar in both studies (Gan, Cheng et al., 2017; Zhao and Haojia, 2015) despite the differences in LCA data sources as indicated in Table 2.

Type of the Structural System

Diverse structural system categorizations for tall buildings are utilized in practical applications and within academic discourse (Ilgın et al., 2021). Günel and Ilgın (2014) proposed a rather comprehensive classification system and categorized the tall building structural systems as rigid frame systems, flat plate/slab systems, core systems, shear wall systems, shear-frame systems (shear trussed/braced frame and shear walled frame), mega column (mega frame, space truss) systems, mega core systems, outriggered frame systems, and tube systems. The selected studies also used different names to refer to tall building structural systems. To address this, the classification system proposed by Günel and Ilgın (2014) is used to define tall building structural systems in Table 3. Nevertheless, Treloar et al. (2001) Drew et al. (2014), and Choi et al. (2016) conducted their studies regardless of the type of the structural system, even if it directly affects the EC emissions.

According to the study by Mavrokapnidis et al. (2019), the EC emissions of a 192-meter building with outriggered frame system are greater than steel trussed tube, steel diagrid, RC tube-in-tube, and RC trussed tube. Similarly, Zhao and Haojia (2015), the RC shear frame system produces less EC than the outriggered frame system for a 69-storey building. Although lateral loads are critical for the structural design of tall buildings, they are not discussed in the research conducted by Zhao and Haojia (2015), as indicated in (Table 3). Furthermore, in contrast to Zhao and Haojia (2015), Gan, Chan et al. (2017) indicated that outriggered frame system is the best alternative to minimize EC emissions compared to a tube-in-tube and mega-frame system for a 60-storey height building. Nevertheless, for 80-storey and 100-storey buildings, the lowest EC emissions are produced by the mega-frame system (Gan, Chan et al., 2017).

Cho et al. (2012) indicated that the chevron-braced structural system's EE per unit area is lower than the X-braced one. Hens et al. (2021) investigated two different structural systems for tall timber buildings: the post-beam-panel and post-and-platform systems. They concluded that the latter has lower EC than the prior for buildings with varying heights (40–140 meters). Through extensive research, Gan, Chan et al. (2017) demonstrated the optimum height for tall buildings regarding EC for various structural systems. Finally, Fakıoğlu Gedik and Ay (2023) investigated the effect of structural core on EC emissions of tall buildings. Although the cumulative carbon emissions increase by reduced core size, the EC per unit area can be decreased by increasing the structural efficiency.

Structural Components

Gan, Chan et al. (2017) categorized the structural system of a tall building as (i) the lateral load-resisting system composed of core walls, columns, and outriggers, (ii) the floor framing system composed of floor slabs and beams, and (iii) the foundation. According to the study, the EC share of the lateral load-resisting system of a 60-storey outriggered frame building is around 70-80% for the floor slabs, 16–25% for the beams, and 2–5% for the foundation. Zhao and Haojia (2015) also examined the amount of EC production according to the structural components for a 69-storey building with alternative structural systems (Table 3). The share of EC is roughly 25% for walls, 22% for columns, 37% for beams, 15% for slabs, and 1% for outriggers. Foraboschi et al. (2014) emphasized the significance of the floor type on the total EE of a tall building structure. They indicated that the EE of the floor slabs and beams ranges from 34.7% to 78%, depending on the floor type, materials, and building height.

According to the study of Mavrokapnidis et al. (2019), the

EC share of building components varies depending on the type of structural system. For instance, the EC share of the lateral load resisting system and the floor framing system are almost equal for RC tube in tube, RC braced tube, steel braced tube, and outriggered frame 64-storey building alternatives. In contrast, the EC share of the lateral load resisting system in the diagrid building is much higher than that of the floor framing system. Despite the variations in the existing studies on the EC or EE share of structural components, floor type is a significant component for the embodied impact assessment of tall buildings (Table 5). Furthermore, Gan, Chan et al. (2017) stated that as building height increases, the EC attributed to the columns and core walls experiences exponential growth, primarily due to the growing impact of wind loads.

DISCUSSION

The scope, materials, and methods of the current literature on EC and EE of tall buildings are investigated in this study. Then, studies comparing the embodied impacts of specific building parameters for tall building structures are analyzed regarding their LCA and structural design methods. Although some variations are inherent to the LCA method, system boundaries, and geographic locations are not indicated in some cases, as shown in Table 2. Another significant problem in the existing studies is the lack of transparency, variations, and uncertainties in the structural design methods, as indicated in Table 3. Furthermore, while some studies establish a lateral deflection limit, others do not provide a precise method for ensuring structural equivalency among different models.

