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Energy Consumption and Carbon Emissions of Nearly Zero-Energy Buildings in Hot Summer and Cold Winter Zones of China

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Abstract: Issues of energy efficiency and sustainability in buildings are gaining increasing attention in the context of the "3060" dual-carbon initiative. In recent years, nearly zero-energy buildings (nZEBs) have emerged as a potentially viable solution to the challenges of the energy crisis in the building sector, and it is important to study the factors influencing their energy consumption and carbon emissions. However, existing research lacks analyses of multifactor interactions, and the problem of high energy consumption has not been sufficiently addressed. Taking a typical residential building in the Yangtze River basin as the study subject, this study, jointly funded by the University of Nottingham and Hubei University of Technology, proposes a hybrid approach that combines building energy simulation and orthogonal experiments to investigate factors pertaining to buildings, people, and the environment to identify key influencing factors and explore the energy consumption and carbon emission characteristics of residential buildings in hot summer and cold winter (HSCW) zones. Our findings reveal the following: (1) The use of renewable energy sources, such as solar photovoltaic power generation and solar hot water, and renewable energy systems such as ground-source heat pumps, in the operation phase of a baseline building can result in a 61.76% energy-saving and a 71% renewable energy utilization rate. (2) To more easily meet the requirements of nZEB standards, it is recommended to keep K_E within the range of 0.20–0.30 W/(m^2·K), K_R within the range of 0.15–0.20 W/(m^2·K), and VT within the range of 0.6–0.7 h^{-1}. This study will help to identify the critical factors affecting energy consumption and provide a valuable reference for building energy efficiency in HSCW zones.

Keywords: nearly zero-energy buildings; residential building; building energy consumption; carbon emissions; orthogonal experiment

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1. Introduction

In recent years, global warming has become increasingly prominent due to heightened energy consumption, drawing widespread attention from governments, international organizations, and individuals worldwide. As a significant contributor to both energy consumption and carbon emissions on a global scale, the construction sector is responsible for approximately 40% of total carbon emissions and 36% of final energy consumption [1]. The high concentration of populations due to rapid economic development and urbanization will lead to an increase in the number of residential buildings, and in the corresponding energy demand and consumption, which are predicted to grow by 50% by 2060 [2,3], inevitably leading to increasingly serious environmental problems. Reducing energy consumption in residential buildings is the key to energy efficiency in the building sector, and the adoption of new technologies and strategies to address the issues of energy efficiency and energy demand in buildings is becoming urgent [4]. In this context, the adoption of nearly zero-energy buildings (nZEBs), which feature high-performance envelope structures, high airtightness, energy-efficient devices, and renewable energy utilization, has emerged as an important and effective approach to reducing energy consumption and achieving energy efficiency in buildings [5]. In recent years, nZEBs have received extensive attention in developed countries [6], and European Union countries have mandated that all new buildings must be nZEBs, starting from 2020. Similarly, countries such as Germany, the United States, and Japan have subsequently established a series of nZEB technical standards and development pathways tailored to their respective national characteristics in response to the increasing energy consumption in the building sector [7,8]. Because nearly zero-energy buildings (nZEBs) cannot only reduce energy consumption and environmental pollution, but also lower building operational costs and enhance occupants' comfort and quality of life, they have also received extensive attention from Chinese scholars.

Hot summer and cold winter (HSCW) zones are mainly located in the middle and lower reaches of the Yangtze River, covering an area of about 1.8 million square kilometers, with a resident population of about 550 million and a gross domestic product that accounts for about 48% of the country's goods and services, making it one of the most densely populated and fastest growing economic zones in China [9]. These zones are hot in summer and cold in winter and less comfortable than other zones of the world at the same latitude, resulting in higher building heating and cooling demands than other climatic zones and making the goal of nearly zero-energy consumption difficult to achieve. With the rapid economic development and rising living standards of people living in these zones in recent years, energy consumption and carbon emissions caused by improving indoor environments to meet human comfort requirements have been increasing, leading to rapid growth in energy demand and a significant increase in energy consumption. Against the background of rapid economic development and energy shortage, nZEBs are becoming increasingly popular and are recognized for their ability to provide clean energy to buildings through the use of renewable energy, effectively reducing energy consumption and carbon emissions [10,11], and are gradually becoming an inevitable trend in the future development of the building sector in China. However, governments around the world have developed many policies to reduce building energy consumption generated by heating equipment, meaning that most research on building performance optimization is focused on cold and severe weather zones [12], while the factors influencing building energy consumption and carbon emissions in HSCW zones are relatively under-researched. In addition, building energy consumption is a complex system whereby various influencing factors interact with each other and even small changes can have a significant impact [13]. Therefore, it is of great practical significance to explore the factors influencing building energy consumption and carbon emissions in HSCW zones and to propose feasible strategies to reduce energy intensity in order to improve the energy performance of buildings and to solve practical problems, such as energy conservation and emission reduction [14].

The factors that influence energy consumption and carbon emissions in buildings are multifaceted and encompass various aspects, such as climate, floor area, building envelope, indoor environment, building operation, and occupant behavior [15–17]. These factors are interconnected, and together, can significantly impact the energy performance of buildings. In recent years, the interactions between influencing factors have been the focus of a growing number of research scholars worldwide [18]. Yang et al. [19] found that reducing the roof heat transfer coefficient, exterior wall heat transfer coefficient, ground heat transfer coefficient, exterior window heat transfer coefficient, and north window-to-wall ratio could effectively enable buildings to meet the standards of nZEBs in the cold and arid regions of northwest China. Liu et al. [20] used an orthogonal experimental design and numerical simulation methods and found that the exterior wall heat transfer coefficient and exterior window heat transfer coefficient had the most significant effects on building energy efficiency. Ding et al. [21] found that in addition to the heat transfer coefficients of exterior walls and exterior windows, factors such as lighting equipment, power density, and air conditioning system power density also had significant effects on building energy efficiency; the authors formulated corresponding energy-saving measures in response to their research results. Sun et al. [22] conducted summer and winter thermal comfort tests on traditional Tibetan residential buildings, and then conducted an orthogonal experiment to create an optimized energy-saving renovation plan, which significantly reduced energy demand. Huang et al. [23] used ENVI-met and EnergyPlus to study the hot and humid climate zone in Taipei, and found that microclimate had a significant impact on building energy consumption. Zhu et al. [24] ranked the environmental factors of buildings by setting an "importance level" and a "satisfaction level" in order to study their importance and provide a reference for optimizing energy-saving strategies. Li [25] used VOS Viewer scientific mapping software to visualize keywords and authors and examine the intrinsic influence mechanisms of environmental factors that affect building energy consumption. Thus, among the literature, the physical performance and environmental aspects of buildings have received much attention from scholars, among others. However, most of the studies in this category have only considered the influence of buildings' physical properties or environments on their energy consumption, ignoring the influence of human factors such as human activities.

As society becomes more aware of energy efficiency in buildings, the focus is now gradually shifting to the study of occupant behavior [26]. Luis Lopez et al. [27] conducted a survey of energy-saving potential in 13 households using a questionnaire, and evaluated the impact of the resulting changes in people's lifestyles on energy consumption. Mansu et al. [28] combined building factors and household characteristics and used multiple regression analysis to derive building factors and household characteristics that can be used to effectively manage residential energy. Xie et al. [29] used multiple regression models to quantitatively analyze factors such as building characteristics, household composition, lifestyle, and household equipment. Zhu et al. [30] presented a simulation method developed by the Building Energy Research Center (BERC) at Tsinghua University using the University of Washington Integrated Design Laboratory (UW IDL) to assess the impacts of different occupant behaviors on building energy consumption and energy-saving potential.

