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Research Article

Application of Life-Cycle Assessment Approach to Zero Energy Buildings: Case Study of an Office Building in South Korea

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This study evaluates the life-cycle carbon footprint of buildings, addressing a key limitation of zero-energy buildings (ZEBs), which primarily focus on operational energy use. This study identified the optimal conditions for structure type and window-to-wall ratio (WWR) of ZEB implementation to evaluate carbon emissions from a life-cycle perspective. Building energy simulations and life-cycle assessment (LCA) analyses were conducted to examine variations in the operational energy consumption and building life-cycle carbon emissions based on different structural materials and WWR configurations. The building selected for this analysis featured a combination of concrete and wood structures, with a WWR of 40% in the north–south direction and 30% in the east–west direction, each increasing by 20%. The findings indicated that increased WWR for both concrete and wood structures increases energy consumption. Moreover, the carbon emissions followed a similar pattern, rising as WWR increases. Regarding life-cycle carbon emissions, the findings suggest transitioning from the current concrete structure to a wood structure while maintaining a low WWR as an effective strategy to achieve carbon neutrality in building operations.

Keywords: building structure; carbon neutrality; energy consumption; life-cycle assessment; life-cycle carbon emissions; window-to-wall ratio

1. Introduction

Countries worldwide face climate change challenges driven by global warming, including extreme weather, rising temperatures, and increasing sea levels [1–4]. In December 2015, the Paris Agreement set a goal to limit the global average temperature increase to below 2°C, with efforts to keep it under 1.5°C above preindustrial levels. According to the Intergovernmental Panel on Climate Change (IPCC) [5], achieving the 1.5°C target requires reaching net-zero emissions by 2050, necessitating transitions across various energy, land, and transportation sectors. Accordingly, the international community has submitted long-term low greenhouse gas (GHG) emission development strategies (LEDSs) and set targets to achieve carbon neutrality according to each country's circumstances.

The European Union (EU) has set a carbon neutrality goal by 2050 through the European Green Deal and aims to reduce carbon emissions by at least 55% by 2030 compared to 1990 levels [6]. After rejoining the Paris Agreement in 2021, the United States set a goal to reduce GHG emissions by 50%–52% by 2030 (compared to 2005 levels) and achieve carbon neutrality by 2050 [7]. Japan aims for a 46% reduction in GHG emissions by 2030 (compared to 2013) and to achieve carbon neutrality by 2050 [8]. China announced it would reduce carbon emissions by 2030 and achieve carbon neutrality by 2060 [9]. South Korea announced its 2050 carbon neutrality goal in 2020 and established the Framework Act on Carbon Neutrality and Green Growth for Coping with the Climate Crisis in 2021. Thus, all major countries have set goals to achieve carbon neutrality, considering their circumstances and enacting relevant laws. Achieving carbon neutrality necessitates reducing GHG emissions in the building sector, reducing emissions by 88.1% by 2050 compared with 2018 through improvements in building energy efficiency and disseminating high-efficiency devices [10].

Carbon neutrality refers to a state where GHG emissions are near zero or offset. It refers to the balance of GHG emissions from buildings, organizations, and countries absorbed by natural ecosystems or balanced through carbon offset projects. The definition of carbon neutrality varies in different contexts, such as buildings, organizations, and countries, depending on the scope of the GHG emission assessment, range of carbon offsets, and assessment period. The International Living Future Institute offers certifications such as the Living Building Challenge, Zero Energy, and Zero Carbon for carbon-neutral buildings. The Living Building Challenge and Zero Carbon certifications evaluate embodied carbon from the production and construction stages (A1–A5) and the energy consumption during the operational phase. Only the energy consumption during the operational phase was evaluated at zero energy. Based on the assessment period, the UK Green Building Council certifies carbon-neutral buildings and distinguishes between embodied, operational, and whole-life carbon. Additionally, the US Green Building Council's LEED Zero Carbon and Australia's Climate Active evaluate carbon neutrality based solely on the energy consumed during the operational phase. Previously, zero-energy buildings (ZEBs) only assessed regulated energy, excluding the energy consumption by users, making it challenging to achieve actual carbon neutrality. However, carbon-neutral and net-zero buildings expand the scope of GHG emissions to include the entire life cycle or metered energy consumption.

ZEBs play a crucial role in realizing carbon neutrality in buildings. A certification system for ZEBs has been implemented in South Korea to promote their adoption. ZEBs are buildings where the primary energy required for heating, cooling, hot water, lighting, and ventilation is below a certain standard. However, current ZEB standards focus on assessing the energy used during operational phases, often resulting in discrepancies between estimated and actual energy consumption. Moreover, carbon emissions from the entire life cycle of a building, including production, construction, and disposal, are excluded from the assessments. While reducing operational carbon emissions is crucial, the substantial carbon emissions associated with the construction and materials must also be addressed. However, the ZEB framework primarily evaluates operational energy consumption, neglecting the carbon emissions generated throughout the building's life cycle. A key limitation of the ZEB framework is its narrow focus on operational energy, overlooking life-cycle carbon emissions [11, 12]. Additionally, implementing a ZEB often requires advanced energy-efficient materials and technologies, which can increase embodied carbon [13–16]. According to Blengini and Di Carlo [14], even if a low-energy house reduces operational energy by 10:1, the overall carbon footprint reduction is only 2.2:1, owing to increased embodied energy. Therefore, achieving true carbon neutrality in ZEBs requires minimizing operational and embodied carbon emissions.

Materials with low embodied carbon should be selected to design buildings efficiently during the planning phase and minimize energy use during construction to minimize embodied energy. Material selection and efficient building design influence the quantity of materials used, the thermal performance of the envelope, carbon emissions from transportation, and energy consumption during the operation. The crucial factors in the design and planning stages include the aspect ratio of the envelope, primary structure materials, window-to-wall ratio (WWR), and building orientation. Specifically, WWR affects the quantity of materials and the energy performance of heating, cooling, and lighting, necessitating a life-cycle carbon emission assessment. However, research integrating these considerations into ZEB planning to evaluate operational energy reduction and life-cycle carbon emissions is insufficient.

Previous research has extensively evaluated energy and carbon emissions resulting from changes in the WWR and structure. However, most studies have been limited to examinations of individual rooms rather than entire buildings [17]. Furthermore, life-cycle assessments (LCAs) are confined to assessing building energy consumption during the operational stage and fail to comprehensively evaluate a building's life cycle [18, 19]. Even in studies conducting complete life-cycle evaluations, WWR variations are rarely accounted for, leading to limitations in assessing structural volume changes and their impact on emissions [20, 21]. Additionally, analyses of global warming potential (GWP) related to structural changes have been confined to stone and concrete without considering and evaluating wooden structures with lower GWP emissions [22, 23]. Existing research lacks a comprehensive focus on structure-related aspects to reduce the GWP. Evaluation of the changes in structural volume resulting from WWR variations, associated energy consumption, and life-cycle carbon emissions is also limited [24–26].

