Article

Quantitative Study on the Life-Cycle Carbon Emissions of a Nearly Zero Energy Building in the Severe Cold Zones of China

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Abstract: This work aimed to quantitatively study the carbon emissions and carbon reduction potential of a nearly Zero Energy Building in a severe cold zone of China from the perspective of its life cycle. The methods were based on China's "Standard for building carbon emission calculation" (GB/T51366-2019), which include the production, transportation, operation, and demolition stages. For the nearly Zero Energy Building, the total carbon emissions over its whole life were 789.43 kg CO₂/m², an 86.20% reduction compared to the 5719.68 kg CO₂/m² for a 65% energy-saving building. The carbon emission percentages of the production stage and operation stage for the building materials are 75.62% and 20.40%, respectively. To enhance the carbon reduction potential, a sensitivity analysis was conducted to explore the impact of the use of a wood structural system, recycled concrete replacement, and photovoltaic power generation. The use of a wood structure system can achieve zero or negative carbon emissions in the production stage. The sensitivity of the carbon emissions of the nearly zero energy building (nZEB) to the increment of photovoltaic power generation is much higher than that of the recycled concrete replacement rate, providing a basis for further exploration of the development of nZEBs into zero carbon buildings.

Keywords: life cycle assessment; carbon emissions; nearly zero energy buildings; potential; sensitivity analysis

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1. Introduction

Energy consumption in buildings is one of the three major sources of energy consumption today. Building energy-saving is especially important for the sustainable development of society as well as environmental protection. The global carbon emissions from building operations amounted to 9.7 Gt of CO₂ in 2018, accounting for 28% of the total global carbon emissions. If the total carbon emissions from the construction industry are taken into account, this would account for 39% of the total global carbon emissions [1]. In China, the carbon emissions from building operations amounted to 2.1 billion tons, while the total carbon emissions from construction amounted to 3.9 billion tons, which accounted for 21.4% and 39.8% of the total carbon emissions for the entire country in 2018, respectively [2,3]. The building sector is attracting more attention due to its energy consumption and carbon emissions [4].

To significantly improve energy-saving in buildings, the European Union (EU) stipulates that all new buildings must be nearly Zero Energy Buildings (nZEBs) by 31 December 2020 [5]. Furthermore, according to the International Energy Agency (IEA), the targets of Zero Energy Buildings (ZEBs) should be achieved by 2030 [6]. The development of nZEBs in Germany mainly relies on the technology system of "Passive House" [7]. In 2013,

relevant regulations were proposed for the “energy-saving method”. From January 2019, all new buildings owned or used by the German government should reach the nZEB level. As of January 2021, all new buildings in Germany have reached the level of nZEBs [8]. Influenced by the EU, Switzerland established the Minergie Association back in 1998 and formulated the first nZEB standard “Mi-nergie”. The emergence of the Minergie-A ZEB Certification Standard in 2011 is of great importance for promoting the development of nZEBs/ZEBs in Switzerland. In 2018, Switzerland issued the energy development plan “Swiss Energy Strategy 2050” and certified the community demonstration of ZEBs [9,10].

The research report “ZEBs: a critical look at the definition” published by the US National Renewable Energy Laboratory in 2006 defines nZEB. In 2009, the United States built a nearly zero energy residential community, Z-Home [11]. Apple’s new headquarters office building was built in 2018 and it is the largest ZEB in the world. Japan proposed a ZEB in the true sense, in 2008, at a meeting of the Cabinet of Japanese Economic Countermeasures, when a plan for the development of ZEBs was formally presented [12]. In 2009, the “ZEB Development and Realization Research Society” of the Ministry of Economy and Industry of Japan was established to popularize and promote ZEBs, and in 2012 it clearly indicated the ZEB technological path to be achieved before 2030 [13]. South Korea’s “ZEB” is defined as requiring that the building “... maximize the thermal insulation performance of the building envelope to minimize energy demand, and then use renewable energy for energy supply, so as to achieve energy self-sufficiency” [14]. In 2013, the Ministry of Industry and Resources of Korea issued a new version of the “Building energy consumption level certification standard”, which issued standards for ZEB certification [15,16].

From the above, it can be seen that developed countries have formulated medium and long-term development goals and policies for buildings to move towards lower energy consumption. Furthermore, they have established technical standards and systems appropriate for their characteristics and promoted buildings to move towards lower energy consumption. This is becoming a trend in the development of global energy-saving in buildings. Germany is part of the EU system, which classifies buildings by primary energy consumption values. The certification of residential nZEBs in the United States and ZEBs in South Korea and Japan determine the grade of buildings based on the relative energy-saving rate [17]. Marszal et al. reviewed the methods for defining and calculating the energy consumption of nZEBs in different zones with the aim of promoting the development of consistent and standardized methods in this field [18]. Overall, the technological path of all countries adopts the strategy of gradual development, i.e., gradual reduction of energy consumption of low-rise buildings, whereby nearly zero energy is achieved first, and then zero energy.

China has become the world’s largest energy producer and consumer [19]. Since 1980, work on energy-saving in buildings has undergone more than 30 years of development and has achieved notable results in reducing the energy consumption needed for heating residential buildings and reduced the energy consumption of public buildings in severe cold and cold zones.