In summary, research on the factors influencing building energy consumption and carbon emissions has been fruitful. However, many scholars have neglected to consider the nature of buildings as complex systems and the interactions between various factors [31,32], and their studies lack quantitative analyses of building energy consumption and carbon emissions, as well as investigations of the primary and secondary relationships and the significance of their effects on energy consumption. To achieve this goal, this study aims to determine the key factors affecting building energy consumption and carbon emissions in HSCW zones through a hybrid approach combining building energy simulation and orthogonal experiments, taking an nZEB jointly funded by the University of Nottingham, UK, and Hubei University of Technology as an example; moreover, we aim to provide certain reference strategies for building energy conservation and emission reduction by considering these factors multidimensionally and comprehensively.

This study consists of four parts: the first part reviews the existing literature and identifies various factors affecting building energy consumption and carbon emissions, including climate, buildings, residents, equipment, and energy use behavior; the second part takes an nZEB in an HSCW zone as an example, establishes a carbon emission model for the building operation phase based on relevant theories, and analyzes the influence of selected factors on building energy consumption and carbon emission; the third part establishes the quantitative relationships of the influencing factors with building energy consumption and carbon emission, and discusses the optimal combination of parameters for reducing building energy consumption and carbon emission, as well as the primary and secondary relationships and the significance of their degrees of influence; and the fourth part summarizes the relevant results of the study.

2. Research Methodology

2.1. Case Building Parameter Settings

2.1.1. Overview of the Case Building

The Bamboo and Wood Eco-House (BWEH) was built by the University of Nottingham, Hubei University of Technology, and the World Sustainable Energy Association. The building is located in Wuhan, Hubei Province, and is based on the design of traditional dwellings in the Yangtze River valley, with an area of 109.8 m^2 and a floor area of 202.1 m^2. As Wuhan is a typical HSCW zone, the building needs to provide cooling in summer and heating in winter to maintain thermal comfort indoors [33,34], and so the building was designed using an nZEB concept and built according to current Chinese energy requirements, as shown in Figure 1. The design of nZEBs follows the principles of prioritizing passive design and optimizing active design [35]. Passive design utilizes external environmental resources for self-regulation, employing high-performance building envelopes, natural lighting and ventilation, shading measures, and other strategies to reduce the demand for building energy under different conditions [36]. Active design involves the use of efficient HVAC systems, lighting systems, environmental monitoring, energy management systems, and other measures to improve building energy efficiency and control energy consumption [37]. In addition to using green building technologies such as green roofs, rainwater harvesting, adjustable shading timber grilles, and enhanced ventilation during the transitional seasons in the inner courtyard, a variety of renewable energy systems are fully utilized to supply the building with energy in a complementary multi-energy manner. Solar photovoltaic (PV) products are integrated into the buildings for self-generated electricity or grid transmission. Solar water heaters convert solar energy into thermal energy to provide domestic hot water (DHW) to customers. Ground-source heat pump systems can provide high-temperature groundwater for heating, ventilation, and air conditioning (HVAC) systems. This reduces energy consumption and increases the use of renewable energy in buildings. Based on the aforementioned design principles of nZEBs, it is possible to reduce building energy consumption and carbon emissions, better adapt to climate change, and achieve climate goals [38].

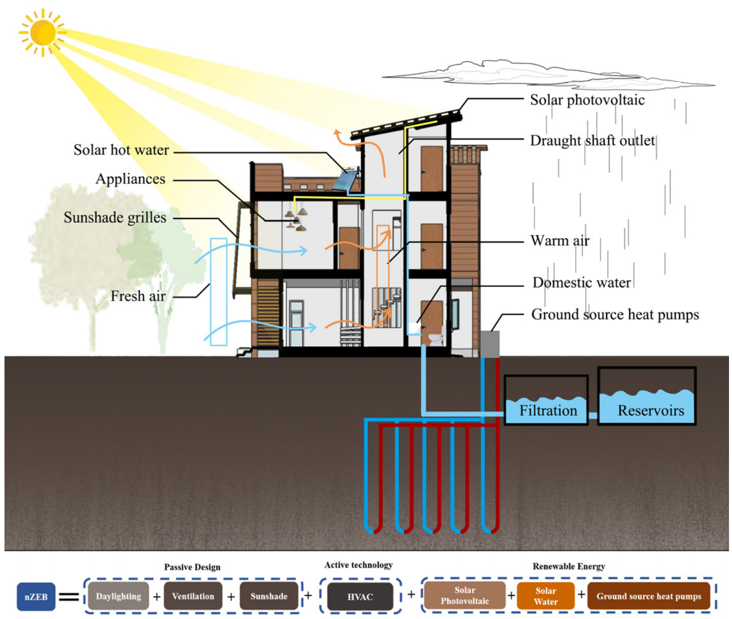


Figure 1. Diagram of the case building.

2.1.2. Parameter Settings

The physical parameters of the building include its geographical location, meteorological conditions, and structural features, while its operational parameters include occupancy density, lighting density, air conditioning settings, and hot water supply. When calculating building energy consumption and carbon emissions, obtaining and analyzing accurate building and operational parameters is essential in ensuring the accuracy and reliability of the results.

The basic parameters of the building are shown in Tables 1 and 2, and the meteorological parameters are based on data from a typical meteorological year in Wuhan. The envelope parameters refer to "*the Design standard for Energy Efficiency of Residential Buildings in Hot-summer and Cold-winter Zone (JGJ134-2010)*" [39]. Indoor temperature, service life, and occupancy rate mainly refer to "*the Technical Standard for nearly zero-energy Buildings (GB/T 51350-2019)*" [40] and "*the General code for energy efficiency and renewable energy application in buildings (GB 5515-2021)*" [41]. The specific parameters are shown in Table 3.

Table 1. Basic information about the building.

Design Content	Basic Information
Building orientation	North–south-facing
Building area	202.1 m^2
Wall	Aerated concrete blocks for external walls and foam wall panels for internal walls
Windows	Glass is double-layered hollow Low-E glass with a surface emissivity control of 0.25 or less
Roof drainage	Organized drainage of roofs
Roofing	Extruded plastic sheet; 80 mm thick
Drainage systems	Roof rainwater harvesting systems

Table 2. Structural parameters of the building.

Building Envelope	Materials	Heat Transfer Coefficient W/(m^2·K)
Roof	Polyurethane rigid foam, cement mortar, and reinforced concrete	0.35
External walls	Extruded polystyrene foam and concrete blocks	0.40
Balcony partition wall	Extruded polystyrene foam, cement mortar, and reinforced concrete	0.25
Floorboards	Extruded polystyrene foam, cement mortar, and reinforced concrete	0.25

Table 3. Operating parameters of the main functional rooms of the building.

Room Type	Cooling (°C)	Heating (°C)	Fresh Air Volume (Times/h)	Ventilation Times (Times/h)	Personnel Density (m^2/Person)	Lighting Power Density (W/m^2)	Electrical Equipment Power (W/m^2)
Master bedroom	26	18	0.5	1	32	6	5
Second bedroom	26	18	0.5	1	32	6	5
Living room	26	18	0.5	0	32	6	5

A large-scale questionnaire study was conducted by Jiang [42] in an HSCW zone to explore the characteristics of household structure and occupant behavior patterns in buildings. Referring to the findings of Laskari et al. [43], this study classified the main household structures and occupant behavior in China into five categories, as detailed in Tables 4 and 5. Taking into account the household structure and lifestyle characteristics of the new generation of Chinese residents, household structure (c) and occupant behavior (1) were chosen as the baseline models for this study.

Table 4. Table of typical household structures.

