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Research and Case Application of Zero-Carbon Buildings Based on Multi-System Integration Function

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Abstract: This study focuses on developing and implementing zero-carbon buildings through the integration of multiple systems to meet China's carbon neutrality goals. It emphasizes the significant role of the building sector in carbon emissions and highlights the challenge of increasing energy consumption conflicting with China's "dual carbon" targets. To address this, the research proposes a comprehensive framework that combines multifunctional envelope structure (MES) systems, photovoltaic power generation, energy storage, direct current (DC) systems, flexible energy management (PEDF), and regional energy stations. This framework integrates different technologies such as phase change materials, radiation cooling, and carbon mineralized cement, aiming to reduce carbon emissions throughout the building's lifecycle. The method has been successfully applied in the Yazhou Bay Zero Carbon Post Station project in Sanya, Hainan, with precise calculations of carbon emission reductions. The carbon emission calculations revealed a reduction of 44.13 tons of CO_2 annually, totaling 1103.31 tons over 25 years, primarily due to the rooftop photovoltaic systems. It demonstrates that the multi-system integration can reduce carbon emissions and contribute to China's broader carbon neutrality goals. This approach, if widely adopted, could accelerate the transition to carbon-neutral buildings in China.

Keywords: zero-carbon building; carbon emission calculation; MES; PEDF; energy storage

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1. Introduction

Energy is the foundation of societal development and a guarantee for establishing a sustainable society. The current severe energy situation in China is closely related to the rapid growth in urban building energy consumption. In recent years, the newly added building area in China accounts for approximately one-third of the global annual increase in building space, and the total building energy consumption has shown a year-on-year upward trend [1]. In 2023, China's carbon emissions from the construction sector were about 2.3 billion tonnes, which accounted for roughly 18.25% of China's total carbon emissions. This sector remains a significant contributor to the nation's overall emissions, reflecting the high energy demand for building materials and construction activities in China [2].

With China's "dual carbon" goals of striving to reach peak carbon emissions by 2030 and achieving carbon neutrality by 2060, the construction sector faces dual pressures from energy and environmental demands. There is an urgent need to transform the existing building energy supply methods, promote a systematic upgrade of urban and building low-carbon technologies, and achieve the greening and decarbonization of building energy [3].

To advance China's "carbon peaking and carbon neutrality" efforts, the Chinese government has issued a series of policy documents calling for the acceleration of electrification and decarbonization in building energy use, and supporting the development of renewable energy building supply systems using solar and geothermal energy. In regions where conditions allow, the government encourages the reform of heating metering and the intelligent construction of heating facilities. Additionally, the government supports the establishment of green energy industrial parks and enterprises, the development of industrial green microgrids, and the utilization of clean and low-carbon energy in self-owned locations.

Energy conservation and carbon reduction in building energy supply is a crucial part of China's efforts to achieve its carbon peaking and carbon neutrality goals. If the current energy consumption methods and supply technologies in the building sector remain unchanged, the carbon peak in this sector will significantly lag behind the national carbon peak, posing a substantial challenge to China's commitment to achieving carbon neutrality by 2060. Under the dual carbon strategy, the main approaches to reducing carbon emissions in buildings include enhancing the efficiency of low-grade energy use, developing zero-carbon buildings with solar energy through multi-energy complementary systems, and leveraging natural resource endowments [4,5].

This study aims to achieve zero-carbon buildings by developing a multi-system integrated smart solution, combining materials science, architecture, HVAC, and computer science. The research focuses on integrating multifunctional envelope, PEDF technology, and regional energy stations. This comprehensive approach was applied to a zero-carbon building project in Yazhou Bay, Sanya, with precise carbon emission calculations validating its effectiveness. The results confirm that this solution significantly contributes to achieving zero-carbon building operations, aligning with the study's core objective. The structure of this paper is as follows:

The first section introduces the background of the research. The second section analyzes the development process and key research points of zero-carbon buildings. The third section presents the multi-system integration technology framework for zero-carbon buildings. The fourth section describes the key technologies for achieving zero-carbon buildings. The fifth section discusses project case studies to validate the feasibility of the technological approach. The sixth section discusses the significance of this research. The seventh section summarizes the research, outlines the existing issues, and proposes goals for future research.

2. Developmental Overview

The origins of zero-carbon buildings can be traced back to the energy crisis of the 1970s. At that time, soaring energy prices and supply instability prompted a growing focus on building energy efficiency. During this period, zero-carbon buildings were primarily represented by passive solar homes in the United States and low-energy buildings in Europe. The focus was mainly on reducing energy consumption and carbon emissions through optimized design and construction techniques [6]. For example, Kang Y et al. [7] proposed a comprehensive data-driven-based PSO-SVM-NSGA-III method that assists in optimizing passive design parameters to realize zero-carbon buildings. Ansah M K et al. [8] proposed a parametric design optimization method for low-carbon buildings considering cost-effectiveness and explored the impacts of confounding factors on achieving low-carbon designs. At this stage, design optimization primarily involved passive design strategies, including building orientation, natural ventilation, and daylight utilization, to minimize the need for heating, cooling, and artificial lighting.