In order to further promote energy-saving in buildings in China and to move towards nZEBs, demonstration projects such as Qinhuangdao ZaiShuiYiFang (Hebei Province), XiShu Garden in Harbin (Heilongjiang Province), and “CABR nearly zero energy demonstration building” of the Academy of Building Research were constructed under the promotion of government departments and have achieved very good energy-saving effects and have had a great social impact since 2011. Since 2017, the state and local governments have introduced policies to encourage the pilot construction of ultra-low energy consumption buildings and nZEBs. The Xu Wei research team of the China Academy of Building Research collects demonstration projects of ultra-low energy consumption buildings in China. Among them, 64 representative demonstration projects built from 2012 to 2019 were analyzed in terms of their technology and economy. They refined the common key technical points of the design, construction, and operation stages of the demonstration projects, thus laying the foundation for the next steps in standards formulation [20]. After almost ten

years of research and exploration relying on foreign experience, and combined with existing Chinese engineering practice, control indicators and technical paths that are suitable for Chinese national conditions and suitable for different climate zones have gradually become clear [21]. In 2019, the “Technical standard for nearly zero energy buildings” was officially proclaimed in the form of national standards for determining the requirements of energy-saving indicators. The construction of nZEBs has taken an important step in reducing the environmental impact of buildings.

Compared to ordinary energy-saving buildings, being an nZEB means that the annual operating energy consumption is close to zero by improving the performance of the envelope to reduce cooling and heating demands, improve system efficiency, and use renewable energy systems [22–24]. For nZEBs, although energy consumption during operation is substantially reduced, the proportion of embodied energy of the building components in the total energy of the whole life cycle is significantly increased compared to ordinary energy-saving buildings [25]. If we blindly and vigorously develop renewable energy production or improve system efficiency, instead of first reducing energy demands as much as possible, this will cause an increase in energy in other stages outside of the operation stage.

Verbeeck and Hens confirmed that the embodied energy in nZEBs is higher than the operating energy, but the total energy consumption is lower than that in ordinary energy-saving buildings [26]. The results of the case study show that even if the ratio of winter heating demands between ordinary energy-saving buildings and nZEBs is 10:1, the ratio of the total energy consumption (embodied energy + operating energy) for 70 years is only 2:1. In 2007, Citherlet and Defaux compared three different energy-saving standards for the same residential building in Switzerland [27]. They confirmed that the final energy of nZEBs will be substantially reduced, but the proportion of the environmental impact over the whole life cycle has changed significantly in the operation stage and other stages. The Swiss energy certification system MINERGIE also limits the maximum embodied energy to 50 kWh/m² per year, which indicates that the embodied energy cannot be neglected.

In 2016, Kristjansdottir et al. noted that carbon emissions associated with the material production stage can reach 60–75% of the total life cycle of nZEBs in Norway [28]. However, it should be emphasized that the reduction of the overall building impact is significant, which means that the impact of operating energy and embodied energy should be considered together, and a comprehensive environmental impact evaluation cannot be achieved with regard to the operating energy of the building only [29,30].

The concept of a nZEB is increasingly being replaced by the concept of a zero-carbon building. According to EN 15978: 2011, the Norwegian Zero Emission Building Research Center provides the definition of a zero-carbon building, in which the equilibrium is measured by the greenhouse gas emissions [31,32]. Moreover, the research perspective of nZEBs is assessed by the “input” energy of the building outside the “operating stage”, while the research perspective of zero carbon buildings is assessed by the “output” carbon emissions from the building into the environment at all stages of the “whole life cycle”. In particular, with a view to carbon neutrality, it is necessary for the building evaluation system to go beyond an energy consumption evaluation and move towards an environmental evaluation. Therefore, the time span of the building assessment is extended to the whole life cycle in order to verify the energy in the operation stage and the embodied energy in the production and transportation stages of the building materials.

There is still a lot of room for development of nZEBs into zero carbon buildings. Scholars such as L. Georges pointed out that zero carbon emissions in operation are easy to achieve, but overall zero carbon emissions including operating energy and embodied energy are difficult to achieve [33]. The use of environmentally friendly materials can substantially reduce the embodied carbon emissions [34]. Zero carbon emissions across the whole life cycle can be achieved by reducing the embodied energy emissions and increasing photovoltaic production [35].

2. Research Contents

At present, mature research on carbon emissions is mainly based on two types. One classification of national carbon emission sources is based on the “IPCC National Greenhouse Gas Guidelines”, which is more comprehensive and extensive [36]. The second carbon emission accounting system is mainly based on the enterprise’s products and projects, mainly including the International Organization for Standardization (ISO) “greenhouse gas verification standard”. However, the carbon emission factor provided by the first algorithm deviates from the actual carbon emission calculation factor of each country. The second type of carbon accounting that places special emphasis on the product has some limitations in regional carbon emissions accounting.

Paleari et al. conducted an environmental analysis of buildings based on the life cycle assessment (LCA) theory and ISO 14040:2006, ISO 14044:2006, EN 15643-2:2011, and EN 1597:2011 [37]. This reference conducts a statistical study of 70 references related to carbon emissions worldwide [38]. Although researchers have done a lot of basic work on carbon emissions, the LCA method and geographical differences lead to incompatibilities in estimating carbon emissions, and urgent action is needed to clarify the confusion in carbon emissions assessment studies.