Household Structure (HS)	Weekday	Weekend
a	Living room: 8:00–12:00; 18:00–22:00 Bedroom: 12:00–14:00; 22:00–8:00	
b	Living room: 18:00–22:00 Bedroom: 22:00–8:00	Living room: 8:00–12:00; 14:00–23:00 Bedroom: 12:00–14:00; 23:00–8:00
c	Living room: 8:00–22:00 Bedroom: 12:00–14:00; 22:00–8:00	Living room: 8:00–12:00; 14:00–23:00 Bedroom: 12:00–14:00; 23:00–8:00
d	Living room: 8:00–12:00; 14:00–16:00; 18:00–22:00 Bedroom: 12:00–14:00; 22:00–8:00	Living room: 8:00–12:00; 14:00–22:00 Bedroom: 12:00–14:00; 22:00–8:00
e	Living room: 8:00–12:00; 14:00–22:00 Bedroom: 12:00–14:00; 22:00–8:00	Living room: 8:00–12:00; 14:00–22:00 Bedroom: 12:00–14:00; 22:00–8:00

Table 5. Table of typical occupant behavior.

Occupant Behavior (OB)	Weekday	Weekend
1	Living room: 0:00–24:00 Bedroom: 0:00–24:00	
2	Living room: 18:00–22:00 Bedroom: 22:00–8:00	Living room: 8:00–22:00 Bedroom: 22:00–8:00
3	Living room: 8:00–22:00 Bedroom: 18:00–8:00	Living room: 0:00–24:00 Bedroom: 0:00–24:00
4	Living room: 18:00–22:00 Bedroom: 22:00–0:00; 6:00–8:00	Living room: 8:00–22:00 Bedroom: 22:00–0:00; 6:00–8:00
5	Living room: 18:00–20:00 Bedroom: 22:00–8:00	Living room: 8:00–10:00; 18:00–20:00 Bedroom: 22:00–8:00

2.1.3. Computational Modeling

There are four main methods used internationally to calculate carbon emissions, including the direct measurement method, the input–output method, the material balance method, and the carbon emission factor method [44]. Although other methods can also be used for carbon emission calculation, the carbon emission factor method was chosen in this study due to its advantages of easy data availability and simple calculations, as well as its suitability for our research requirements [5]. Therefore, in this study, the carbon emission factor method was used to study the energy consumption and carbon emissions of the building during its operational phase. The carbon emission factor is an important parameter for measuring the characteristics and environmental impact of energy-related greenhouse gas emissions, and correlating greenhouse gas emissions with energy use represents the basis for calculating the carbon emissions of a building [45]. The specific calculation formula is as follows (1):

$$C_O = \sum_{i=1,j=1}^{n} E_{i,j} EF_i \tag{1}$$

where C_O represents the carbon emissions from the operational phase of the building (t).

$E_{i,j}$ is the type i energy consumption of the type j system (kWh).

EF_i is the carbon emission factor for energy type i ($kgCO_2/kWh$). The carbon emission factors used in this study were taken from the Central China Regional Grid Factor.

This study used Tsinghua University's energy simulation software to calculate the energy consumption and carbon emissions during the operation of the case building. The software is based on the DOE2 kernel and provides fast and accurate results. The specific calculation route is shown in Figure 2. Firstly, the building parameters and operational parameters were determined to ensure the accuracy of the simulations. Then, the energy consumption and carbon emissions generated by the building's HVAC system, lighting system, and other energy-consuming devices were simulated. Finally, detailed data on energy consumption and carbon emissions during the operational phase of the building were outputted.

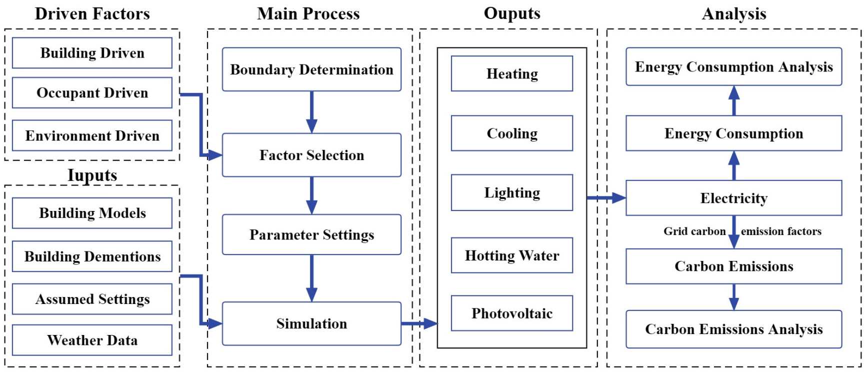


Figure 2. Routes for calculating energy consumption and carbon emissions in nZEBs.

2.2. *Selection of Influencing Factors and Values*

In order to examine the extent and variation patterns of the influencing factors, the energy consumption and carbon emissions of the case buildings were accounted for, and single-factor analysis and orthogonal experiments were conducted to study them. Firstly, a quantitative analysis of the selected factors was conducted through single-factor analysis to determine the degree of influence and variation patterns of key factors on building operational energy consumption (OE), building operational carbon emissions (OC), cooling energy consumption (CE), and heating energy consumption (HE). Secondly, orthogonal experiments were designed to investigate the different factors affecting OE, OC, CE, and HE, and we analyzed the optimization of their combinations. Finally, the analysis yielded a comprehensive design method for optimizing building indicators and enabled us to propose feasible carbon reduction strategies, providing a reference for analyzing nZEBS in HSCW zones in China.

2.2.1. Single-Factor Analysis

The total energy consumption of an nZEB is determined using several factors, including environmental factors, building function, and occupant behavior. In this study, the external wall heat transfer coefficient (K_E), roof heat transfer coefficient (K_R), household structure (HS), occupant behavior (OB), building orientation (BO), and number of ventilation times (VT) were selected as the key factors to be studied. With the other five factors fixed, one of the factors was varied, and ranges and gradients of variations were set. Through this method, the extent of the influence of these factors on building energy consumption and carbon emissions, their effects, and the quantitative relationships between them were investigated. The changes in the levels of each factor are detailed in Table 6.

Table 6. Values of impact factors for single-factor analysis.

	Test Factor					
Level	K_E	K_R	HS	OB	BO	VT
Benchmarking programmer	0.40	0.35	c	1	Due north (0)	1
Contrast programmer	0.35	0.30	a	2	30° west of due north (−30)	0.9
	0.30	0.25	b	3	15° west of due north (−15)	0.8
	0.25	0.20	d	4	15° east of due north (15)	0.7
	0.20	0.15	e	5	30° east of due north (30)	0.6

2.2.2. Orthogonal Experiment Design

If there were 5 levels for each factor, 5^6 simulations would be required, which would be very time-consuming and difficult to complete. The orthogonal test method is one of the most commonly used methods for optimizing test designs today, and enables researchers to carry out tests efficiently and economically. This method allows for the selection of representative sections to be tested. Therefore, in this study, six factors with five levels each were selected and an L25(5^6) orthogonal test table was used, which only requires 25 trials to be conducted to represent the full test. For more information on the influencing factors and the levels of each factor in the orthogonal tests, please refer to Table 7; details of the orthogonal experimental design are provided in Table A1 in Appendix A.

Table 7. Statistical table of impact factors and levels of orthogonal experiment simulations.

Factor	Level 1	Level 2	Level 3	Level 4	Level 5
K_E	0.40	0.35	0.30	0.25	0.20
K_R	0.35	0.30	0.25	0.20	0.15
HS	a	b	c	d	e
OB	1	2	3	4	5
BO	−30	−15	0	15	30
VT	1	0.9	0.8	0.7	0.6

3. Results and Discussion

3.1. Case Results and Analysis

The levels of energy consumption and carbon emissions during the operation of the building are shown in Table 8. The total energy consumption during the operation phase is 193.91 MWh and the total carbon emission is 101.93 t. The annual building energy consumption per unit area is 19.18 kg/m^2/a and the annual building carbon emission per unit area is 10.08 kg/m^2/a. The annual cooling- and heating-related energy consumption rates are 12.42 kWh/m^2/a and 8.42 kWh/m^2/a, respectively. The building is equipped with 3 m^2 of solar hot water collectors and 6 m^2 of solar PV panels to provide clean energy, enabling the building to achieve 71% renewable energy use per year.