With the advancement of renewable energy technologies, solar and wind energy have gradually been integrated into building systems, driving the achievement of zero-carbon goals [9]. For example, the widespread use of photovoltaic systems not only provides clean energy for buildings but also reduces dependence on traditional fossil fuels. Additionally, other renewable energy technologies, such as wind and geothermal energy, are gradually being integrated into buildings to further reduce carbon emissions [10]. Deymi-Dashtebayaz M et al. [11] established a dynamic model of an innovative multigenerational solar–wind-based system from energetic, exergetic, economic, and environmental approaches, which is integrated into a near-zero energy building in St. Petersburg of Russia, with the purpose of covering the hourly cooling, heating, and electricity loads of the building.

Entering the twenty-first century, standards and certification systems for zero-carbon buildings, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), have significantly improved industry norms and practices [12]. These certification systems encourage building projects to adopt best practices in sustainability during design, construction, and operation by setting strict assessment criteria. Additionally, government incentive policies and regulations have globally promoted the development of zero-carbon buildings. Many countries and regions encourage developers and building owners to use zero-carbon technologies through measures such as tax incentives, financial subsidies, and technical support [13]. For example, China's Green Building Action Plan and the European Union's Climate and Energy Framework provide strong policy support for the development of zero-carbon buildings. In recent years, advancements in technologies such as artificial intelligence and digital twins have enabled the real-time monitoring and optimization of building energy through smart building management systems, significantly enhancing operational energy efficiency and further promoting the adoption and sustainable development of zero-carbon buildings [14]. Haidar N et al. [15] established a new consumer-dependent energy management system to reduce cost and carbon impact in smart buildings. Yu L et al. [16] summarized the deep learning algorithms in intelligent building energy management and pointed out possible research directions in the field of building energy management in the future.

The development and application of emerging materials, such as high-performance insulation materials and renewable building materials, will further reduce the carbon footprint of buildings. The innovation of these technologies and materials not only helps achieve zero carbon goals but also enhances the overall performance and comfort of buildings [17]. Kalbasi R and Afrand M [18] researched how to realize zero-carbon buildings through different percentages of phase change materials and thermal insulation materials. Du F et al. [19] have developed a multifunctional cement aerogel material as an external wall of buildings. Its remarkable thermal insulation performance and fire resistance performance will contribute to the realization of zero-carbon buildings. Hua W, Lv X, and Zhang X, et al. [20] researched the progress of seasonal thermal energy storage technology based on supercooled phase change materials.

The PEDF system is an energy management solution that integrates multiple technologies, aiming to achieve efficient energy utilization and reduce carbon emissions. The PEDF system has seen extensive development and application in the building sector, particularly in zero-carbon buildings [21,22]. Kong Y, Zhao Z, and Zhang Z, et al. [23], taking a public building in Xiong'an New District as an example, designed a PEDF system to achieve energy conservation and carbon reduction in the building. Mao T and Xu J [24] introduced the important evaluation index of PEDF building photovoltaic system and took a real project as a case to introduce the whole design process such as model selection, configuration, model construction, system simulation, etc., of PEDF building photovoltaic system.

Integrated energy stations provide strong energy support for zero-carbon buildings by integrating multiple energy resources, improving energy efficiency, and reducing carbon emissions. They are one of the key technologies for achieving carbon neutrality in buildings [25]. Dou Z, Zhang C, and Wang W, et al. [26] provided an overview of integrated energy station technology from multiple perspectives including planning, design, and operation. Xu X, Wang Y, and Ruan Y, et al. [27] proposed an integrated energy planning scheme that is based on a three-step planning method with the objective of achieving the Near-Zero Carbon Emission Demonstration District.

From the above discussion, achieving zero-carbon buildings requires a multifaceted approach involving the selection of building materials and the design of energy supply solutions. It is a complex system engineering challenge [28,29]. The primary technical issue currently limiting the large-scale construction and promotion of zero-carbon buildings is how to develop a universally applicable and scalable multi-system integration solution for zero-carbon buildings.

3. Multi-System Integrated Functional Architecture for Zero-Carbon Buildings

Based on the above analysis, our research team has conducted a lot of research work. The focus is on the key issues and countermeasures in the quantitative mechanism research of zero-carbon buildings, as well as the theoretical framework of energy utilization, conservation, and production in zero-carbon buildings [30–32]. Through these studies, this article proposes the multi-system integrated functional architecture for zero-carbon buildings, as shown in Figure 1.