The Ministry of Housing and Urban–Rural Development, referring to foreign advanced technical standards, summarizes the results of carbon emissions research related to construction and building materials in China. In 2019, China’s “Standard for building carbon emission calculation” (GB/T51366-2019) was proclaimed and implemented. This standard is more suitable for the calculation of a building’s carbon emissions according to the national conditions of China [39]. As this standard was soon published, there is no available literature to inquire about the practice of calculating specific carbon emissions according to this standard. The use of this carbon emission standard for the quantitative analysis of carbon emissions of current ordinary energy-saving buildings and nZEBs in China is still missing.

To solve this problem, we take an office building in Changchun city, Jilin province, which is located in a severe cold zone, as our research object. This building achieves the goal of a nZEB through the national “Technical standards for nearly zero energy buildings” certification. We explore the carbon emission characteristics at each stage within a “building carbon emission calculation standard” system, which not only analyzes the carbon saving potential compared to ordinary energy-saving buildings, but also seeks to use low-carbon building materials or increase the use of renewable energy to achieve the goal of life-cycle carbon reduction and provides the technical basis for the further development of nZEBs into zero carbon buildings.

3. Research Methods

3.1. Life Cycle Assessment and Carbon Emission Calculation Standards

The LCA theory is usually used to evaluate the resource consumption and environmental impact of a product during its life cycle. Since it was proposed in 1990, it has been recognized as an important tool for evaluating the environmental impact of products. The building, as a product, is constantly flowing in and out of energy and materials. This process will be followed throughout the life cycle of the building, and there are different levels of environmental impacts at different stages. The whole life cycle of a building includes not only the traditional process from construction to operation, but also the extraction and production of building materials. After the operation of the building, there are additional stages, such as the demolition and cleaning of the building and the recovery and reuse of resources. The whole process is said to be from “cradle” to “grave” [40,41].

At present, the assessment of carbon emissions in construction in China is mainly based on the life cycle assessment of ISO standards. Through a qualitative evaluation of buildings and the experimental calculations of representative buildings, we progressively explore a common methodological standard for calculating the carbon emissions from buildings [42]. The Ministry of Housing and Urban–Rural Development summarized

the research results on carbon emissions related to construction and building materials in China and drew on foreign normative standards and achievements to promulgate the “Standard for building carbon emission calculation” (GB/T 51366-2019). The whole life cycle is divided into three stages: the production and transportation of building materials, construction and demolition, and the operation of buildings. The calculation method for carbon emissions in the different stages is also given [39].

3.2. Case Study

The object of the study is a nZEB located in a severe cold zone. The exterior of the building is shown in Figure 1.

Figure 1. Building exterior view.

The building functions as two offices, two classrooms, and four laboratories. The geometric characteristics of the building are shown in Table 1.

Table 1. The main geometric characteristics of the study object.

Description	Numerical Values
Total floors	2
Total construction area (m ²)	1180
Heating volume (m ³)	3150
External wall area (m ²)	592
Roof area (m ²)	425
Window and exterior door area (m ²)	92.4

The building adopts a high-performance envelope, thermal bridges, and air tightness treatment to reduce the cooling and heating requirements, and the specific parameters are shown in Table 2.

Table 2. Envelope performance parameters of the research object.

Building Envelopes	Structural Parameters	Value W/m ² K
External wall	190 mm block + 140 mm Expanded Polystyrene (EPS) insulation board + 80 mm rock wool + 50 mm thermal insulation mortar + 12 mm inorganic resin decoration panel	0.1
Ground	40 mm fine aggregate concrete + 80 mm concrete cushion + Insulation of extruded board with 50 mm thickness in 2000 mm wide range around external wall + 80 mm gravel filled with cement mortar	0.1
Roof	300 mm Expanded Polystyrene (EPS) insulation board + 200 mm reinforced concrete roof panel	0.1
Window	The frame is a combination of imported solid wood and thermal insulation materials Three-glass two-cavity double low-E argon-filled hollow glass	0.8

At the same time, solar, wind, and geothermal energy are used to form a multi-energy complementary system to meet the load demand, as shown in Table 3.

Table 3. Research object renewable energy system.

Renewable Energy Systems	Equipment and Specifications	Quantities	Nominal Parameter
PV power generation system	Polycrystalline silicon photovoltaic panels/LN240(30)-3-250	112 pieces	28 kW
Solar Thermal System	Heat pipe solar collector/Z-QB/20-58	48 groups	158.4 m ²
Breeze power generation system	Breeze force generator set/CXF-600 Wdn150	4 sets	2.4 kW
Ground Source Heat Pump System	Capacity with cooling 62.5 kW and heating 46.5 kW	1 set	62.5 kW/46.5 kW

In this study, a nZEB in good operational condition and its energy consumption are based on field measurements. The measurement data were derived from the energy monitoring platform provided at the time of project construction (Figure 2). According to the requirements of the “Technical standard for nearly zero energy buildings” (GB/T 51350-2019) [43], key parameters of the indoor environment and energy consumption of the building classification are monitored and recorded.