Table 8. Energy consumption and carbon emissions during the operational phase of the building.

Sub-Categories	Energy Category	Electricity Consumption (kWh/m^2)	Carbon Emission Factors (kgCO_2/kWh)	Energy Consumption (MWh)	Carbon Emissions (tCO_2)
Cooling	Electricity	621.09	0.5257	125.57	66.01
Heating		421.03		85.12	44.75
Lighting		405.35		81.95	43.08
Domestic hot water		105.46		21.32	11.21
Photovoltaics	Renewable energy	593.91		120.05	63.12
	Total			193.91	101.93

3.2. Single Impact Factor Results and Analysis

3.2.1. Impact of Heat Transfer Coefficients in External Walls

Figure 3a shows the effect of K_E on OE and OC. As K_E increases, both OE and OC show an increasing trend. When K_E is 0.20 W/(m^2·K), OE reaches a minimum value of 16.94 kWh/m^2/a and OC reaches a minimum value of 8.9 kg/m^2/a. When K_E rises to 0.40 W/(m^2·K), OE reaches a maximum value of 19.18 kWh/m^2/a and OC reaches a maximum value of 10.08 kg/m^2/a. In the 0.20–0.40 W/(m^2·K) range, both OE and OC meet the criteria of nZEBs. Therefore, it is recommended to choose the thickness of the insulation material carefully and to give priority to its economic value in the process of external wall insulation.

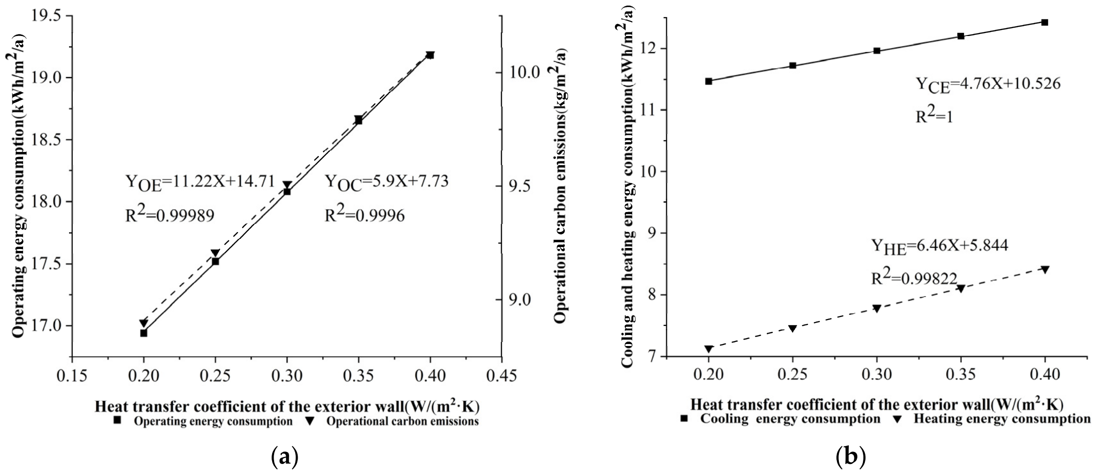


Figure 3. (**a**) Impact of K_E on OE and OC; (**b**) impact of K_E on CE and HE.

Figure 3b illustrates the positive correlation between K_E and CE, as well as HE, with the linear relationship between K_E and CE being the most pronounced. When K_E is within the range of 0.20–0.30 W/(m^2·K), it facilitates the attainment of nZEB goals, providing more precise experimental results and a more targeted selection of external wall structures.

3.2.2. Impact of Roof Heat Transfer Coefficient

Figure 4a illustrates the effect of K_R on OE and OC, showing an increasing trend with increasing K_R. At a K_R of 0.15 W/(m^2·K), OE reaches a minimum value of 18.00 kWh/m^2/a and OC reaches a minimum value of 9.46 kg/m^2/a. At a K_R of 0.35 W/(m^2·K), OE reaches a maximum value of 19.18 kWh/m^2/a and OC reaches a maximum value of 10.08 kg/m^2/a.

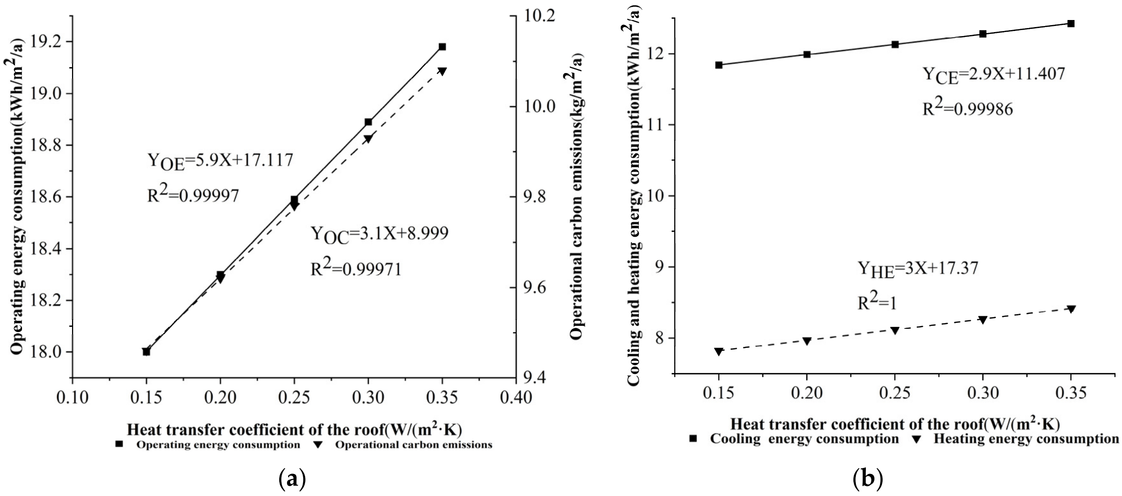


Figure 4. (**a**) Impact of K_R on OE and OC; (**b**) impact of K_R on CE and HE.

Figure 4b displays the impact of K_R on CE and HE in buildings. When K_R is within the range of 0.15–0.35 W/(m^2·K), both OE and CE meet the criteria for nZEBs. Additionally, HE satisfies the nZEB criteria when K_R is in the range of 0.15–0.20 W/(m^2·K). Thus, maintaining K_R between 0.15 and 0.20 W/(m^2·K) facilitates the achievement of the nearly zero-energy consumption goal.

3.2.3. Impact of Household Structure

Figure 5a depicts the effect of HS on OE and OC, showing non-linear variation. Specifically, HS(e) brings OE to a maximum value of 24.75 kWh/m^2/a and OC to a maximum value of 9.01 kg/m^2/a. OE and OC reach a minimum value of 17.05 kWh/m^2/a and 8.96 kg/m^2/a, respectively, at HS (b). For the OE indicator, an increasing trend is shown from HS (a) to HS (e). For the OC indicator, the lowest carbon emission levels are found at HS (b) and the highest is found at HS (e), indicating that different indoor activities have different impacts on building energy consumption and carbon emissions. Based on Figure 5b, HS also influences CE and HE differently. Higher CE corresponds to relatively lower HE, whereas lower CE is associated with relatively higher HE.