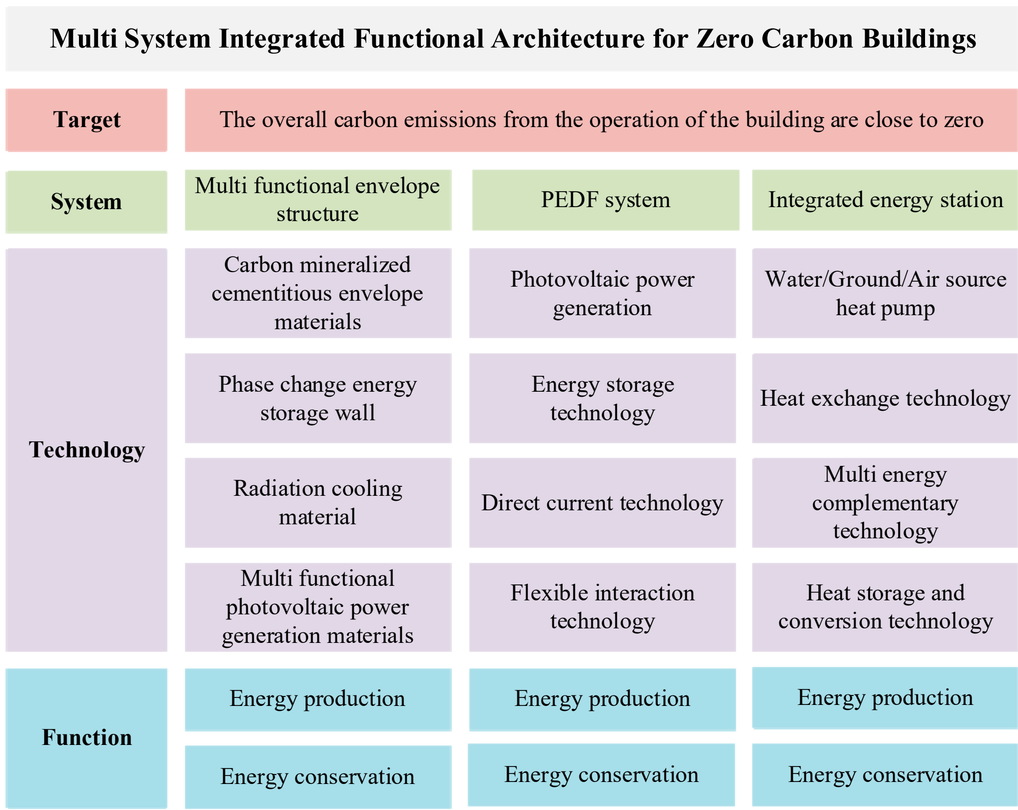

Figure 1. The multi-system integrated functional architecture for zero-carbon buildings.

Achieving near-zero carbon emissions in building operations can be realized through the integration of multifunctional envelope systems, PEDF systems, and regional energy station networks.

Among them, the multifunctional envelope structure system is implemented using technologies such as carbon mineralized cementitious enclosure materials, phase change energy storage walls, radiation cooling materials, and multifunctional photovoltaic power generation materials. (Carbon mineralized cementitious enclosure materials can improve energy efficiency and durability while reducing the building's carbon footprint by utilizing mineralization and recycled content. Phase change energy storage walls incorporate phase change materials (PCMs) to store and release heat, stabilizing indoor temperatures and reducing energy use for heating and cooling. Radiation cooling materials passively cool buildings by emitting heat as infrared radiation, reducing the need for air conditioning. Multifunctional photovoltaic power generation materials generate electricity from sunlight while also providing thermal insulation or shading, supporting energy efficiency and on-site renewable energy generation.)

PEDF system contains photovoltaic power generation technology, energy storage technology, direct current technology, and flexible interaction technology. The PEDF system's components interact directly to optimize energy efficiency in buildings. Photovoltaic (PV) panels generate electricity, which is either used immediately or stored by the energy storage system for later use. The direct current (DC) technology minimizes energy loss by avoiding AC/DC conversion, enhancing the overall efficiency of the energy flow. The flexibility component dynamically adjusts energy consumption and production, responding to fluctuations in demand and supply, thus ensuring stable and efficient energy management, which is crucial for achieving zero-carbon building operations.