This study addresses these gaps by evaluating building life-cycle carbon emissions while recognizing the limitations imposed by ZEB, which primarily focus on operational energy consumption [27]. We propose architectural planning approaches for achieving carbon neutrality from a whole-life carbon perspective. Specifically, we analyze the current state of LCA evaluations for ZEBs, present the status of whole-life carbon emissions, and provide foundational insights for reducing carbon emissions through material selection and WWR optimization in the early planning stages of ZEBs.

2. Methodology

This study was conducted in the following steps (Figure 1): First, a survey of newly constructed office buildings certified by G-SEED was undertaken to investigate their whole life cycle. This survey facilitated establishing a framework for reducing embodied carbon emissions by analyzing GHG emissions across all life-cycle stages. Furthermore, verification was performed to ensure the reliability of the simulation model.

Next, a simulation model was developed to analyze changes in GHG emissions across the building's life-cycle stages from different building materials and WWR. This analysis provided

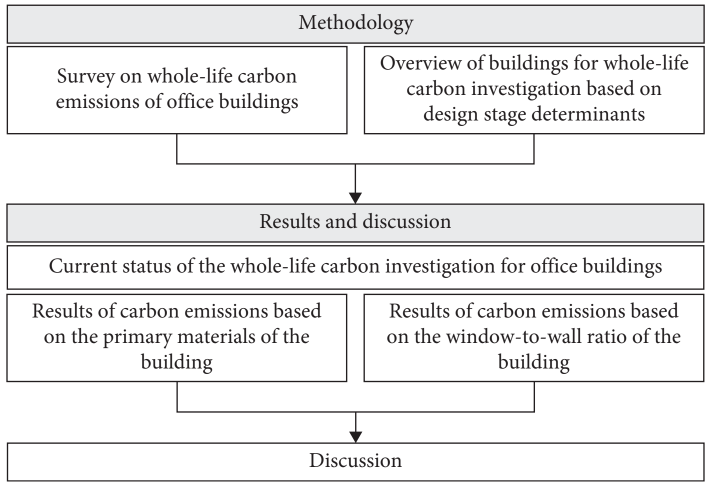


Figure 1: Research process.

a comprehensive understanding of the impact of material selection and design choices on overall carbon emissions.

2.1. Survey on Whole-Life Carbon Emissions of Office Buildings. The survey focused on newly constructed offices that underwent LCA in 2022 and received G-SEED certification. Out of 97 buildings, 30 were selected for analysis after excluding three outliers with unique characteristics. In South Korea, a building qualifies as a ZEB if it has a primary energy use intensity (EUI) of 140 kWh/m^2 or lower and achieves an energy self-sufficiency rate of at least 20%.

Based on these criteria, the 30 buildings were categorized into those certified as ZEBs, low-energy buildings (that met the ZEB criterion of a primary EUI of 140 kWh/m^2 but were not officially certified), and new buildings that did not meet the ZEB certification standards. The results showed that six buildings were certified as ZEBs, 19 were low-energy buildings, and 5 were new buildings that did not meet the ZEB criteria.

The LCA method was conducted according to ISO 14044 and underwent third-party verification. The material inventory for each building was derived from completion documents and the bill of quantities, with materials verified by the supervising inspector. A 99% cutoff was applied to the material input during production. Although the evaluator can further subdivide the life-cycle stages, the LCA report analyzed in this study divided the evaluation scope into four stages: production, construction, operation, and disposal. The building lifespan was 50 years, including the materials used for maintenance during the operational phase. The energy consumption during the operational phase was calculated based on the simulation results used for the building energy efficiency ratings.

The environmental impact categories included GWP (GHG emissions). Additionally, the analysis considered at least two of the six major impact categories: resource consumption, global warming, ozone layer impact, acidification, eutrophication, and photochemical oxidant creation. Finally, the study compared the GHG emissions among six major environmental impact categories.

2.2. Overview of Buildings for Whole-Life Carbon Investigation Based on Design Stage Determinants. According to the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA), nonresidential buildings consume more energy and produce more carbon than residential buildings [28]. Among nonresidential structures, office buildings with the highest occupancy rates offer significant social and economic benefits through improved energy efficiency [29, 30]. Medium and large office buildings exhibit heightened sensitivity to internal heat loads from appliances and lighting, making them less responsive to passive design strategies. However, small office buildings, such as envelope-dominated buildings, are highly sensitive to passive strategies. Therefore, this study focuses on small office buildings to evaluate GHG emissions in the early design stage based on passive strategies. Table 1 presents the selected buildings. The target building location was assumed to be Seoul, South Korea, which experiences a warm, humid climate with four distinct seasons, classified as ASHRAE Climate 4A according to the Köppen climate classification [31].

Simulations were performed using existing concrete and wood materials to evaluate the impact of carbon emissions on altering the structural materials. Additionally, the energy consumption and carbon emissions were evaluated by modifying the WWR for each structure. Table 2 presents the WWR for each case. Following the Zero Energy Design Guidelines [32], which recommend WWRs of 40%–45% for south-facing, 35%–40% for north-facing, and 25%–30% for east-west-facing orientations, an optimized baseline WWR of 40% for the north–south façade and 30% for the east–west façade was selected. Changes in the WWR were implemented in 20% increments, either increasing or decreasing.

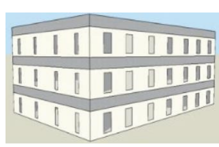
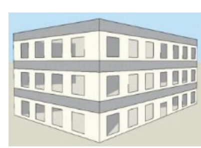
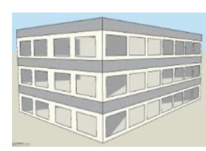
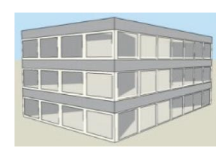
The building design was based on a prototype developed by the U.S. Department of Energy (DOE). Table 3 presents the configuration details, which comply with ISO 18523-1:2016 and ASHRAE Standard 90.1_2019 [33–35].

The building's energy performance evaluation included lighting, cooling, heating, appliance, and water heating loads.

Table 1: Target building overview.

Parameter	Value
Location	Seoul, South Korea
Building type	Office
Building envelopment	
Floor area	508.75 m^2
Number of floors	3
Floor total area	1526.25 m^2
Floor-to-ceiling height	2.75 m
Floor to floor	4.05 m
Internal loads	
Lighting density	7.5 W/m^2
Electric equipment	12.0 W/m^2
Occupancy	0.1 $people/m^2$
Setpoint	
Heating	22°C
Cooling	24°C
Period	
Heating	November to March
Cooling	May to September
Transition	April and October
Occupancy schedule	09:00–18:00
Weather	4A

Table 2: Window-to-wall ratio overview.