Considering the numerical values in terms of building height, supertall buildings (+300m) are mostly overlooked in the existing literature (Figure 2). Moreover, despite the recent popularity of timber as a structural material compared to reinforced concrete, steel, and composite (RC and steel), there is a growing interest in the current literature for timber tall buildings (Bohne et al., 2017; Li et al., 2019; Hens et al., 2021). However, there is a lack of research dedicated to timber tall buildings surpassing 50 storeys, given the limited examples of such structures.

The majority of the structural systems of tall buildings defined by Günel and Ilgın (2014) are examined in the existing literature, except rarely used structural systems, specifically flat plate/slab systems, core systems, shear wall systems, mega core systems, and bundled tube systems. According to Ilgın et al., (2021), the most common structural system used in supertall buildings is the outriggered frame system, followed by tube systems. This observation aligns with the numerical data presented in Figure 2.

Current studies investigated the effects of various design parameters of tall building structures in EC and EE assessment. There is no consensus in the existing literature regarding the optimum building height for minimized EC and EE. In fact, there is a broad variation in the optimum building height, which ranges between 7 and 58 storeys. Gan, Chan et al. (2017) found that the optimum building height varies depending on the type of the structural system in a tall building. Thus, optimum building height can vary depending on the research scope.

The amount of recycled content is decisive in identifying less carbon-intensive materials. According to the existing literature, the EC and EE of RC structures are lower than the steel alternatives for buildings up to 60-storey, when all the structural materials are virgin. However, the steel alternatives become less carbon-intensive when the steel scrap is more than approximately 70% for a 60-storey building. Therefore, the recycled content in steel can significantly change the results. Steel can be more advantageous for supertall buildings (+300m) regardless of its recycled content. Trabucco et al. (2015) indicated that 120-storey steel diagrid buildings are less carbon-intensive than RC alternatives. Nevertheless, further investigation is required.

There is not a single deterministic result for the proportional EC or EE share of structural components of tall buildings. However, previous research has shown that the floor framing system contributes significantly to the overall EC or EE of a tall building structure. Moreover, as the building height increases, the EC or EE share of the lateral load-resisting system increases exponentially.

CONCLUSION

The construction of tall buildings leads to significant energy and carbon emissions due to the massive use of structural materials. Therefore, decisions in the early design phase of a tall building are critical for reducing energy use and carbon emissions. Recent studies investigated the effects

Table 5. EC and EE share of the structural components according to the existing studies

	Gan, Chan et al. 2017	Zhao and Haojia, 2015	Foraboschi et al., 2014	Mavrokapnidis et al., 2019
Lateral load resisting system	70–80% (EC)	48% (EC)	35–78% (EE)	50–63% (EC)
Floor framing system	16–25% (EC)	52%	-	37–50% (EC)
Foundation	2–5% (EC)	-	-	-

of various design parameters on the EC assessment of tall building structures. This study analyzed the scope, materials and methods, and findings of these comparative studies, considering the design parameters of tall building structures.

There is no consensus on the optimum height of tall buildings since the scope and the method of these studies vary. Only a few studies investigated the environmental impacts of tall buildings on a larger scale. Resch et al. (2016) highlighted that when considering the optimum building height in terms of carbon and energy, the lifespan of the building and the population of a city plays a significant role. Furthermore, Drew et al. (2014) claimed that carbon and energy can be saved by using PV panels to generate energy in high-rise development zones where the land is saved compared to low-rise development areas. The optimum building height depends on various factors. Instead of seeking a one-size-fits-all solution, future studies can establish standards for environmental impact assessment based on the level of details in categorized spatial scales to determine the optimum building height.

According to this study, the lack of uniformity and the uncertainties in the LCA and the structural design methodologies lead to an extensive variation in the results. To establish consistency among diverse design parameters of tall buildings in terms of their EC or EE, it is crucial to develop a uniform methodology to estimate their EC or EE. This would effectively eliminate the uncertainties, variations, and inconsistencies previously identified in the LCA and structural design methods. In future studies, a standardized procedure can be developed for running various scenarios based on categorizations to consistently evaluate the effects of various design parameters on the environmental impacts of tall buildings. By revealing the effects of various design parameters on tall building structures, a holistic framework can be generated to guide designers in the early design stage.

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