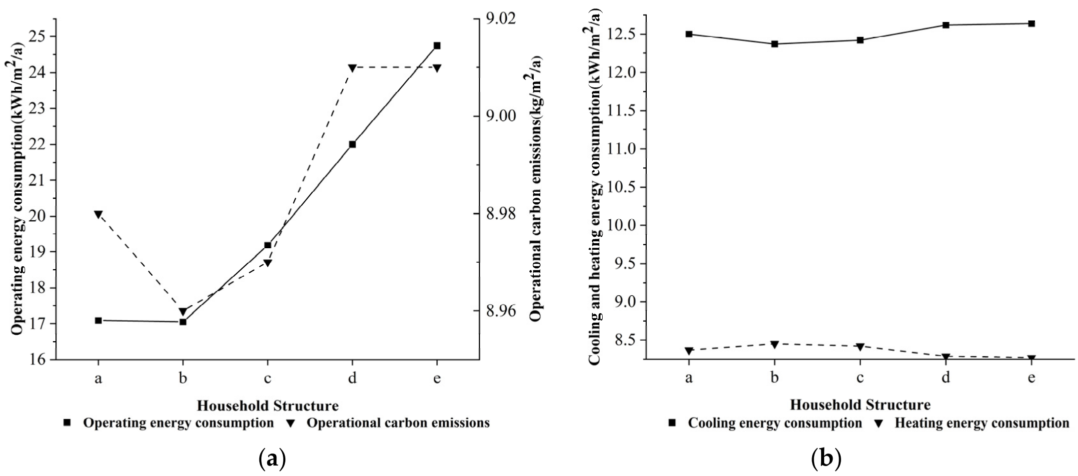


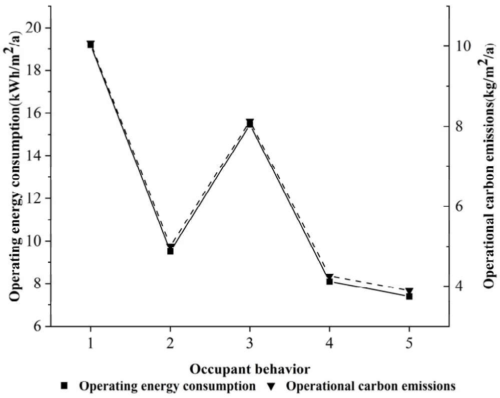
Figure 5. (**a**) Impact of HS on OE and OC; (**b**) impact of HS on CE and HE.

Although different household structures have varying effects on these two indicators, the overall changes are minor, with gradual trends. Among the five different family structure patterns, only OE and CE meet the criteria for nZEBs, while OC and HE fall short. This highlights the significant impact of different household structures on building energy consumption and carbon emissions, underscoring substantial potential for energy savings.

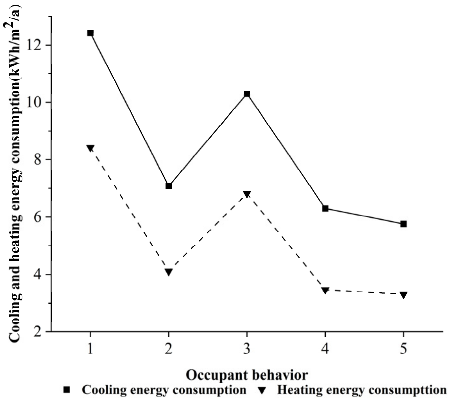
3.2.4. Impact of Occupant Behavior

Occupant behavior is an important factor that influences building energy consumption in three main ways: time of use, operational control, and energy-saving awareness. Figure 6a reveals the non-linear characteristics of the impact of occupant behavior on total building energy consumption and carbon emissions. OE reaches a maximum value of 19.18 kWh/m^2/a and OC reaches a maximum value of 10.08 kg/m^2/a at OC (1). OE reaches a minimum value of 7.40 kWh/m^2/a and OC reaches a minimum value of 3.89 kg/m^2/a at OC (5). As can be observed in Figure 6b, OB has a similar effect on CE and HE, reaching a maximum value of 12.42 kWh/m^2/a for CE and 8.42 kWh/m^2/a for HE at OB (1), and a minimum value of 5.76 kWh/m2/a for CE and 3.3 kWh/m^2/a for HE at OB (5).

The four occupant behaviors are generally compliant, except for the OC and HE indicators, which do not meet the nearly zero-energy standard at OB (1). In addition, there are significant differences between the highest and lowest levels of energy consumption and carbon emissions across the different occupant behaviors. This is due to the fact that OB (1) uses continuous operations throughout the day, while the other behaviors involve intermittent operations with lower overall operating hours. The variation in energy consumption caused by intermittent and continuous operation demonstrates the substantial differences brought about by the different hours of use.



(**a**)

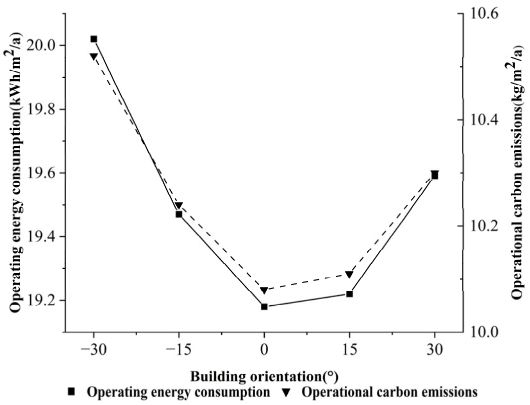


(**b**)

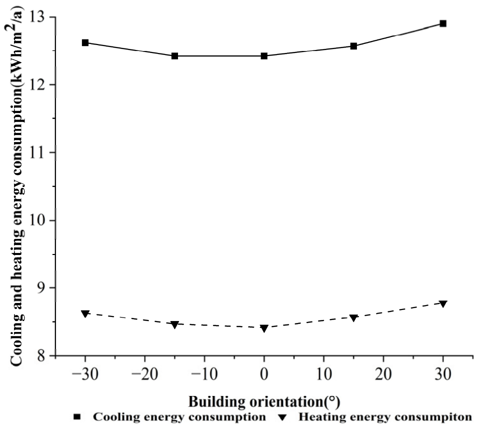
Figure 6. (**a**) Impact of OB on OE and OC; (**b**) impact of OB on CE and HE.

3.2.5. Impact of Building Orientation

Figure 7a illustrates the significant impact of building orientation (BO) on OE and OC. In the north-facing direction (0°), OE reaches a minimum value of 19.18 kWh/m^2/a and OC reaches a minimum value of 10.0 kg/m^2/a. When the building is oriented 30° west of north (−30°), OE reaches a maximum value of 20.02 kWh/m^2/a and OC reaches a maximum value of 10.52 kg/m^2/a. The trends of OE and OC are consistent with the change in building orientation, with a gradual decrease from −30° to 0° and a gradual increase from 0° to 30°.



(**a**)



(**b**)

Figure 7. (**a**) Impact of BO on OE and OC; (**b**) impact of BO on CE and HE.

As shown in Figure 7b, CE and HE reach their minimum values at due north (0°), measuring 12.42 kWh/m^2/a and 8.42 kWh/m^2/a, respectively. The maximum values for CE and HE occur at 30° east of north (30°). This indicates a similar trend in the effect of BO on OE and OC, but the extent of its effect on CE and HE varies. Overall, orienting buildings in a north-facing (0°) direction is most suitable for HSCW zones.

3.2.6. Impact of the Number of Ventilation Times

The infiltration of hot or cold outdoor air through building envelope components such as doors and windows has become a crucial factor influencing building performance. As energy-efficient buildings, nZEBs have strict energy performance requirements. Excel-lent airtightness ensures effective ventilation, reduces moisture loads, and provides a healthy indoor environment. It also helps to minimize infiltration heat loss and lower heating and cooling loads, thereby reducing building energy consumption and carbon emissions.