Figure 2. Interface diagram of energy monitoring platform.

The energy monitoring platform was based on the WCCV10-7.3 software (Changchun, China; the software version used is 7.3) system developed by the school–enterprise cooperation. The platform mainly completes the monitoring and recording of the following data: (I) All kinds of energy classification items are calculated; (II) Monitoring of indoor environmental parameters; (III) Monitoring of outdoor environmental parameters; and (IV) Energy consumption of renewable energy system is measured separately. The collection of energy consumption data in this study was from October 2019 to September 2020, covering the heating season (October 2019–April 2020) and the cooling season (July–August 2020). In 2020, it obtained the certificate based on the “Evaluation standard for nearly zero energy buildings” (T/CABEE JH-2019004) [44]. The requirements for energy efficiency were met, as shown in Table 4.

To further analyze the carbon emissions more comprehensively over the whole life cycle, we compared the nZEB with an 65% energy-saving building (the 65% energy-saving building is explained in Appendix A).

The carbon emissions of the two types of buildings are calculated based on a life cycle evaluation [39] and the carbon emission characteristics of the two buildings at various stages are compared. The specific calculations are shown in Table 5.

Table 4. Energy efficiency index of research objects.

Project	Numerical Number	Standard Requirements	Whether to Meet the Requirements
Comprehensive building energy efficiency rate (%)	163.70	$\geq 60\%$	Satisfy
Renewable Energy Utilization Rate (%)	135.01	$\geq 10\%$	Satisfy
Ontology of Architecture Energy Conservation rate (%)	82.85	$\geq 10\%$	Satisfy
Ventilation rate N_{50}	0.60	≤ 1.0	Satisfy

Table 5. Calculation basis of carbon emission in each stage.

Building Type	Design Standards	Data Acquisition	Calculation Basis
65% Energy-saving building	“Design Standard for Energy Efficiency of Public Buildings (Energy-Saving 65%)” (DB22/JT 149-2016)	The 65% energy-saving building was simulated using eQUEST software (San Francisco, USA; the software version used is 3.6.5), and data collection was extracted from the building information model (BIM) available in the project	Standard for building carbon emission calculation (GB/T 51366-2019)
nZEB	“Technical Standard for Nearly zero Energy Buildings”(GB/T51350-2019)	Invoices paid by builders, quantities of construction operations and consumed materials in construction site reports, and design drawings obtained, and energy consumption data collected by energy monitoring platforms	

4. Carbon Emission Calculation Results and Analysis

4.1. Carbon Emissions in the Production and Transportation Stages of Construction Materials

4.1.1. Building Materials Production Stage

The calculation equation of the carbon emissions during the production of building materials is shown in Equation (1).

$$C_{sc} = \sum_{i=1}^n M_i F_i \quad (1)$$

In Equation (1), C_{sc} is the carbon emission in the production stage of building materials (kg CO_2); M_i is the consumption of main building materials (i); F_i is the carbon emission factor of the i type building material ($\text{kg CO}_2/\text{unit number of building materials}$).

The data collection of building material consumption for the nZEB and 65% energy-saving building in this study was based on Table 5 (above), and the main building material carbon emission factors were obtained from references [39,45].

The results of the main carbon emission factors, building materials consumption, sub-items, and total carbon emissions are shown in Table 6.

Table 6. Carbon emissions in the production stage of building materials for two types of buildings.

Building Types	Building Materials	Carbon Emission Factors	Consumption of Building Materials	Sub-Items Carbon Emissions kg CO ₂ /m ²	Subtotal of Carbon Emissions kg CO ₂ /m ²
65% Energy-saving building	Concrete	320 kg CO ₂ /m ³	1258 m ³	341.15	595.33
	Reinforcement	2617 kg CO ₂ /t	109 t	241.74	
	Polystyrene	4.487 kg CO ₂ /kg	1325 kg	5.04	
	Low-E glass	1071 kg CO ₂ /t	0.38 t	0.34	
	Alloy window Frame	253.7 kg CO ₂ /m ²	32.8 m ²	7.06	
nZEB	Concrete	320 kg CO ₂ /m ³	1258 m ³	341.15	596.98
	Reinforcement	2617 kg CO ₂ /t	109 t	241.74	
	Polystyrene	4.487 kg CO ₂ /kg	2484 kg	9.45	
	Low-E glass	1071 kg CO ₂ /t	0.56 t	0.51	
	Wood window frame	147 kg CO ₂ /m ²	32.8 m ²	4.09	
	PV photovoltaic panels	2 kg CO ₂ /kW	28 kW	0.05	

4.1.2. Building Materials Transportation Stage

The carbon emission basis for the transportation stage of the construction materials is shown in Table 7.

Table 7. Construction material transportation stage calculation basis.

Transport Stage	Sub-Items	Basis
The transportation of building materials from the place of production to the site of construction	Mining and processing of energy consumed during the transportation of building materials	Calculation
	Production of transportation vehicles	The influence of incomplete basic data is small and can be ignored
	Construction of infrastructure such as transportation roads	

The calculation of the carbon emissions in the transportation stage of the building materials is shown in Equation (2).

$$C_{ys} = \sum_{i=1}^n M_i D_i T_i \quad (2)$$

In the equation, C_{ys} is the carbon discharge over the transportation of construction materials (kg CO₂); D_i is the average transportation distance (km) of the building materials; The carbon emission factor [kg CO₂/(t·km)] for the transport distance per unit weight when T_i is the transport mode of the i type building materials.