An energy station system is a comprehensive energy management solution that integrates multiple renewable and efficient energy technologies. It typically includes water, ground, or air source heat pumps that transfer thermal energy for heating and cooling. Heat exchange systems optimize energy transfer between different sources, while multi-energy complementary systems ensure a balanced energy supply from various resources. Additionally, heat storage and conversion technologies store surplus energy for later use, improving overall efficiency and ensuring a continuous, reliable energy supply in zero-carbon building operations.

This study classified the various functional systems of zero-carbon buildings according to energy production, energy conservation, and energy utilization. All the systems have an energy conservation function.

4. The Key Technologies for Zero-Carbon Buildings

4.1. Multifunctional Envelope Structure

The zero-carbon building MES refers to a building envelope structure that integrates multiple materials to achieve energy conservation, environmental protection, and improved living comfort. This research integrated the four technologies, which are carbon mineralized cementitious enclosure materials, phase change energy storage walls, radiation cooling material, and multifunctional photovoltaic power generation materials into the envelope system of zero-carbon buildings exemplifies a holistic approach to building design. Each technology serves multiple functions, contributing to energy efficiency, thermal comfort, and carbon reduction in complementary ways. This research also designed the roof structure and wall structure of zero-carbon buildings, as shown in Figure 2.

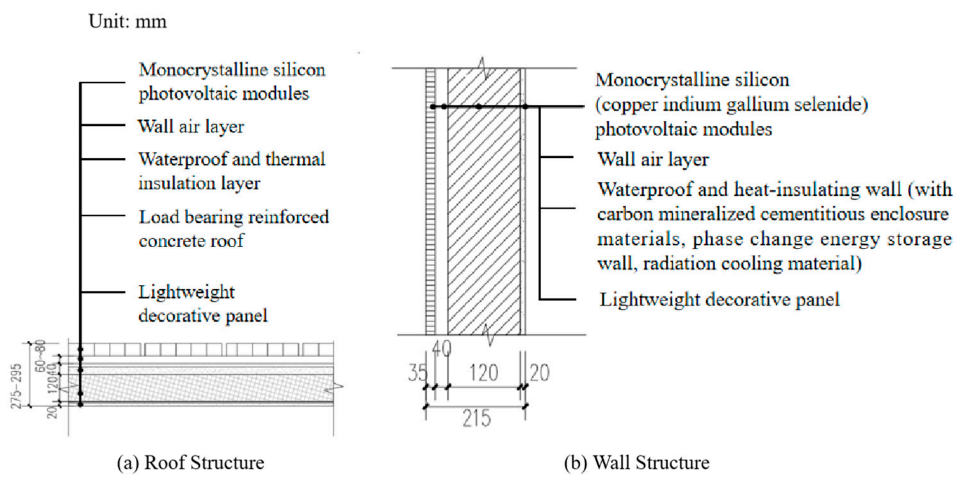

Figure 2. The roof structure and wall structure of zero-carbon buildings.

Figure 2 illustrates the design and composition of the roof and wall structures in zero-carbon buildings. The key materials integrated into the building envelope include carbon mineralized cementitious materials, which absorb CO_2 during their production, reducing the carbon footprint of the building. It also highlights the use of phase change energy storage walls that regulate indoor temperatures by absorbing and releasing heat, thereby reducing energy demands. The radiation cooling materials applied to the roof and walls contribute to passive cooling by emitting thermal radiation, minimizing the need for active cooling systems. Additionally, multifunctional photovoltaic power generation materials are embedded into the structure to produce renewable energy while providing insulation and shading. Together, these materials create a highly efficient envelope system that enhances the building's energy performance and contributes to zero-carbon operation.

(1) Carbon mineralized cementitious enclosure materials

Carbon mineralized cementitious materials are advanced building materials that incorporate carbon dioxide (CO_2) into their structure during the production process. This is achieved through a chemical process known as carbonation, where CO_2 is reacted with calcium compounds in the cement to form stable calcium carbonates. This process not only sequesters CO_2, reducing the carbon footprint of the material, but also enhances the material's mechanical properties such as strength and durability.

These materials are used in constructing the structural components of buildings, such as walls, floors, and roofs. By integrating carbon mineralized cementitious materials into the enclosure system, the building can significantly reduce its embodied carbon. This contributes to the overall goal of zero-carbon buildings by lowering the carbon emissions associated with construction.

(2) Phase change energy storage wall

Phase change materials (PCMs) are substances that absorb or release significant amounts of latent heat when they change their physical state (e.g., from solid to liquid or vice versa). A phase change energy storage wall incorporates PCMs to regulate indoor temperatures. When the temperature rises, the PCM absorbs excess heat by melting. When the temperature drops, the PCM releases stored heat by solidifying. This thermal energy storage capability helps to maintain a stable indoor environment and reduces the demand for heating and cooling.