As shown in Figure 8a, OE reaches a minimum level of 14.71 kWh/m^2/a and OC reaches a minimum level of 7.73 kg/m^2/a at VT = 0.6 h^{-1}, while OE reaches a maximum level of 19.18 kWh/m^2/a and OC reaches a maximum level of 10.08 kg/m^2/a at VT = 1 h^{-1}. Figure 8b shows that different VTs have an effect on CE and HE. Each increase of 0.1 in VT increases CE by kWh/m^2/a and HE by 0.54 kWh/m^2/a.

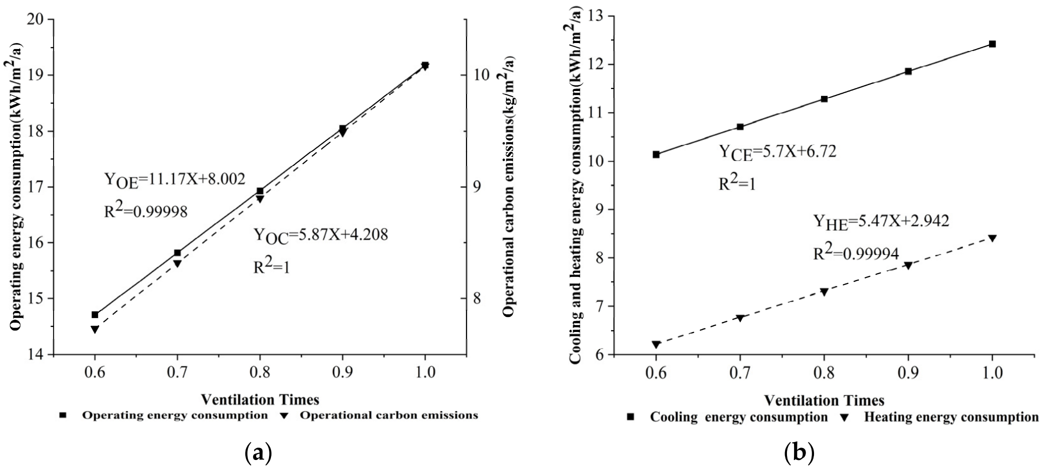


Figure 8. (**a**) Impact of VT on OE and OC; (**b**) impact of VT on CE and HE.

It is evident that VT has the most significant impact on HE, followed by OE and CE. Considering that the minimum VT required for residential buildings set by national regulations is 0.45 h^{-1}, and considering its overall influence on the three indicators, a VT of 0.6 h^{-1} not only meets the requirements but also provides an adequate amount of fresh air.

Single-factor analysis can only investigate the effect of a particular factor on the indicators of an nZEB. However, building energy consumption is influenced by several factors, including the physical characteristics of the building, building technology, climate, and the behavior of the occupants [46]. The results of this study show that the heat transfer coefficient of the external walls, the heat transfer coefficient of the roof, and the number of air changes have a significant effect on the energy consumption and carbon emissions of the building, which is in line with the results of other studies. In order to consider the effects of building ontology, occupant use characteristics, and environment on an nZEB, we selected these six factors for an orthogonal experiment to explore their effects on energy consumption and carbon emissions when many different factors were combined.

3.3. Results and Analysis of Orthogonal Experiment

3.3.1. Results of Orthogonal Experiments

As can be seen in Table 9, OE and OC reached maximum values of 21.36 kg/m^2/a and 11.23 kg/m^2/a, respectively, in experiment L9. OE and OC reached minimum values of 3.27 kg/m^2/a and 1.72 kg/m^2/a, respectively, in experiment L22.

CE and HE reached maximum values of 12.97 kWh/m^2/a and 13.97 kWh/m^2/a in the L1 experiment and minimum values of 4.96 kWh/m^2/a and 5.97 kWh/m^2/a in the L22 experiment.

This shows that L22 is the optimal solution for both building operating energy and carbon emissions and for cooling and heating energy consumption. Compared to the baseline building, OE and OC can be reduced by 82.94% and 82.93%, respectively, while CE and HE can be reduced by 59.98% and 29.1%, respectively.

Table 9. Results of orthogonal experiment.

No.	OC (kg/m^2/a)	OE (kWh/m^2/a)	CE (kWh/m^2/a)	HC (kWh/m^2/a)
L1	9.42	17.93	12.97	13.97
L2	3.69	7.02	6.88	7.88
L3	6.98	13.29	9.22	10.22
L4	4.94	9.40	5.67	6.67
L5	5.99	11.40	5.19	6.19
L6	5.08	9.66	8.45	9.45
L7	4.15	7.89	6.25	7.25
L8	5.49	10.44	6.28	7.28
L9	11.23	21.36	10.97	11.97
L10	2.43	4.63	5.83	6.83
L11	3.40	6.46	5.39	6.39
L12	5.52	10.50	6.53	7.53
L13	7.30	13.88	6.67	7.67
L14	9.86	18.76	9.34	10.34
L15	2.37	4.51	5.68	6.68
L16	5.644	10.73	6.53	7.53
L17	7.79	14.81	8.90	9.9
L18	1.88	3.58	5.23	6.23
L19	1.94	3.69	5.05	6.05
L20	8.01	15.24	10.56	11.56
L21	6.48	12.32	5.86	6.86
L22	1.72	3.27	4.97	5.97
L23	5.95	11.32	9.67	10.67
L24	3.38	6.43	5.80	6.80
L25	7.24	13.77	8.10	9.10

3.3.2. Analysis of Orthogonal Experiment Results

SPSS software was used to analyze the results of the orthogonal test by means of a polar difference analysis to further analyze the relationships between the factors in terms of their influence on the test indicators. The magnitude of the extreme difference reflects the relationships between the factors and the test indicators. The larger the extreme difference, the greater the influence of the influencing factor on the test indicator. The k and R values of the orthogonal experiment results are illustrated in Figures 9 and 10.