According to the standard, the default transportation distance of concrete is 40 km and the default transportation distance of the other building materials is 500 km. In this study, a medium-sized (8 t load capacity) diesel vehicle was selected for transport and the carbon emission factor was 0.179 kg CO₂/(t·km) for the calculation. The carbon emissions of the transportation of various building materials are calculated according to the consumption of the building materials, and the calculated results are shown in Table 8.

Table 8. Carbon emissions in the transportation stage of building materials.

Building Types	Building Materials	Transport Weight t	Transportation Distance km	Sub-Items Carbon Emissions kg CO ₂ /m ²	Subtotal of Carbon Emissions kg CO ₂ /m ²
65% Energy-saving building	Concrete	3019	40	18.32	26.74
	reinforcement	109	500	8.27	
	Polystyrene	1.33	500	0.10	
	Low-E glass	0.38	500	0.03	
	alloy window Frame	0.26	500	0.02	
nZEB	Concrete	3019	40	18.32	27.04
	reinforcement	109	500	8.27	
	Polystyrene	2.48	500	0.19	
	Low-E glass	0.56	500	0.04	
	wood window frame	0.98	500	0.07	
	PV photovoltaic panels	1.96	500	0.15	

Based on the above calculations, the carbon emissions from the production and transportation of the construction materials are 622.07 kg/m² and 624.02 kg/m² for the 65% energy-saving building and the nZEB, respectively. The carbon emission of the nZEB is increasing slightly, but the difference is not significant.

4.2. Carbon Emissions in the Operation Stage

The carbon emissions in the operation stage mainly refer to the energy emissions from the process of building use, which covers the heating, refrigeration, outdoor air, domestic hot water, lighting, renewable energy, carbon sink of buildings, etc. The carbon emissions in the operation stage of the building should be determined according to the different energy consumption types of each system and the carbon emission factors of the different energy consumption types, and the total carbon emissions per unit of building area are calculated via Equations (3) and (4).

$$C_M = \frac{\left[\sum_{i=1}^n (E_i EF_i) - C_p \right] y}{A} \quad (3)$$

$$E_i = \sum_{j=1}^n (E_{i,j} - ER_{i,j}) \quad (4)$$

where C_M is the total carbon emissions during the operation stage (kg CO₂/m²); E_i is the annual energy consumption of the i type (unit/a); EF_i is the carbon emission factor of the i type; $E_{i,j}$ is the energy consumption of the i type of system j (unit/a); $ER_{i,j}$ is the energy consumption of the i type provided by the renewable energy system j (unit/a); i is the energy consumption type; j is the type of energy system; C_p is the annual carbon reduction of the green space carbon sink (kg CO₂/a); y is the design life cycle of the building (a), taken as 50 years; and A is the building area (m²).

The nZEB used the actual data from the 2019–2020 energy monitoring platform, and the 65% energy-saving building was simulated using eQUEST software (San Francisco, USA; the software version used is 3.6.5), as shown in Table 9.

Table 9. The energy use intensity of the two types of buildings in operation (kWh/m²a).

Building Type	Heating	Refrigeration	Outdoor Air	Lighting	PV Power	Energy Consumption
65% Energy-saving building	45.06	16.15	21.71	11.59	0.00	94.51
nZEB	16.08	9.28	4.56	6.34	31.71	4.56

According to the carbon emission factor values in Reference [39], the different energy consumptions are converted into the carbon emissions of the buildings and the carbon emissions at all stages of the whole life cycle are summarized. The results are shown in Table 10.

Table 10. Carbon emissions of the two types of buildings in operation.

Building Type	Energy Consumption Convert to Carbon Emissions kg CO ₂ /m ² a	Green Space Carbon Sin kg CO ₂ /m ² a	Annual Carbon Emissions kg CO ₂ /m ² a	Whole Life Cycle Carbon Emissions kg CO ₂ /m ²
65% Energy-saving building	103.64	1.78	101.86	5093.22
nZEB	5.00	1.78	3.22	161.02

4.3. Carbon Emissions during Construction and Demolition

The carbon emissions during the construction stage should include the carbon emissions resulting from the completion of each part of the sub-construction and the implementation of various measures. The key is to determine the consumption of electricity, gasoline, diesel, gas, and other energy sources during the construction stage. The carbon emissions during the demolition stage are mainly the energy consumption from the process of dismantling the buildings by equipment on site.

However, judging from the recent literature, since data on these two stages are not easy to obtain and considering the whole life cycle, the carbon emissions during the construction and demolition stages account for a relatively small proportion overall [46,47]. Given the difficulty of obtaining data and the small proportion, they are generally ignored or estimated. This case adopts the estimation equation of the building construction stage given in the literature [48] and shown in Equation (5).

$$C_{JZ} = X + 1.99 \quad (5)$$

where C_{JZ} is the carbon emission per unit of building area in the construction stage (kg CO₂/m²); X is the number of floors of the building. According to Equation (5), the carbon emission in the construction stage is 3.99 kg CO₂/m² after substituting the number of floors, $X = 2$. In the absence of relevant data for the demolition stage, it can be assumed that 10% of the construction stage is 0.40 kg CO₂/m² according to the relevant literature. For both types of buildings, the carbon emission is 4.39 kg CO₂/m².