Phase change energy storage walls are integrated into the building's envelope, acting as both thermal insulation and a thermal buffer. By absorbing and releasing heat, these walls help to moderate indoor temperatures, reduce energy consumption for heating and cooling, and enhance overall energy efficiency. This contributes to the zero-carbon building's energy performance, ensuring comfort while minimizing energy use.

(3) Radiation cooling material

Radiation cooling materials are designed to passively cool buildings by radiating heat away from the building's surface to the sky, particularly at night. These materials have high emissivity in the infrared spectrum, allowing them to effectively emit thermal radiation. They can also have selective reflection properties, reflecting most of the solar radiation while allowing the building to cool through radiative heat loss.

These materials can be applied to roofs and exterior walls, playing a crucial role in reducing the cooling load of the building. By incorporating radiation cooling materials into the enclosure system, the building can dissipate excess heat more effectively, lowering indoor temperatures without the need for active cooling systems. This passive cooling strategy is essential for reducing energy consumption and achieving zero carbon status.

(4) Multifunctional photovoltaic power generation materials

Multifunctional photovoltaic (PV) materials combine traditional PV technology with additional functions such as thermal insulation, shading, and aesthetic enhancement. These materials are often integrated into building elements like facades, roofs, and windows (Building-Integrated Photovoltaics or BIPV). They generate electricity from sunlight while simultaneously serving other architectural functions.

In a zero-carbon building, these materials are key components of the building's energy system. By integrating PV materials into the building's envelope, the structure can produce renewable energy on-site, reducing reliance on external power sources and contributing to net zero energy goals. Additionally, their multifunctional nature means they provide additional benefits such as insulation and shading, further enhancing the building's energy efficiency.

4.2. Photovoltaic, Energy Storage, Direct Current, Flexibility (PEDF) System

By incorporating the PEDF system, zero-carbon buildings can achieve high energy efficiency, enhance reliability, and significantly reduce their carbon footprint. Among them, photovoltaic technology provides a sustainable and renewable source of electricity. Energy storage technology ensures that this renewable energy is available when needed, overcoming the intermittency of solar power. Direct current technology improves the efficiency of energy systems by minimizing conversion losses. Flexibility technology enables smart, adaptive energy management, optimizing the balance between energy supply and demand. These technologies work together to create an energy ecosystem that supports sustainability goals, reduces dependence on non-renewable energy sources, and paves the way for a resilient, low-carbon future in the built environment. The relationship between these four technologies is shown in Figure 3.

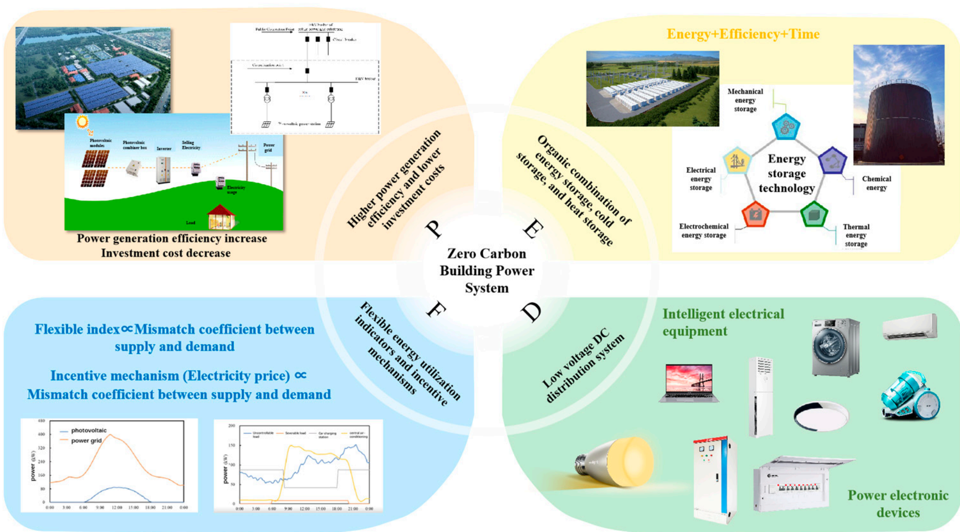

Figure 3. The interrelationships of PEDF technologies.

Figure 3 outlines the interaction between the four core technologies of the PEDF system: photovoltaic (PV) technology, energy storage, direct current (DC) systems, and flexibility. The PV technology generates electricity from sunlight, which is either used immediately or stored via the energy storage system. DC technology optimizes the system's energy efficiency by reducing the losses associated with AC/DC conversions. Flexibility refers to the system's capacity to adjust energy production and consumption in response to demand changes, optimizing overall energy use. These technologies work synergistically to maximize the use of renewable energy and ensure efficient energy management in zero-carbon buildings.