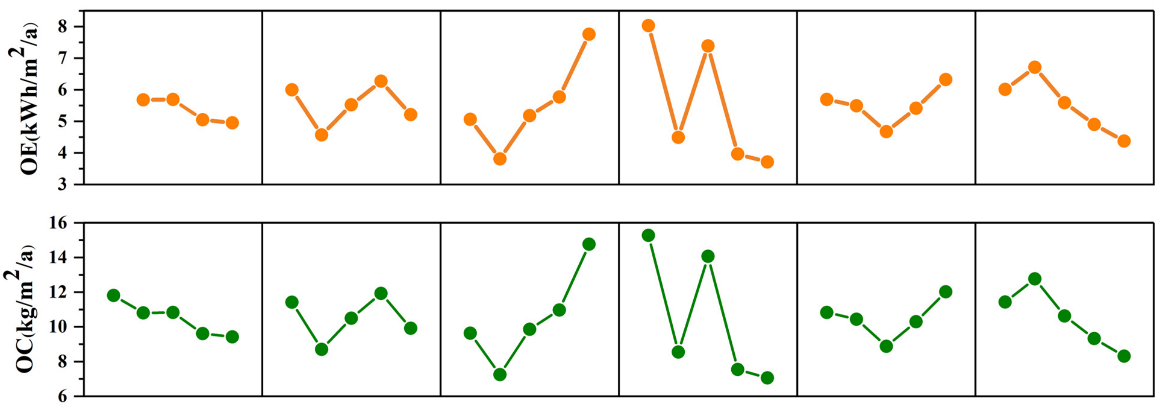


Figure 9. *Cont.*

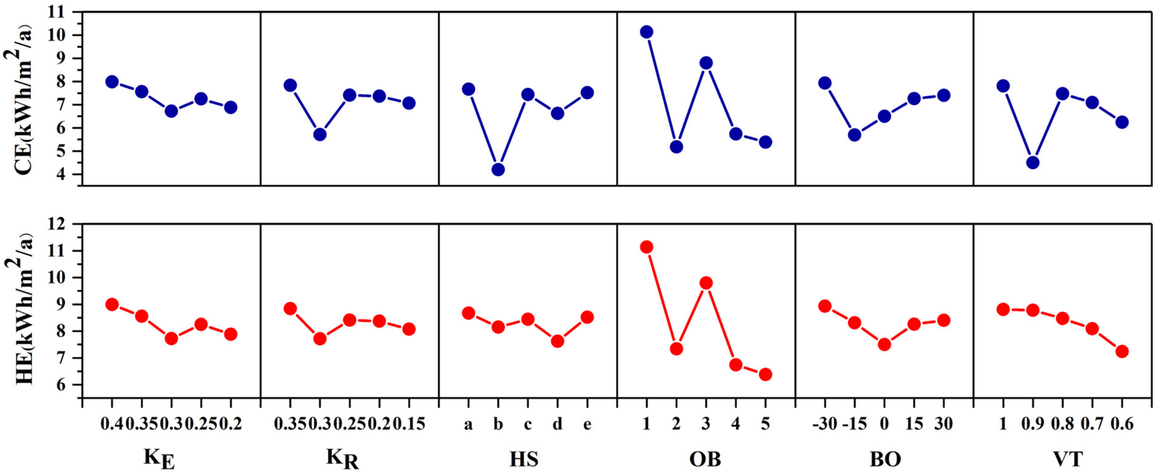


Figure 9. Level values for each factor.

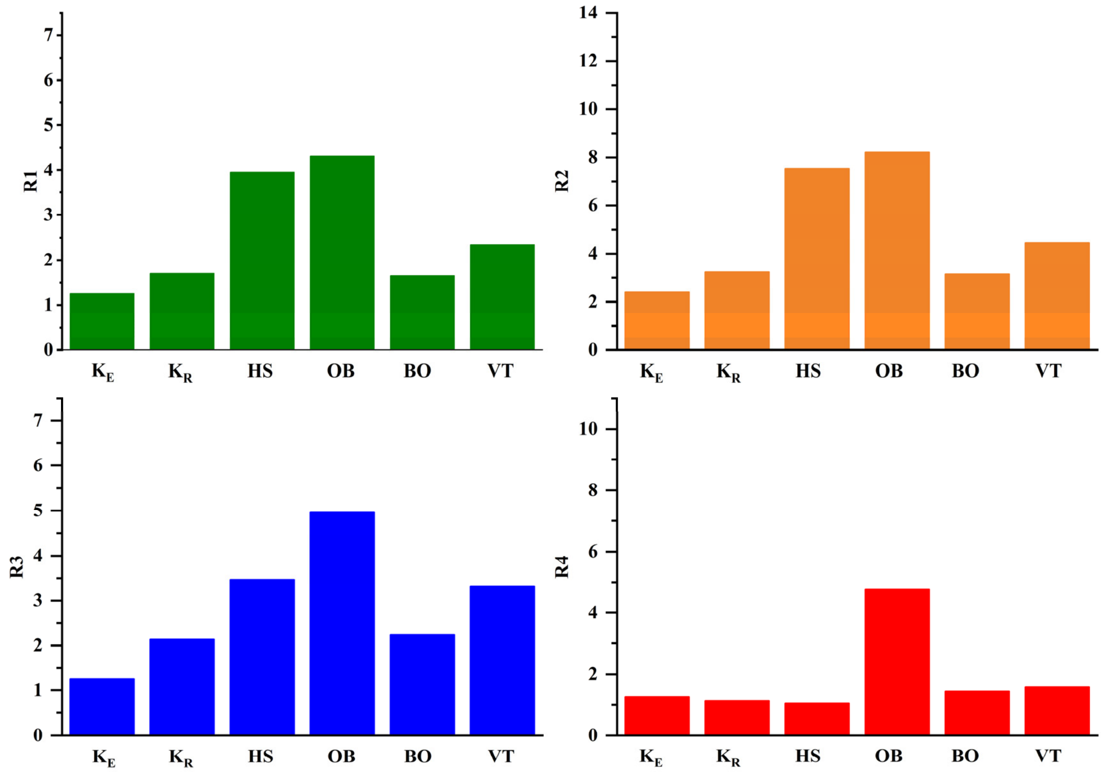


Figure 10. Extreme value of each factor.

The extreme difference values can be calculated using Equations (2) and (3):

$$k_{ij} = \frac{1}{n}\sum_{j=1}^{n} K_{ij} \tag{2}$$

$$R_i max(k_{ij}) - min(k_{ij}) \tag{3}$$

where K_{ij} is the test value corresponding to the jth level taken in the *i*th factor; k_{ij} is the average of the test values corresponding to the *j*th level taken in the ith factor; n is the number of *j*th level taken in the ith factor; R_i is the extreme difference value of the ith factor.

As can be observed from Figure 9, the effect of KE on OE and OC shows an overall decreasing trend, and is optimal for each indicator when taken at a value of 0.20 W/(m^2·K).

The effect of K_R on all four indicators is basically the same (first, it decreases; then, it increases; and then, it decreases again) and is optimal for each indicator when taken at a value of 0.30 $W/(m^2 \cdot K)$. For HS, HS (b) has the lowest value, while HS (e) has the highest value. HS (b) is optimal for the OE, OC, and CE indicators, and HS (d) is optimal for the HC indicator. For OB, the trends are largely consistent, with OB (5) having the smallest value and OB (1) having the largest value; so, OB (5) is optimal for each indicator. BO is largely consistent for the OE, OC, and HE indicators, but optimal at -15° for the CE indicator. The effect of VT on the OE and OC indicators is essentially the same, increasing for both, and then decreasing. In contrast, the effect of VT on the CE indicator shows a decrease followed by an increase. Additionally, the HE indicator keeps decreasing and reaches an optimal level when VT = 0.6 h^{-1}.

From Figure 10, it is evident that the factors exhibit the same order of significance for the OE and OC indicators, namely OB, HS, VT, K_R, BO, and K_E. Among these factors, OB has the most significant effect on both OE and OC, followed by HS. There are significant variations in carbon emissions and energy consumption for residential buildings across different levels of OB. The highest carbon emissions are observed at OB (1), while the lowest emissions are observed at OB (5). For both OE and OC, the influence of OB becomes the primary factor of influence. Previous studies [17] have shown that different activities of occupants can lead to significant differences in overall energy consumption and carbon emissions, even between two neighboring flats. The interaction between occupants and the building can have a considerable impact on the total energy consumption of the building due to various activity patterns, such as opening or closing windows, switching lights on or off, and turning air conditioning on or off to meet basic needs. All OE indicators were met in the orthogonal experiments, and 76% of the experiments also met the OC indicators. This success can be attributed to the implementation of government policies that aim to improve energy efficiency in buildings to reduce energy consumption and carbon emissions. To achieve the goal of zero energy consumption and zero carbon emissions, the energy mix can be adjusted by reducing reliance on conventional energy sources and increasing the utilization of renewable energy sources, such as solar, wind, and geothermal energy [47]. Unlike European and American countries, where three-story or shorter buildings are commonly used, Chinese buildings are characterized by high density and volume ratios [48]. Considering that the studied building is double-story, a renewable energy system was implemented. In China, solar energy is extensively utilized in photovoltaic systems, solar water heating, and heating systems [49]. Research indicates that the use of solar water heating systems can lead to a 76% reduction in energy consumption compared to electric water heaters [50]. Furthermore, the widespread adoption of integrated PV systems in cities can fulfill 35% of total electricity consumption [51], thereby reducing reliance on conventional energy sources and decreasing carbon emissions.