4.4. Total Carbon Emissions in the Whole Life Cycle

The total carbon emissions and their proportion in the whole life cycle are shown in Table 11.

As seen in Table 11, the carbon emissions of the nZEB are greatly reduced compared with 65% energy-saving buildings. The carbon emissions for the whole life cycle are 789.43 kg/m², compared with the 65% energy-saving building's, which are 5719.68 kg/m²—a reduction of 86.20%. It can be seen from Table 11 that, over the whole life cycle, the nZEB has a very obvious carbon reduction advantage in the operation stage.

As seen in Figure 3, for the 65% energy-saving building, the largest proportion of carbon emissions in the whole life cycle is in the operation stage, which accounts for 89.05%, followed by the production stage, which accounts for 10.41%.

Table 11. Total life-cycle carbon emissions of the two buildings.

Various Stages	Energy-Saving 65% Building		nZEB	
	Carbon Missions kg CO ₂ /m ²	Proportion	Carbon Missions kg CO ₂ /m ²	Proportion
Building materials production	595.33	10.41%	596.98	75.62%
Building materials transportation	26.74	0.47%	27.04	3.43%
Operation	5093.22	89.05%	161.02	20.40%
Construction	3.99	0.07%	3.99	0.51%
Demolition	0.4	0.01%	0.4	0.05%
Total	5719.68	100.00%	789.43	100.00%

Figure 3. Proportions of life-cycle carbon emissions at different stages of the 65% energy-saving building.

As seen in Figure 4, for the nZEB, the largest proportion of carbon emissions in the whole life cycle is not in the operation stage, but in the building material production stage, which accounts for 75.62%, followed by the operation stage, which accounts for 20.40%.

Figure 4. Proportions of life-cycle carbon emissions at different stages of the nZEB.

5. Carbon Reduction Potential Analysis

According to the analysis of the carbon emissions data in Section 4.4, to achieve further carbon reduction over the whole life cycle of a nZEB, the focus should be on the production stage. The production stage of the building materials is mainly reflected in the energy of the material itself, i.e., the embodied energy. The priority of using low-carbon materials

and replacing materials has become the trend in carbon reduction. The role of material replacement in energy-saving in buildings and carbon reduction is reviewed in article [49].

Reddy shows that the use of material substitution technology can reduce the embodied energy of buildings by about 50% [50]. Thormark describes how the choice of materials affects the embodied energy of one of Sweden's most energy-saving housing projects. The studied object is the Swedish scheme within the CEPHEUS project in the European Thermie programme [51]. Initially, the embodied energy accounted for 40% of the total energy needed for a 50-year life cycle. Embodied energy can be reduced by about 17% by replacing the material. Habert and Roussel evaluated a sustainable concrete mixture, which is designed to replace clinker in cement with mineral additives in order to reduce the environmental cost of materials needed for a certain volume of concrete. Improving the concrete replacement levels can reduce 15% of carbon dioxide emissions [52]. Research by Buchanan and Levine shows that wooden buildings consume less process energy than other materials, such as steel and concrete, resulting in lower carbon emissions [53].

The latest research collected and collated the embodied energy and carbon emissions of various building materials, including 47 studies on concrete material, 26 studies on steel material, 32 studies on brick material, 22 studies on geotechnical material, and 17 studies on wood material [54]. As the most studied material, concrete can be mixed with other materials. Following the summary, the general situation and scope of the embodied energy and embodied carbon emissions of different materials are reported at the material level, which is a valuable reference to scholars in different countries to conduct further research.

In order to further reduce the carbon emissions of nZEBs, the following will explore specific measures to reduce carbon by giving priority to the use of low-carbon materials and local renewable energy.

5.1. Analysis of the Influencing Parameters

5.1.1. Adopt a Timber Structure

Compared to traditional concrete and other high-energy-consumption building materials, timber is an environmentally friendly building material that can achieve a negative overall carbon footprint. Given that CO₂ can be aggregated and fixed during the growth of trees, its carbon emission factor is negative. Therefore, promoting the use of timber is also an important means of reducing carbon emissions. In order to further explore the carbon reduction potential of this nZEB, a timber structure system is assumed to be used for the carbon emission analysis. The carbon emissions of different tree species at the production stage are different, and, in this study, two types of wood—northeastern fir and northeastern larch—were selected for analysis. Considering that the geographical characteristics are in close proximity to the northeastern species [55,56], the carbon emissions during the production stage were $-32.25 \text{ kg CO}_2/\text{m}^3$ and $-374.41 \text{ kg CO}_2/\text{m}^3$. The calculation results are shown in Table 12.