(1) Photovoltaic (PV) technology

Photovoltaic technology involves the conversion of sunlight into electricity using semiconductor materials that exhibit the photovoltaic effect. Solar panels, composed of multiple solar cells, capture solar energy and convert it into direct current (DC) electricity. This technology is central to harnessing renewable energy from the sun.

In zero-carbon buildings, PV technology is essential for generating on-site renewable energy. By installing solar panels on rooftops and facades, or integrating them into building materials (Building-Integrated Photovoltaics or BIPV), buildings can produce a significant portion of their energy needs from a clean, sustainable source. This reduces dependence on fossil fuels, lowers carbon emissions, and supports the goal of achieving net zero energy consumption.

(2) Energy storage technology

Energy storage technology involves capturing energy produced at one time for use at a later time. The most common form is battery storage, which stores electricity in chemical form and releases it as needed. Other forms include thermal storage, where excess heat or cold is stored and later used for heating or cooling, and mechanical storage such as pumped hydro or compressed air.

Energy storage systems are crucial for balancing supply and demand in zero-carbon buildings. They enable the storage of excess energy generated by PV systems during peak production periods (e.g., sunny days) and provide power during periods of low or no solar generation (e.g., nighttime or cloudy days). This ensures a stable and reliable energy supply, enhances energy security, and optimizes the use of renewable energy, thereby reducing the need for grid electricity and associated carbon emissions.

(3) Direct Current (DC) Technology

Direct current technology refers to the use of DC electricity, which flows in one direction, as opposed to alternating current (AC) electricity, which periodically reverses direction. Many modern electronic devices, as well as solar panels and batteries, inherently use DC power. Utilizing DC systems can reduce energy losses associated with AC/DC conversion.

In zero-carbon buildings, employing DC technology can improve energy efficiency. By creating DC microgrids or using DC distribution systems, buildings can directly connect PV systems and battery storage without the need for multiple conversions between AC and DC, which typically result in energy losses. This streamlined approach enhances the overall system efficiency, reduces energy waste, and supports the integration of renewable energy sources, thereby contributing to the zero carbon goal.

(4) Flexibility Technology

Flexibility technology encompasses a range of systems and strategies designed to adapt energy production, consumption, and storage in response to changing conditions. This includes demand response (adjusting energy use based on grid signals), flexible loads (appliances or systems that can shift their operation times), and grid-interactive efficient buildings that actively manage energy use in coordination with grid needs.

Flexibility technology is key to optimizing energy management in zero-carbon buildings. By dynamically adjusting energy usage patterns, integrating real-time data, and interacting with the grid, buildings can enhance their energy efficiency, reduce peak demand, and better utilize renewable energy. For instance, during periods of high solar generation, a flexible building might increase energy consumption for tasks like charging batteries or pre-cooling spaces, while reducing usage during peak grid demand times. This intelligent energy management helps to maximize the use of renewable energy, stabilize the grid, and further reduce carbon emissions.

4.3. Integrated Energy Station Technology

Integrated energy station technology is one of the important technologies for achieving zero-carbon buildings. It provides efficient heating and cooling by utilizing renewable thermal energy sources, like water/ground/air source heat pumps and heat exchange technology. To ensure a balanced, resilient, and efficient energy supply, the integrated energy station can integrate various renewable sources, storage solutions, and conversion technology. By integrating the integrated energy station technology, zero-carbon buildings can achieve high energy efficiency, reliability, and sustainability. This comprehensive approach reduces reliance on fossil fuels, lowers carbon emissions, and supports the broader goals of energy security and environmental stewardship. Taking the energy storage ground source heat pump energy station as an example, the system process principle is illustrated in Figure 4.