Cases		CONC1/WOOD1	CONC2/WOOD2	CONC3/WOOD3	CONC4/WOOD4
Building image					
Window area on each floor (m^2)		45.12	101.5	157.06	213.74
Window area by direction on each floor (m^2)	N/S	16.91	33.82	50.40	67.40
	E/W	5.65	16.93	28.13	39.47
WWR (%)	N/S	20	40	60	80
	E/W	10	30	50	70

The energy performance was assessed using a power-to-primary energy conversion factor of 3.4. DesignBuilder, an energy analysis software designed to assess and optimize energy efficiency, was utilized to evaluate the building's energy performance. This software enables the evaluation of both the design and operational phases of energy consumption and performance, facilitating simulations for designing more efficient buildings [36, 37].

The one-click LCA program was employed for the LCA analysis of an office building. This program is utilized for sustainability assessments and life-cycle analyses in the building and construction industries. A one-click LCA supports evaluating building environmental performance, impact analyses, and decision-making regarding environmental design and building operations. By studying various environmental metrics across the building life cycle, the program allows the assessment of GHG emissions, energy consumption, water use, and material use [38, 39]. The program also evaluates the use of renewable energy, waste management, and the internal environment and encompasses GHGs such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which can be converted and evaluated based on their GWP as kg CO_2eq/m^2 values. LCA was conducted following ISO 14040:2006 [40–42].

The structure and WWR type, a passive design strategy, were set as variables to compare and analyze the correlation between energy use and carbon emissions across different cases. The LCA scope was established using the cradle-to-cradle approach to assess the impacts over the entire building life cycle. Additionally, a building life cycle of 50 years was set based on ISO 15686-8 to determine the service life of construction products and building equipment [43]. As concrete is typically covered with finishing materials, resulting in minimal

Table 3: Building input variables.

Input variables			Value
Thermal value for envelope	External wall U-value		0.239 W/m^2 K for concrete building 0.190 W/m^2 K for wooden building
	Ground floor U-value		0.285 W/m^2 K for concrete building 0.217 W/m^2 K for wooden building
	Flat roof U-value		0.143 W/m^2 K for concrete building 0.123 W/m^2 K for wooden building
	Window/door	U-value	1.338 W/m^2 K
		SHGC	0.568
		VT	0.745
Lighting	Power density		7.5 W/m^2
	Control		Linear
HVAC	Type		PTHP (packaged terminal heat pump)/ FCU air chiller
	Setpoint		Heating 22°C/Cooling 24°C
	COP		Heating 3.5/Cooling 3.5
	Fuel		Electricity from grid
PV system	Type		Monocrystalline silicon
	Efficiency		20.7%
	Active area of total PV modules		190.44 m^2
	Orientation		South
	Tilt angle		30°C
	Capacity		55 kW

exposure to the external environment, carbonation during usage was not considered.

The input categories for LCA evaluation are presented in Table 4. The selected building materials included external walls and facades, internal and nonbearing walls, floors and horizontal elements, and doors and windows. Energy consumption was evaluated using DesignBuilder, while water consumption was represented by tap water consumption. Construction site operations were excluded from the analysis to focus exclusively on changes attributable to the building structure and WWR variations. For emissions and removals, the carbonation of cementitious materials was selected as an input. Additionally, the building area and calculation period were also included as inputs.

Tables 5 and 6 present the inputs for one-click LCA and outline the assumed values for each dataset. Notably, because the LCA program did not consider photovoltaic systems, a carbon footprint of 51.88 gCO_2/kWh was applied to the monocrystalline silicon module. This study did not consider repair, disposal, and subsequent reuse processes [44].

3. Results and Discussion

3.1. Current Status of the Whole-Life Carbon Investigation for Office Buildings. Table 7 presents the results of the whole-life GHG emissions investigation for the selected office buildings. The average GHG emissions for zero-energy-certified, low-energy, and new buildings were 1488.0, 2184.2, and 2897.7 kg CO_2eq/m^2, respectively. As shown in Figure 2, the whole-life environmental impact exhibited a significant correlation with primary EUI.

The emissions analysis by life-cycle stage revealed that low-energy buildings exhibited the highest emissions during the production stage, while zero-energy-certified buildings and other new buildings exhibited similar emissions. Emissions during the construction stage remained identical across all three building categories. However, the most notable differences were observed during the operational stage. Assumed to span 50 years and include annual energy consumption and replacement costs, the operational stage was significantly influenced by the energy demand. The operational stage emissions for Zero Energy Certified Buildings ranged from 446.9 to 1390.0 kg CO_2eq/m^2, whereas new buildings exhibited significantly higher emissions ranging from 1444.1 to 3181.0 kg CO_2eq/m^2. The emissions during the disposal stage were similar to those during the production and construction stages, with minimal variation among the building groups.

As shown in Figure 3, the proportion of GHG emissions at each stage revealed that the share of emissions during the operational stage decreased from 81% in new buildings to 64% in ZEB-certified buildings. This reduction is likely due to the increased use of building materials to lower building energy consumption. Similar findings have been observed in previous studies evaluating low-energy buildings or net ZEBs, where the operational stage emissions decreased, leading to a higher proportion of embodied carbon or energy [45]. When net zero energy is achieved through renewable energy, the operational energy consumption decreases further, making

Table 4: One click LCA input category.

Category	Subcategory	Inclusion status
Building materials	Foundation and subsurface	X
	External walls and façade	O
	Columns and load-bearing walls	X
	Internal and nonbearing walls	O
	Floors and horizontal elements	O
	Other materials	X
	Doors and windows	O
	Finishes	X
	External areas	X
	Building systems	X
Energy consumption, annual	Fuel use	X
	Fuels used in nearby or on-site heat suppliers	X
	District cooling use	X
Water consumption, annual	Tap water consumption	O
Construction site operations	Construction site scenarios	X
	Deconstruction/demolition scenarios-C1	X
	Site electricity consumption	X
	Site district heating consumption	X
	Site fuel consumption	X
	Machine hours	X
	Material use (that does not constitute part of the asset)	X
	Water consumption	X
	Construction waste	X
	Additional transportation	X
Emissions and removals	Carbonization of cementitious materials	O
	Vegetation and landscaping scenarios	X
Building area	—	O
Calculation period	—	O

emissions from the production, construction, and disposal stages more prominent. Therefore, to achieve carbon-neutral buildings, optimizing building design, minimizing material usage, and developing low-emission materials to reduce embodied carbon is essential.