The significance order of the effects of factors on CE is OB, HS, VT, BO, K_R, and K_E, while the significance order of their effects on HE is OB, VT, BO, K_E, K_R, and HS. There is a clear distinction between these two indicators, with OB and HS remaining the most influential factors for CE. Although VT and BO are not direct environmental factors, they can still impact the environment. For the HE indicator, VT and BO exert a significant influence on the environment, leading to increased heating energy consumption, while the building envelope's impact surpasses that of the household structure. Changes in K_E have a more pronounced effect on HE than K_R. This is primarily because the heat transfer coefficient of the building envelope is considerably higher in the colder and harsher zones of northern China, and inadequate insulation often leads to significant heat loss during the cold season. Conversely, the use of high-performance building envelopes can reduce building energy consumption by 22% [52]. For zones with severe cold climates and where heating energy consumption is significant, optimizing the building envelope through advanced energy-saving design concepts and efficient insulation materials can enhance its thermal insulation performance and reduce the winter heat load. This, in turn, leads to reduced energy consumption throughout the year. Conversely, in zones where air conditioning and cooling are the primary concerns, such as HSCW zones, improving the insulation performance of the roof envelope may not be as effective for achieving energy savings as enhancing the insulation performance of the external wall envelope. This indicates that achieving the target of reducing heating-related energy consumption in winter is more challenging for residential buildings in HSCW zones compared to achieving the target of reducing cooling-related energy consumption in summer. Therefore, when designing nZEBs in HSCW zones, the focus should be on the targets of reducing building carbon emissions and heating-related energy consumption.

While the results of multiple experiments may meet the targets for OE or OC, they may not meet the targets for HE. Additionally, there can be a disparity between the predicted energy consumption and actual usage. Therefore, it is important to consider energy-conscious occupant behavior, such as setting sensible temperature limits for summer air conditioning and turning off air conditioning or lighting when not in use. Studies [36] have demonstrated that occupants' activities can result in substantial variations in total energy consumption and carbon emissions, even between two flats in close proximity to each other. The interaction between occupants and the building significantly influences the overall energy consumption of the building. In practice, occupants often prioritize their comfort and finances. They only use their air conditioning and heating units intermittently when necessary, adjusting the temperature or even turning them off once they are comfortable, and sometimes, heating units are used for no more than three hours a day. However, the fixed air conditioning and heating settings specified in the regulations are 26 °C throughout the day in summer and 18 °C throughout the day in winter. These settings deviate from the actual energy consumption patterns, leading to the phenomenon of artificially inflated energy consumption in many buildings. Therefore, the evaluation of nZEBs should take into account the combined effects of occupants' energy consumption behavior and other factors on the evaluation indicators of such buildings.

The results of this study mainly highlight the main factors influencing energy consumption and carbon emissions during the operational phase of residential buildings in HSCW zones. In contrast to previous research, the OB factor exerts a more substantial influence on overall energy consumption and carbon emissions compared to other factors. Additionally, HS and K_E play key roles in influencing HE and CE. These findings contribute to a deeper understanding of the underlying mechanisms of energy consumption and carbon emissions. They not only provide novel ideas and directions for future research, but also offer a scientific basis for future energy conservation and carbon reduction efforts.

Nevertheless, this study has certain limitations and potential biases that should be acknowledged. Firstly, due to spatial constraints, a limited number of factors influencing energy consumption and carbon emissions were considered, and the range of factors and their levels might not have been adequately addressed. Additionally, while dynamic simulations were employed to calculate energy consumption and carbon emissions, this study did not account for the temporal variations in energy consumption and carbon emissions resulting from changes in building performance and carbon emission factors over time.

To address these limitations, future research could incorporate a broader range of influencing factors for a more comprehensive analysis and assessment. Moreover, incorporating dynamic measurements and considering the temporal changes in energy consumption and carbon emissions would provide a more accurate representation of real-world scenarios.

In conclusion, this study sheds light on the primary factors influencing energy consumption and carbon emissions in the operational phase of nZEBs located in HSCW zones. It offers valuable scientific insights and serves as a basis for future efforts to achieve energy conservation and carbon emission reduction. While acknowledging the limitations and potential biases of this study, further research can build upon these findings to refine and expand our understanding. Future investigations should explore additional methods and technologies for achieving energy savings and emission reduction, thereby advancing research in this field in a more comprehensive manner.

4. Conclusions

The aim of this study is to simulate energy consumption and carbon emissions during the operational phase of a case building, in order to explore its sustainability. Single-factor analysis and orthogonal experiments were employed to simulate six key factors: K_E, K_R, HS, OB, BO, and VT. Based on our results, we draw the following conclusions:

1. During the operational phase of residential buildings, the HVAC system accounted for the highest energy consumption, and achieving nearly zero-energy consumption solely through energy-saving measures was challenging. The combination of solar PV panels and energy efficiency measures within the building in this case allowed for a 61.76% energy-saving rate and 71% renewable energy utilization. To ensure that buildings meet the nearly zero-energy requirements, it is recommended that developers use renewable energy systems such as solar photovoltaics, solar hot water, and ground-source heat pumps.
2. Univariate analysis revealed that HS and OB played a more significant role in nZEBs, while K_E, K_R, and VT exhibited a strong linear relationship with energy consumption and carbon emissions, showing consistent impacts. To facilitate compliance with nZEB standards, it is recommended that K_E is kept within the range of 0.20–0.30 $W/(m^2 \cdot K)$, K_R is kept within the range of 0.15–0.20 $W/(m^2 \cdot K)$, and VT is kept within the range of 0.6–0.7 h^{-1}.
3. Based on orthogonal experiment analysis, the order of significance for the OE and OC indicators was observed to be OB > HS > VT > K_R > BO > K_E. Similarly, for the CE indicators, the order of significance was OB > HS > VT > BO > K_R > K_E. Regarding the HE indicators, the order of significance was found to be OB > VT > BO > K_E > K_R > HS. OB and HS had the most significant impacts on OE, OC, and CE, while OB was shown to have a significant effect on HE, although HS had a relatively smaller effect on HE.
4. The CE requirement in the experiment was mostly met, whereas the HE indicator showed a dissatisfaction rate of nearly 40%. Achieving the heat consumption requirement for winter heating in residential buildings located in HSCW zones proved to be more challenging compared to meeting the cold consumption requirement for summer cooling. Therefore, it is recommended that nearly zero-energy design in HSCW zones should prioritize heating design.
5. Depending on a single indicator as the sole evaluation criterion for nZEBs lacks rigor, and persisting in making energy-saving improvements solely to meet a specific indicator may lead to economic inefficiency. It is recommended that different design solutions are adopted for different evaluation indicators during the building design phase, with the aim of reducing energy consumption, minimizing carbon emissions, and achieving sustainable development goals.

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

Appendix A

Table A1. Orthogonal experiment design matrix.

No.	A (K_E)	B (K_R)	C (HS)	D (OB)	E (BO)	F (VT)
L1	1	1	1	1	1	1
L2	1	2	2	2	2	2
L3	1	3	3	3	3	3
L4	1	4	4	4	4	4
L5	1	5	5	5	5	5
L6	2	1	2	3	4	5
L7	2	2	3	4	5	1
L8	2	3	4	5	1	2
L9	2	4	5	1	2	3
L10	2	5	1	2	3	4
L11	3	1	3	5	2	4
L12	3	2	4	1	3	5
L13	3	3	5	2	4	1
L14	3	4	1	3	5	2
L15	3	5	2	4	1	3
L16	4	1	4	2	5	3
L17	4	2	5	3	1	4
L18	4	3	1	4	2	5
L19	4	4	2	5	3	1
L20	4	5	3	1	4	2
L21	5	1	5	4	3	2
L22	5	2	1	5	4	3
L23	5	3	2	1	5	4
L24	5	4	3	2	1	5
L25	5	5	4	3	2	1

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