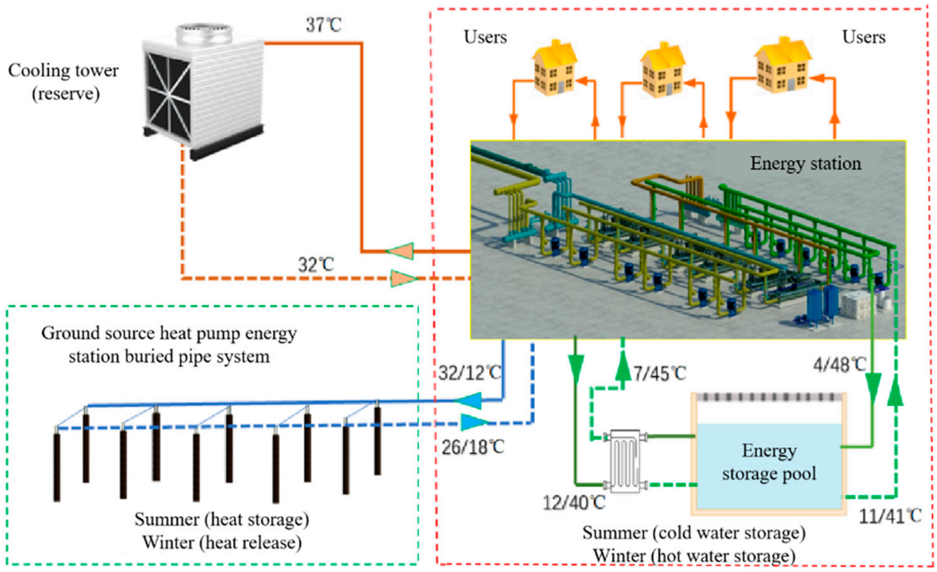

Figure 4. The system process principle of the energy storage ground source heat pump energy station.

Figure 4 presents the operational process of an energy station that uses a ground source heat pump in conjunction with energy storage. The system transfers heat between the ground and the building, utilizing renewable geothermal energy to provide heating and cooling. Additionally, heat exchange technology enhances energy efficiency by recycling thermal energy within the building. The integration of multi-energy complementary technologies allows for the combined use of various energy sources, ensuring a consistent energy supply. The energy station stores surplus energy during periods of high renewable generation and utilizes it during low-generation periods, improving the overall system resilience and reducing carbon emissions.

(1) Water/Ground/Air source heat pump

Heat pumps are devices that transfer heat from one location to another using a refrigeration cycle. They are highly efficient because they move heat rather than generating it directly. Depending on the source of heat's difference, heat pumps can be classified as follows:

- Water source heat pump: Extracts heat from a water source (such as a lake, river, or underground water).
- Ground source heat pump (geothermal): Extracts heat from the ground, typically through buried pipes filled with a heat transfer fluid.
- Air source heat pump: Extracts heat from the outside air.

Heat pumps are crucial for zero-carbon buildings due to their high efficiency and ability to utilize renewable energy sources. By leveraging water, ground, or air as heat sources, these systems can reduce the reliance on fossil fuels for heating and cooling significantly. This leads to lower carbon emissions and enhances the building's energy efficiency, contributing to the overall goal of achieving zero carbon status.

(2) Heat exchange technology

Heat exchange technology involves the transfer of heat between two or more fluids without mixing them. Common types of heat exchangers include the following:

- Plate heat exchangers: Use metal plates to transfer heat between two fluids.
- Shell and tube heat exchangers: Consists of a series of tubes, one set containing the fluid to be heated or cooled and the other set containing the heating or cooling fluid.

- Heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs): Transfer heat (and sometimes moisture) between incoming and outgoing air streams in ventilation systems.

Heat exchange technology enhances the energy efficiency of zero-carbon buildings by recovering and reusing waste heat. For example, HRVs and ERVs can capture heat from exhaust air and use it to preheat incoming fresh air, reducing the need for additional heating. Efficient heat exchange systems minimize energy wastage and optimize the use of available thermal energy, thereby reducing overall energy consumption and carbon emissions.

(3) Multi-energy complementary technology

Multi-energy complementary technology involves the integration and optimization of multiple energy sources to meet the energy demands of a building or region. By combining multiple energy sources and storage solutions, buildings can maximize the use of renewable energy, minimize dependence on fossil fuels, and enhance energy security. The complementary use of different energy forms allows for flexible and efficient energy management, which is critical for maintaining low carbon emissions and achieving zero carbon goals.

(4) Heat storage and conversion technology

Heat storage and conversion technology is an important method for converting low-value energy into high-value energy, which is widely used in energy stations. It is essential for zero-carbon buildings because they enable the efficient use of intermittent renewable energy. By storing excess thermal energy when renewable generation is high and using it when generation is low, these technologies ensure a consistent and reliable energy supply. This reduces the need for backup fossil fuel-based systems, lowers carbon emissions, and enhances the building's energy independence and resilience.

5. Comprehensive Carbon Emission Calculation Method

Combining the introduction in the previous text, this research presents a comprehensive carbon emission calculation method, including energy consumption calculation, renewable energy generation calculation, energy storage and utilization efficiency calculation, carbon emission calculation, and carbon offset and net emissions. In this method, each formula builds upon the previous one, providing a step-by-step approach to calculating the building's energy consumption, renewable energy contributions, storage efficiency, and net carbon emissions. It offers a comprehensive tool for achieving and assessing zero-carbon building operations together.