3.2. Results of Carbon Emissions Based on the Primary Materials of the Building. The operational energy consumption was analyzed to assess GHG emissions due to changes in the primary materials of the building. To ensure reliability, the base model was set as CONC2, a concrete building with a north–south orientation WWR of 40% and an east–west orientation WWR of 30%. The building adhered to Korea's ZEB certification criteria, which excludes plug loads and requires a primary energy consumption of less than 140 kWh/m^2 per year for heating, cooling, hot water, lighting, and ventilation. The primary energy simulation results for the baseline building indicated a total consumption of 223.07 kWh/m^2, with 24.89 kWh/m^2 for heating, 39.69 kWh/m^2 for cooling, 51.42 kWh/m^2 for lighting, 7.78 kWh/m^2 for domestic hot water, and 99.29 kWh/m^2 for plug loads. Excluding plug loads, the primary energy consumption was 123.78 kWh/m^2, meeting ZEB certification requirements and validating the reliability of the model.

To verify the reliability of the LCA, the evaluation assessed stages A1–C4, incorporating energy consumption derived from the simulation results (Table 8). Water use was limited to energy associated with supply, excluding water used for building operation, maintenance, repair, replacement, and refurbishment activities. The total GHG emissions were compared against the average values of the certified ZEBs investigated in Section 3.1. The LCA evaluation results showed that total GHG emissions were 1483.5 kg CO_2eq/m^2, representing a 0.3% difference from the average value in the current status survey. The observed differences are relatively small, with the most significant deviations occurring in the construction and end-of-life stages. Given that the total emissions variation was just −0.3%, the simulation values for CONC2 closely aligned with the average for certified ZEBs, confirming the model's accuracy in estimating GHG emissions across building life-cycle stages.

The differences in GHG emissions resulting from varying the primary building material from concrete to wood are

Table 5: Input variables for LCA analysis of concrete frame.

Items		CONC1	CONC2 (baseline)	CONC3	CONC4
Project type		New constructions whole building			
Frame type		Concrete frame			
Included parts		Structure and enclosure, finishing, and other materials			
Calculation period		50 years			
Vertical structures and facade	Ready-mix concrete (m^3)	141.24	107.82	74.40	39.89
	PUR (polyurethane foam) insulation (m^3)	133.62	102.00	70.38	16.28
	Reinforcement steel (m^3)	6.68	5.10	3.52	1.88
	Precast concrete wall elements (m^3)	186.11	142.07	98.03	52.57
Horizontal structures	Precast concrete wall elements (m^3)	495.93	495.93	495.93	495.93
	PUR (polyurethane foam) insulation (m^3)	347.59	347.59	347.59	347.59
	Ready-mix concrete (m^3)	55.1	55.1	55.1	55.1
	Reinforcement steel (m^3)	11.25	11.25	11.25	11.25
Other structures and materials	Clear glass 6 mm (m^2)	405.36	912.06	1418.76	1925.46
	Low reflection float glass—Low-E, 6 mm (m^2)	405.36	912.06	1418.76	1925.46
Annual electricity consumption (MWh)		34.24	36.36	39.41	42.49
Annual the water consumption (m^3)		57.14	57.14	57.14	57.14
End of life		36.10	31.60	27.00	22.30

Table 6: Input variables for LCA analysis of wood frame.

Items		WOOD1	WOOD2	WOOD3	WOOD4
Project type		New constructions whole building			
Frame type		Wood frame			
Included parts		Structure and enclosure, finishing, and other materials			
Calculation period		50 years			
Vertical structures and facade	PUR (polyurethane foam) insulation (m^3)	133.62	102.00	70.38	16.28
	Swan timber, planed (m^3)	334.03	254.99	175.95	94.34
Horizontal structures	PUR (polyurethane foam) insulation (m^3)	347.59	347.59	347.59	347.59
	Swan timber, planed (m^3)	562.28	562.28	562.28	562.28
Other structures and materials	Clear glass 6 mm (m^2)	405.36	912.06	1418.76	1925.46
	Low reflection float glass—Low-E, 6 mm (m^2)	405.36	912.06	1418.76	1925.46
Annual electricity consumption (MWh)		32.69	35.59	39.66	43.24
Annual the water consumption (m^3)		57.14	57.14	57.14	57.14
End of life		93.30	86.60	79.30	71.70

presented in Table 9 and Figure 4. Considering that the *U*-values of the concrete and wooden buildings were adjusted to meet legal standards, their operational energy consumption was analyzed. The source EUI was 68.82 kWh/m^2 for the concrete building and 67.36 kWh/m^2 for the wooden building, indicating no significant difference in operational energy use. However, the total GHG emissions for the wooden building were significantly lower (1101.0 kgCO_2eq/m^2) compared to the concrete building (1483.5 kgCO_2eq/m^2), representing a reduction of ~25.8%.

The most notable differences based on the structural material throughout the life cycle were observed in the production and end-of-life stages. Concrete buildings exhibited significantly higher emissions during the product stage, primarily because of the energy-intensive production of cement and steel reinforcements. Conversely, wooden buildings have higher emissions during end-of-life stages. This could be due to the challenges associated with the disposal or treatment of wood, especially if preservatives or chemicals are used. In contrast, concrete buildings tend to have lower end-of-life emissions, as concrete and steel components are often recyclable. Although wooden buildings have higher end-of-life emissions, they do not outweigh the significant reductions achieved during the earlier stages of their life cycle. Emissions during the construction stage were higher for concrete buildings, likely owing to the transportation of heavier materials and the energy

Table 7: Greenhouse gas emissions by life-cycle stage according to the energy performance of the building (unit: $kgCO_2eq/m^2$).

Life-cycle stages	Product (A1–A3)	Construction (A4–A5)	Use (B1–B7)	End of life (C1–C4)	Total (A1–C4)
Certified ZEB					
Minimum	419.0	5.4	446.9	3.0	929.7
Average	494.2	20.8	950.5	22.5	1488.0
Maximum	583.0	26.8	1390.0	50.6	2002.6
Low-energy building					
Minimum	303.0	5.4	803.0	3.0	1328.1
Average	557.5	21.2	1588.2	17.3	2184.2
Maximum	872.0	41.0	2610.0	142.3	3524.3
New building					
Minimum	410.0	15.2	1444.1	3.0	1969.0
Average	509.3	19.1	2335.1	39.9	2896.3
Maximum	620.0	23.6	3181.0	62.8	3792.9