With the adoption of a timber structure, the carbon emissions in the building material production stage are -56.23 and $168.78 \text{ kg CO}_2/\text{m}^2$, and the carbon emissions in this stage can achieve zero or negative values. Assuming the same carbon emissions for the other stages for previous nZEBs, the total carbon emissions are 136.22 and $361.23 \text{ kg CO}_2/\text{m}^2$, which are 82.74% and 54.24% lower than the previous $789.43 \text{ kg CO}_2/\text{m}^2$.

Table 12. Carbon emissions in the production stage of building materials.

Building Types	Building Materials	Carbon Emission Factors kg CO ₂ /m ²	Quantity of Work	Carbon Emissions kg CO ₂ /m ²	Subtotal of Carbon Emissions kg CO ₂ /m ²
Timber building	Northeast fir	−374.41 kg CO ₂ /m ³	776 m ³	−246.22	Northeast fir timber structure
	Northeast larch	−32.25 kg CO ₂ /m ³		−21.21	
	Concrete	320 kg CO ₂ /m ³	436 m ³	118.24	−56.23
	Reinforcement	2617 kg CO ₂ /t	26 t	57.66	Northeast larch timber structure
	Polystyrene	4.487 kg CO ₂ /kg	2484 kg	9.45	168.78
	Low-E glass	1071 kg CO ₂ /t	0.56 t	0.51	
	wood window frame	147 kg CO ₂ /m ²	32.8 m ²	4.09	
	PV panels	2 t/kW	28 kW	0.05	

5.1.2. Adopt Low-Carbon Building Materials

Concrete accounts for the largest proportion of building materials' carbon emissions, so we should choose low-carbon materials such as recycled concrete as a replacement. Recycled concrete is distinguished by the mechanical, fire-resistant, and seismic properties of its components, which are basically equivalent to those of ordinary concrete. However, through the integrated use of waste concrete, we can minimize energy consumption and reduce greenhouse gas emissions. The authors of [57] studied the life-cycle carbon emission of recycled concrete. The carbon emission factor of recycled concrete used in this paper is 314.2 kg CO₂/m³, which is compared with the carbon emission factor of 320 kg CO₂/m³ of ordinary concrete that is used in the nZEB in Table 6.

5.1.3. Increase the Area of Photovoltaic Panels

For nZEBs, the application of photovoltaic power generation is an important way to achieve zero emissions in their operation stage, especially for the whole life cycle. Although an increase in photovoltaic panels will lead to an increase in the production of building materials, it has a more important impact on reducing the carbon emissions in the operation stage. One way to do this is through a carbon sink that is brought by renewable energy production in the operation stage, the other is the calculation of the carbon emissions over the whole life cycle of the operation stage, which is calculated based on a building life of 50 years.

The number of PVs in this project has been sufficient to supply energy only to theoretically study the impact of PV increases on carbon emissions.

5.2. Sensitivity Analysis

Sensitivity analysis studies help us to understand the impact of various design parameters on carbon emissions throughout the whole life cycle of a building and determine which parameters are the key factors affecting carbon emissions. For the nZEB studied in this paper, the whole life carbon emissions of the building were selected as the output parameter, and the recycled concrete replacement rate and photovoltaic panel power increment were selected as the input parameters for the sensitivity analysis.

A sensitivity analysis is an uncertainty analysis technique, analyzing the relevant factors from a quantitative perspective and considering the degree of impact on relevant key indicators when changes occur. The evaluation index is the sensitivity coefficient, which is calculated by the Equation (6).

$$S_i = \frac{(\Delta L / L_n)}{\Delta P_i / P_{i,n}} \quad (6)$$

where: S_i is the sensitivity coefficient; ΔP_i is the change of input parameter, $\Delta P_i = P_i - P_{i,n}$; P_i is the value of the input parameter; $P_{i,n}$ is the base value for each input parameter

i ; $\Delta L = L_i - L_n$; L_n is the reference value of the output parameter. The sensitivity coefficient represents the percentage of the “relative change in result” relative to the “relative change in a given input parameter”. If the value of a parameter is 0.5, it means that when its value increases by 10% the final result increases by 5% [58]. The higher the absolute value of the sensitivity coefficient, the greater the impact of the input parameters on carbon emissions and, therefore, the more important the parameter.

5.3. Analysis of Results

The recycled concrete replacement rate and PV panel power generation increment are all considered in 20% step changes—that is, the input parameter changes from 0% to 20%, then 40%, 60%, 80%, and 100% based on the existing parameter benchmark values. The carbon emission accounting is re-performed according to Equations (1)–(5), and the calculation results are shown in Figure 5.

Figure 5. Calculated results of carbon emissions under different parameter changes.

According to the above carbon emission accounting results, it can be seen that, with an increase in the amount of change, carbon emissions have all decreased to varying degrees, and the substitution of recycled concrete in the building materials and the increase in PV area have all had an impact on the whole life cycle carbon emissions of nZEBs. From the example data in Figure 5, it can be seen that the increase in PV panels will significantly reduce the carbon emissions, and when the PV panels are increased by 60% or more, the whole life cycle carbon emissions will have reached zero or negative values.

However, the results show that although parameter changes will reduce carbon emissions, the degree of impact is different. The impact of the change in each parameter is evaluated, and the sensitivity analysis is performed according to Equation (6). The results of the analysis are shown in Table 13.