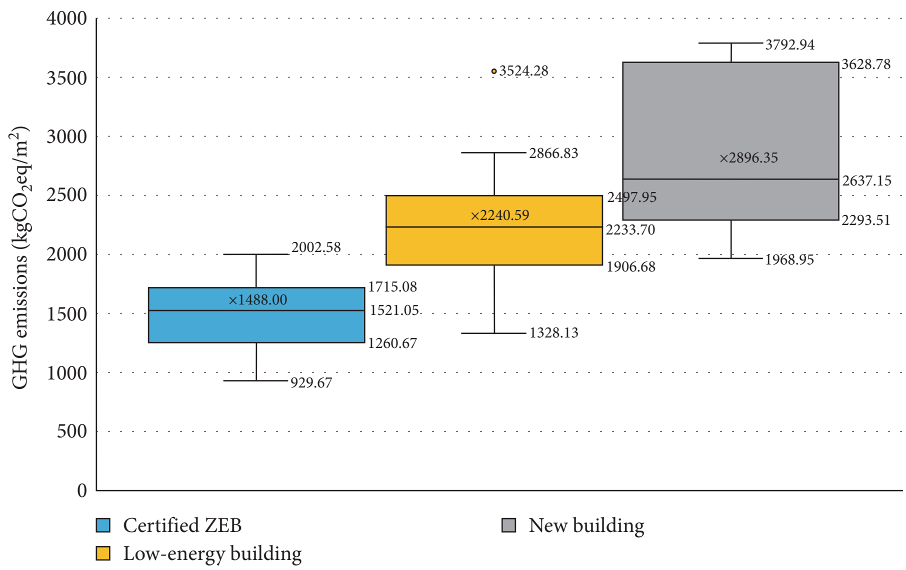


Figure 2: Distribution of greenhouse gas emissions by energy performance of the building.

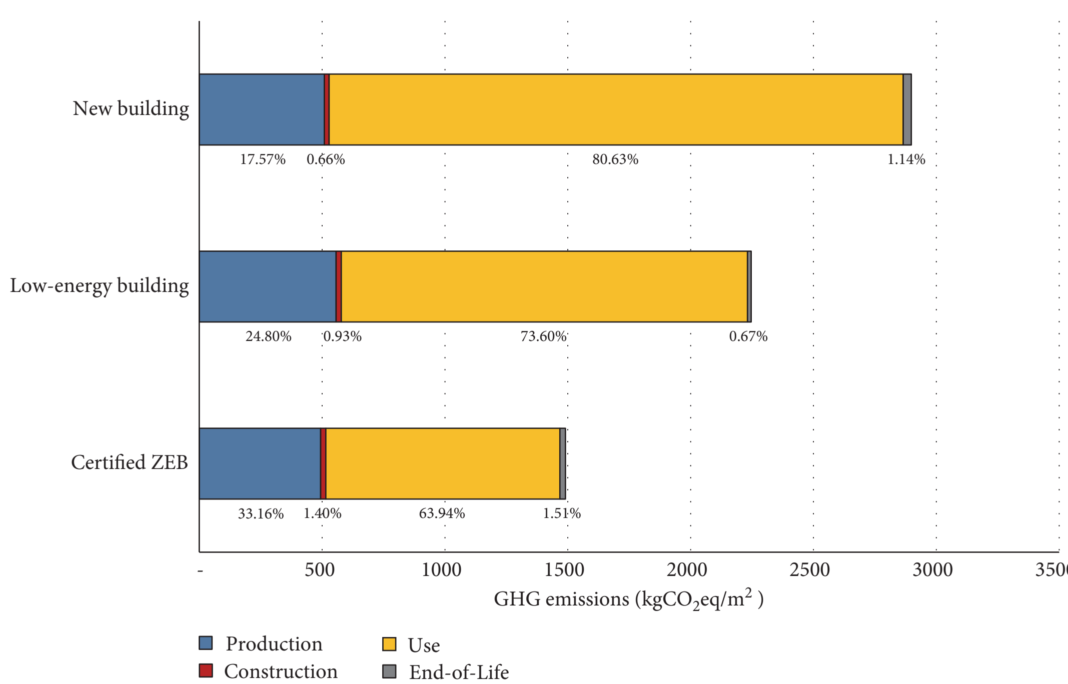


Figure 3: Average greenhouse gas emissions by life-cycle stage.

TABLE 8: Comparison of simulation values and statistical data (unit: $kgCO_2eq/m^2$).

Life-cycle stages	Product (A1–A3)	Construction (A4–A5)	Use (B1–B7)	End of life (C1–C4)	Total (A1–C4)
The average of certified ZEB	494.2	20.8	950.5	22.5	1,488.0
Base model (CONC2)	505.2	21.3	935.4	21.7	1,483.5
Difference	2.2%	2.2%	−1.6%	−3.3%	−0.3%

TABLE 9: Greenhouse gas emission: comparison of concrete and wooden buildings (unit: $kgCO_2eq/m^2$).

Building types	Product (A1–A3)	Construction (A4–A5)	Use (B1–B7)	End of life (C1–C4)	Total (A1–C4)
CONC2	505.2	21.3	935.4	21.7	1483.5
WOOD2	111.5	15.2	914.7	59.6	1101.0

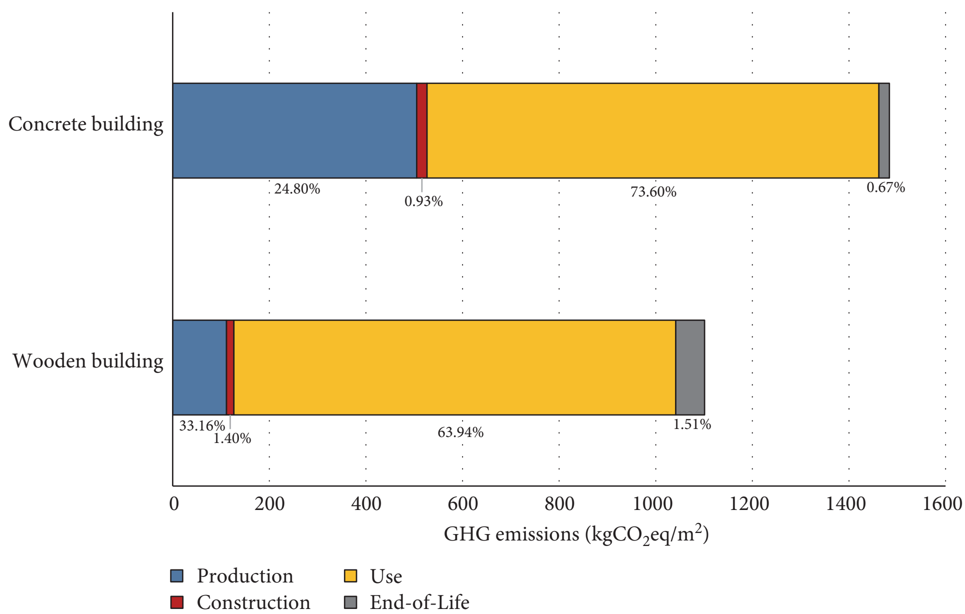


FIGURE 4: Greenhouse gas emissions by life-cycle stages of concrete and wood buildings.

required for concrete mixing and setting. Wooden buildings, lighter and easier to assemble, exhibited lower construction-stage emissions. Despite these differences, both buildings exhibit similar emissions during the usage stage, suggesting that both building types showed similar energy efficiency and operational energy use, possibly due to the same insulation and energy performance regulatory standards. However, the operational stage emissions for wooden buildings accounted for a higher proportion of the total emissions than concrete buildings. Therefore, strategies for reducing GHG emissions during the operational stage of wooden buildings are necessary. Although concrete buildings also have high emissions during the operational stage, their production stage emissions account for 34.1% of the total emissions. Therefore, integrating low-carbon materials in concrete construction could be a key strategy for mitigating its environmental impact.