The sensitivity coefficients in Table 13 are negative, which means that the carbon emissions decrease with increasing values of the design parameters. However, the influence of various design parameters is different. The sensitivity coefficient of the photovoltaic power increase is nearly 80 times the sensitivity coefficient of the recycled concrete replacement rate; that is, the sensitivity of the photovoltaic power increase to carbon emission reduction is relatively higher.

Table 13. Sensitivity analysis and calculation results.

Sensitive Parameters	P_i	ΔP_i	$\Delta P_i/P_{i,n}$	L_i	ΔL	$\Delta L/L_n$	Sensitivity Factor S_i	Average Value of S_i
PV power increments	33.6	5.6	0.2	441.82	−347.61	−0.319	−1.595	−1.603
	39.2	11.2	0.4	94.51	−694.92	−0.638	−1.594	
	44.8	16.8	0.6	−252.95	−1042.38	−0.956	−1.594	
	50.4	22.4	0.8	−638.55	−1427.98	−1.31	−1.638	
	56	28	1	−947.87	−1737.3	−1.594	−1.594	
Recycled concrete re-placement rate	0.2	0.2	0.2	786.47	−2.96	−0.004	−0.019	−0.020
	0.4	0.4	0.4	783.50	−5.93	−0.008	−0.019	
	0.6	0.6	0.6	780.53	−8.9	−0.011	−0.019	
	0.8	0.8	0.8	777.57	−11.86	−0.015	−0.019	
	1	1	1	769.60	−19.83	−0.025	−0.025	

For achieving zero carbon emissions over the whole life cycle, through blindly adding photovoltaic panels or other embodied energy-saving devices—although the energy consumption during the operation stage is apparently offset—the embodied energy of the equipment and building materials will also increase accordingly. However, from a whole life cycle perspective, it is particularly difficult to know whether to reduce carbon emissions or not. Quantifying the carbon emission results of the different types of structures based on the comparison of carbon emissions of different building types can provide a reference for designers.

6. Conclusions

1. From the perspective of the whole life cycle evaluation theory, based on the “Standard for building carbon emission calculation” (GB/T 51366-2019), we calculated the carbon emissions of a nZEB built in a severe cold zone and certified it at each stage and analyzed the carbon emission characteristics of each stage. From high to low, the building materials production stage accounted for 75.62%, the operation stage accounted for 20.40%, the building materials transportation stage accounted for 3.43%, and the construction and demolition stage accounted for 0.56%; these proportions are very different from those of a 65% energy-saving building.

2. We conducted a horizontal comparative analysis of the carbon emissions of a nZEB and a building of the same size implementing the current local energy-saving standard of 65%. The life cycle carbon emissions of a nearly zero energy building are 789.43 kg/m². Compared with the 5719.68 kg/m² of a 65% energy-saving building, the carbon emissions were reduced by 86.20%. It can be seen that the outstanding advantage of nZEBs in terms of carbon reduction is also the only way for buildings to achieve zero carbon.

3. The largest proportion of carbon emissions in 65% energy-saving buildings was in the operation stage, accounting for 89.05%, and its carbon emissions were 5093.22 kg/m²; if 65% energy-saving buildings want to reduce carbon emissions; the most effective way is to reduce the carbon emissions in the operation stage. The nZEB in this study has reduced the carbon emissions in the operation stage to 161.02 kg/m², a decrease of 96.84%, through measures such as high-performance envelope structures, high-efficiency equipment, and the use of renewable energy, and the carbon reduction advantage in the operation stage is particularly obvious.

4. Considering the whole 50-year life cycle of the building, the total carbon emissions of the nZEB are 789.43 kg/m², which is still far from zero. The carbon reduction potential of nZEBs should be placed first in the production stage of the building materials, followed by the operation stage. The nZEB is further analyzed for its carbon reduction potential by adopting timber structures and recycled concrete and increasing the photovoltaic power pathways, and the impact of these different parameters is quantified using sensitivity analysis methods to provide a reference for designers.

5. Through the study and analysis of the carbon emissions of nZEBs in severe cold zones, we can understand the current situation of carbon emissions in the production and transportation of building materials, construction and demolition, and operation stages under the current standard in China. Although the research perspective is different, it is consistent with the goals of the carbon neutral strategy. Our research also provides a case study for the next step of promoting zero carbon buildings in different climate zones. To realize the transition from nZEBs into zero carbon buildings, a stronger strategic focus on low-carbon structural systems, low-carbon building materials, and renewable energy use than currently exists is required.

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Appendix A

According to China's staged building energy-saving policy, the energy consumption level of local general design from 1980 to 1981 is the benchmark. The first stage (1986–1995) saves 30 percent of the energy consumption benchmark. The second stage (1996–2004) saves 30 percent more energy on the basis of meeting the requirements of the first stage, which is equivalent to 50 percent of the total energy consumption benchmark (30 percent + 70 percent $\times$ 30 percent $\approx$ 50 percent). Since 2005, the energy consumption level of the third stage should be saved by 30% on the basis of the second stage, which is equivalent to 65% of the total energy consumption benchmark (50% + 50% $\times$ 30% = 65%). 65% Energy-saving buildings are to meet the requirements of the third stage of the energy consumption level, which referred to as a 65% energy-saving building.

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