3.3. Results of Carbon Emissions Based on the WWR of the Building. Table 10 and Figure 5 present the variations in the source EUI and GHG emissions for concrete and wooden buildings based on the WWR. The source EUI represents the building's operational energy consumption. Since factors such as lighting, DHW, plug loads, and PV generation remained constant regardless of WWR adjustments, only heating, cooling, and annual energy consumption are listed in Table 10. As the WWR increased, heating decreased, whereas cooling increased. The increase in cooling energy may be because, when the solar heat gain increases, the cooling peak load occurs during occupancy hours, and the system operates in accordance with the peak load. Regarding heating, even if heat loss occurs because of increased WWR, the system does not operate during the peak load. This is because the peak load occurs in non-real time, and the system operation decreases during occupancy due to increased solar radiation gain. Concrete buildings exhibited greater sensitivity to WWR changes in heating energy consumption, whereas wooden buildings responded more significantly to cooling energy. This is because although the U-value of the glass was applied equally to both types of buildings, the U-value of the rest of the envelope was lower in wooden buildings. Consequently, wooden buildings are more sensitive

Table 10: Energy consumption and greenhouse gas emissions with window-to-wall ratios of concrete and wooden buildings.

Cases	Source EUI (kWh/m^2)			GHG emissions ($kgCO_2eq/m^2$)				
	Heating	Cooling	Annual	Product (A1–A3)	Construction (A4–A5)	Use (B1–B7)	End of life (C1–C4)	Total (A1–C4)
CONC1	27.9	32.7	64.8	514.8	23.0	850.4	24.8	1413.0
CONC2	24.9	39.7	68.8	505.2	21.3	935.4	21.7	1483.5
CONC3	22.4	47.9	74.6	495.5	19.5	1034.3	18.6	1567.9
CONC4	20.7	55.5	80.4	484.5	17.7	1139.6	15.3	1657.2
WOOD1	23.2	34.5	61.9	86.7	16.0	815.9	64.6	983.3
WOOD2	20.8	42.4	67.4	111.5	15.2	914.7	59.6	1101.0
WOOD3	19.1	51.7	75.1	136.3	14.3	1041.1	54.6	1246.3
WOOD4	17.9	59.7	81.8	161.0	13.4	1160.2	49.3	1384.0

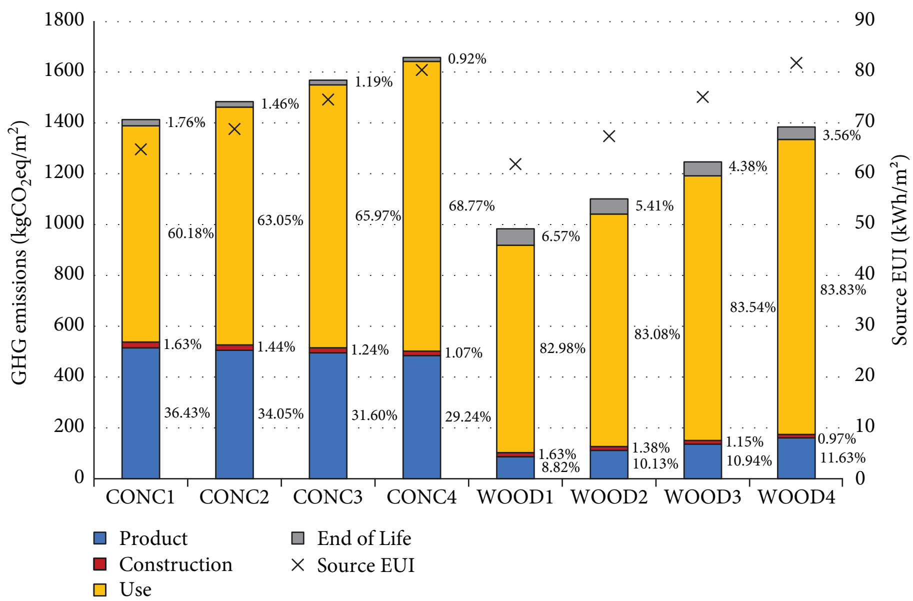


Figure 5: Energy use intensity and greenhouse gas emissions with window-to-wall ratios of concrete and wooden buildings.

to increases in the cooling load owing to solar heat gain rather than heat transfer through the building envelope.

GHG emissions from concrete buildings decreased slightly as the WWR increased from 514.8 $kgCO_2eq/m^2$ for CONC1 (20% WWR) to 484.5 $kgCO_2eq/m^2$ for CONC4 (80% WWR). This reduction could be attributed to the reduced requirements for concrete materials with an increased window area. Conversely, GHG emissions increased from 86.7 $kgCO_2eq/m^2$ (WOOD1) to 161.0 $kgCO_2eq/m^2$ (WOOD4). This increase might be due to the higher embodied energy in the window materials than the wood used in the walls. During the operational stage, the concrete and wooden buildings experienced a significant increase in GHG emissions with larger WWRs, reflecting higher cooling energy consumption due to increased solar heat gains.

The product-stage emissions exhibited contrasting trends between concrete and wooden buildings. In concrete buildings, emissions decreased slightly with increasing WWR due to a reduction in concrete usage, while in wooden buildings, emissions increased as the proportion of window materials increased. As the WWR increased, the amount of concrete used decreased, whereas the quantity of glass increased. Since glass has lower embodied energy and emits less GHG per unit compared to concrete, increasing the window area can lead to a reduction in structural carbon emissions. Conversely, in wooden buildings, although the amount of wood decreases with increasing WWR, the increased use of glass, which has a higher embodied carbon content than wood, increases emissions during production. Both concrete and wooden buildings exhibited increased total GHG emissions as the WWR increased, mainly driven by the higher energy consumption during the use stage for cooling. However, wooden buildings exhibited a more pronounced increase in emissions due to their superior insulation properties, which reduce heat loss but make them more sensitive to cooling loads. The overall trend emphasizes balancing the WWR to optimize energy performance and minimize GHG emissions.

Furthermore, applying sensitivity analysis to the changes in cooling and heating loads from increased WWR provides a clearer understanding of carbon emission variations across

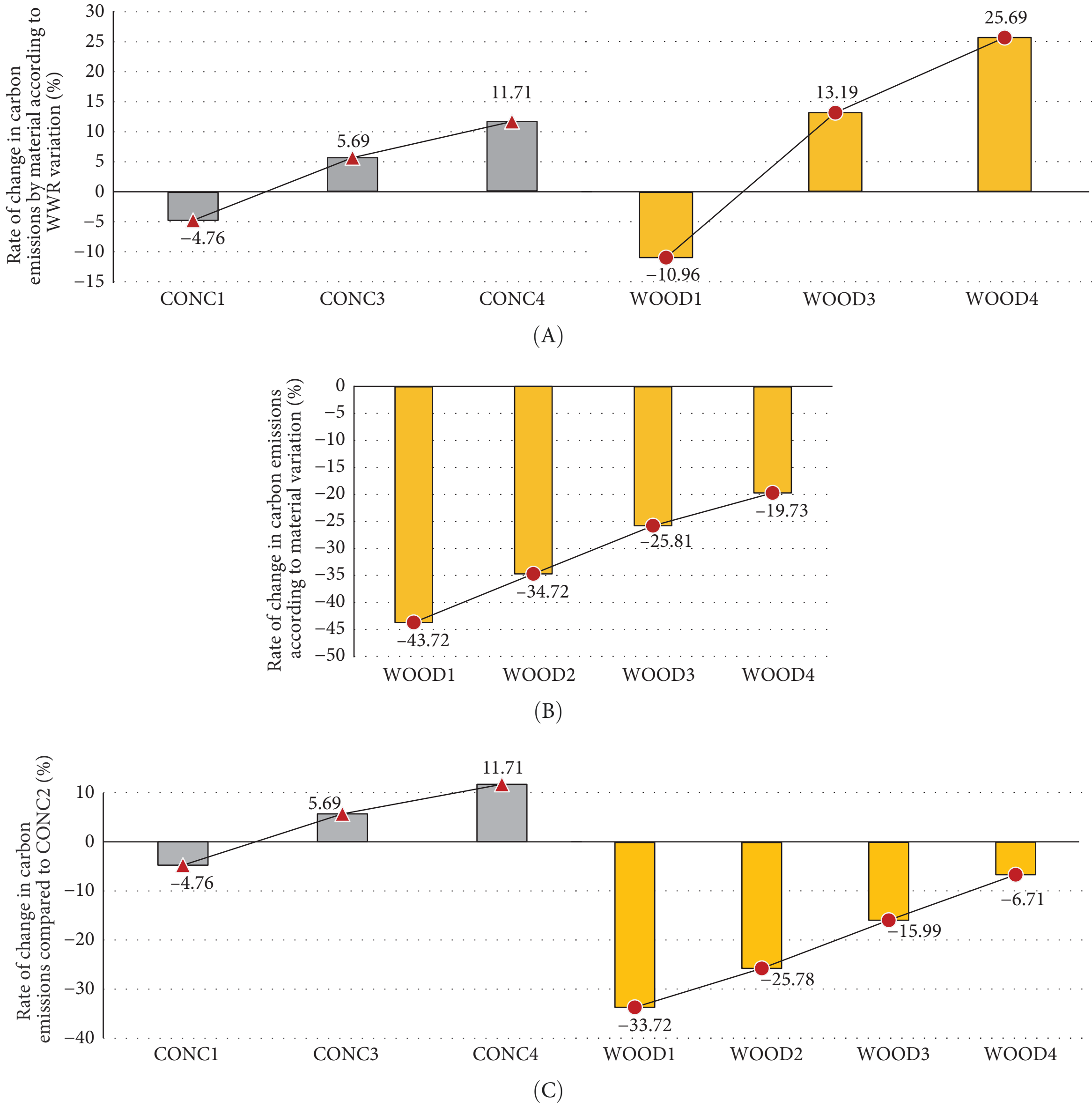


Figure 6: Sensitivity to changes in carbon emissions. (A) Carbon emissions by material according to WWR variation. (B) Carbon emissions according to material variation. (C) Carbon emissions compared to CONC2.

different design options and building types. This approach offers specific design guidelines for achieving carbon neutrality [46]. Integrating changes in carbon emissions based on structure and WWR with a quantitative sensitivity analysis approach provides more precise decision-making support during early design stages. Such an integrated evaluation method can further enhance the effectiveness of carbon emission reduction strategies.

A sensitivity analysis, presented in Figure 6, analyzed the rate of change in carbon emissions due to WWR variations based on a baseline WWR of 20% for each structure. The analysis revealed that wooden buildings were more sensitive to WWR changes than concrete buildings, owing to glass's higher life-cycle carbon footprint than wood. Therefore, maintaining a low WWR is desirable for both structures but particularly critical for wooden structures.

Additionally, the rate of change in carbon emissions due to material variations at a constant WWR was analyzed. The results showed that the rate of change in carbon emissions tended to decrease with increasing WWR. This can be interpreted as a consequence of the high carbon emissions associated with glass. As WWR increases, the quantity of wood decreases, thereby gradually reducing the rate of change in emissions.

Finally, the combined effect of material and WWR variations relative to the baseline (CONC2) was analyzed. The results showed that, despite an increasing WWR, total carbon emissions remained lower in wooden structures than in CONC1. Even in the highest WWR scenario for wooden buildings (Case 4), emissions were still lower than those of the lowest-WWR concrete building. This confirms the crucial role of reducing structural carbon emissions in achieving overall emission reductions.

3.4. Discussions. The LCA evaluation results indicated a significant reduction in overall GHG emissions due to substantial use-stage emissions reductions. Conversely, emissions during the production, construction, and end-of-life stages were comparable to those of low-energy and newly built buildings. Moreover, the overall reduction in emissions increased the total life cycle in these stages. This shift highlights the importance of minimizing emissions from materials used in ZEBs. Therefore, it is crucial to consider the reduction in embodied carbon in materials as an essential factor in designing and constructing ZEBs to enhance their environmental benefits further.

The effects of the material on GHG emissions indicate that concrete buildings generally exhibit higher GHG emissions during the production stage than wooden buildings. This difference can be attributed to the energy-intensive processes involved in the production of concrete and steel reinforcements, which are substantial contributors to emissions. However, wooden buildings, which have lower emissions in the production stage, exhibit a higher end-of-life emission profile. This increase is likely due to the complexities involved in the disposal and treatment of wood, particularly when preservatives or chemicals are used.

Despite the differences in emissions during the various stages, concrete and wooden buildings demonstrated similar trends during the use stage. The use-stage emissions, which span 50 years and include the energy consumption for heating, cooling, lighting, and other plug loads, were notably higher in new buildings than in ZEBs. This observation underscores the effectiveness of the ZEB standards in reducing operational emissions through energy-efficient design and renewable energy integration. Currently, the evaluation of ZEBs excludes the energy consumption by occupants during the operational phase. However, whole-life GHG emissions assessments account for occupant energy consumption, highlighting the need to incorporate this factor in ZEB evaluations. Considering occupant energy consumption is crucial for achieving true carbon neutrality, as it provides a more comprehensive understanding of a building's overall environmental impact.

This study further explored the effects of varying the WWR on the GHG emissions in concrete and wooden buildings. The findings indicate that as the WWR increases, heating energy consumption decreases while cooling energy consumption rises due to increased solar heat gains. Although this study did not vary the solar heat gain coefficient (SHGC) of the windows, the results suggest that both SHGC and *U*-value become critical design factors at higher WWRs. Higher SHGC values can significantly affect cooling loads owing to increased solar heat gains, making it essential to optimize both the SHGC and *U*-value for effective energy management.

For concrete buildings, GHG emissions in the product stage decrease slightly with a higher WWR because of the reduced use of concrete materials and the lower embodied energy in glass than concrete. Conversely, wooden buildings exhibit increased product-stage emissions with a higher WWR, as the embodied carbon in glass exceeds that of wood. This difference highlights the material-specific impacts of WWR adjustments on the carbon footprint of a building. Moreover, both building types showed a marked increase in GHG emissions during the operational phase with increasing WWR. However, this increase was more pronounced in wooden buildings, which are more sensitive to cooling loads because of their lower *U*-values for the building envelope, making them more responsive to solar heat gains. Consequently, the overall emissions from wooden buildings increased more significantly than from concrete buildings as the WWR increased.

This study analyzed the difference in carbon emissions generated during the disposal and recycling process of wood and concrete buildings. Concrete is mainly recycled as aggregate through the crushing, transportation, and processing processes during demolition, but its structural performance is reduced compared to existing concrete, so its use is limited. On the other hand, wood has high recyclability as it can be reused as structural materials, furniture, and plywood through cutting and processing, so it was expected that the carbon emissions of wood at the end of its life would be lower [47].

However, in this study, the carbon emissions of wood structures at the end of their life were higher than those of concrete. This is because CO_2 stored during the disposal process of wood can be re-released when incinerated, and CH_4 can be generated through microbial decomposition when landfilled. Due to these characteristics, if wood is not entirely recycled and a certain amount is disposed of, it is judged that it may have a disadvantageous effect compared to concrete in terms of reducing carbon emissions. It suggests that considering carbon emissions during the disposal and recycling process is an essential factor in assessing GHG emissions throughout the life cycle, and it was confirmed that a strategy to optimize this could contribute to improving the sustainability of buildings [48, 49].

4. Conclusion

This study aimed to evaluate building life-cycle carbon emissions by addressing the limitations of ZEB. To achieve this goal, the study analyzed variations in energy consumption and carbon emissions resulting from changes in the passive element structures and WWR. Concrete and wooden structures were selected to evaluate buildings and assess energy consumption and life-cycle carbon emissions with varying WWR for each structure. The findings are summarized as follows:

1. The investigation into whole-life GHG emissions for certified ZEBs, low-energy buildings, and new buildings revealed 1488.0 kg CO_2eq/m^2, 2184.2 kg CO_2eq/m^2, and 2896.3 kg CO_2eq/m^2, respectively. Analysis revealed that emissions during the operational stage decreased from 81% in new buildings to 64% in certified ZEB, likely owing to the increased use of building materials to lower energy consumption.
2. This study analyzed the GHG emissions due to changes in primary materials using a concrete building (CONC2) as a base model. The total GHG emissions for the wooden building were significantly lower (1101.0 $kgCO_2eq/m^2$) compared to the concrete building (1483.5 $kgCO_2eq/m^2$), representing a reduction of

~25.8%. The greatest differences were observed in the production and end-of-life stages, with concrete buildings having higher emissions in the product stage owing to the energy-intensive production of cement and steel reinforcements.

3. The choice of primary material significantly impacts the life cycle of GHG emissions. Despite higher emissions in the product stage with increased WWR, wooden buildings generally have lower total emissions than concrete buildings. Therefore, using materials with lower embodied energy and emissions is beneficial.

This study illustrates the complex interplay between building materials, design choices (such as WWR), and their cumulative impact on GHG emissions over the life cycle of a ZEB. Material selection, particularly between concrete and wood, plays a crucial role in determining the environmental impact, with concrete contributing more to product-stage emissions and wood showing higher end-of-life emissions. The choice of WWR also significantly influences operational emissions, particularly cooling loads, which can vary considerably depending on the building envelope properties and local climate.

To achieve carbon neutrality and reduce the overall carbon footprint of buildings, optimizing the design strategies that balance energy efficiency and material sustainability is essential. This includes selecting low-carbon materials, optimizing the WWR, and implementing energy-efficient systems. The findings suggest that, although ZEB and other low-energy building standards can effectively reduce operational emissions, a comprehensive approach addressing embodied carbon in materials is necessary for a holistic reduction in GHG emissions.

These results emphasize the need for continuous innovation in building materials and design strategies to reduce embodied energy and operational emissions, fostering a way for more sustainable building practices in the future. Future research will expand carbon emissions assessment under various passive and active conditions and develop strategies for improving energy efficiency. However, limitations in LCA data prevented the inclusion of specific parameters, underscoring the need for more comprehensive datasets in future studies.

To advance carbon-neutral building design, future work will refine the evaluation of indoor comfort by integrating occupant satisfaction with carbon emissions analysis. Additionally, research will explore the impact of material disposal and recycling to optimize end-of-life emissions. By incorporating these factors, we aim to develop a more holistic and precise evaluation method for sustainable building design.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Disclosure

All scientific content and interpretations are the sole responsibility of the authors.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Yong Gi Jung: conceptualization, writing–original draft. **Ji Young Yun:** software, data curation, formal analysis. **Kang Woo Bae:** methodology, data curation, investigation. **Se Hyeon Lim:** data curation, software, resources, visualization. **Min Hee Chung:** supervision, funding acquisition, writing–review and editing. **Jin Woo Moon:** data curation, formal analysis, writing–review and editing. **Jin Chul Park**: data curation, methodology, validation.

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The authors affirm that ChatGPT (OpenAI) was used solely for language editing purposes, particularly for improving grammar and fluency.

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