(1) Energy Consumption Calculation

$$E_{total} = E_{heating} + E_{cooling} + E_{lighting} + E_{appliances} + E_{ventilation} \quad (1)$$

Formula (1) sums up the total energy consumption of a building, accounting for all primary energy uses. E_{total} represents the total energy consumption, and $E_{heating}$ and $E_{cooling}$ represent the major energy consumers in buildings. Advanced heating technologies like water/ground/air source heat pumps can significantly reduce these energy needs by utilizing renewable heat sources. $E_{lighting}$ represents the energy consumption of lighting systems. $E_{appliances}$ represents the energy consumption of appliances. $E_{ventilation}$ represents the energy consumption of ventilation systems. This formula calculates the total energy consumed by the building, including contributions from major energy-consuming systems such as lighting, appliances, and ventilation. It also considers advanced heating technologies, like heat pumps, which can reduce the overall energy demand by utilizing renewable heat sources.

(2) Renewable Energy Generation Calculation

$$E_{renewable} = E_{PV} + E_{other} \quad (2)$$

Formula (2) represents the renewable energy generated by the building, including photovoltaic (solar) energy and energy from wind, biomass, or geothermal sources.E_{PV} represents the energy generated by photovoltaics, and E_{other} represents the energy generated by other renewable energy technologies. This formula assesses the amount of renewable energy generated by the building, primarily through photovoltaic systems, as well as other renewable sources like wind, biomass, or geothermal energy. It plays a key role in determining how much of the building's energy consumption can be offset by renewable generation.

(3) Energy Storage and Utilization Efficiency

$$E_{storage} = \eta_{storage} \times (E_{PV} - E_{direct\_use}) \quad (3)$$

Considering storage efficiency, Formula (3) determines the effective energy stored for later use. $\eta_{storage}$ represents the efficiency of energy storage systems, and E_{direct_use} represents the energy from PV systems used immediately without being stored. This formula evaluates the efficiency of the energy storage systems, which capture surplus renewable energy for later use. It also accounts for the energy used immediately from photovoltaic systems, ensuring that energy is efficiently utilized without unnecessary wastage.

(4) Carbon Emission Calculation

$$C_{total} = \sum_i (E_{consumed,i} \times EF_i) - \sum_j (E_{renewable,j} \times EF_{renewable,j}) \quad (4)$$

Formula (4) calculates the total carbon emissions by considering both the energy consumed from non-renewable sources and the energy offset by renewable sources. $E_{consumed,i}$ represents the energy sourced from non-renewable resources such as natural gas or coal. EF_{i} represents the carbon emissions per unit of energy for each non-renewable source. $E_{renewable,j}$ represents the carbon emission offset of renewable energy. $EF_{renewable,j}$ represents the emission factors for renewable energy, which are generally zero since renewable energy sources like solar and wind do not produce direct carbon emissions. This formula calculates the total carbon emissions by considering the energy consumed from non-renewable sources and subtracting the carbon offset from renewable energy. It factors in emission rates for different energy sources, recognizing that renewable energy sources like solar and wind produce no direct carbon emissions.

6. Case Study

6.1. Case Introduction

Hainan Province has abundant solar energy resources, with a high annual average of sunshine hours, making it ideal for developing zero-carbon buildings. The province has introduced several key policy initiatives to promote this development, including the "Zero Carbon Island" initiative, which aligns with China's carbon neutrality goals. This initiative aims to reduce energy demand, improve energy efficiency, and expand the use of renewable energy sources.

This project in this research is located in the Yazhou Bay area of Sanya, Hainan Province, China, and is part of a government-funded initiative that employs new technologies. The project includes two types of public convenience structures: coastal city post stations and city block post stations. The former is constructed with brick and concrete, while the latter utilizes prefabricated steel structures. Both types of buildings are single-story and cover an area of approximately 250 to 300 square meters. Due to the limited natural resources in the project's location and the constraints of the project budget, the project only achieves green energy conservation in buildings through the use of PV technology on rooftops.

To ensure a stable power supply and to save on independent storage costs, the rooftop photovoltaic system is directly connected to the public grid. At the same time, the project adopts a household lithium-ion battery energy storage method to meet more than 6 h of electricity usage demand at night. The project is shown in Figure 5.

Figure 5. Top view of zero carbon building project. (**a**) City block post station. (**b**) Coastal city post station.

6.2. Carbon Emission Calculation

(1) Installed capacity

The suitable area for installing photovoltaics on the roofs of a coastal city post station is 192 square meters, while for a city block post station, it is 100 square meters. This project utilizes tempered laminated power glass (240 W per piece) with dimensions of 1200 × 1600 mm and a composition of 3.2 CdTe (Cadmium Telluride) + 0.5 POE (Polyolefin Elastomer) + TP (Tempered Glass) 3.2 to complete the rooftop photovoltaic power generation system. In total, 100 roofs were equipped with photovoltaic systems at the coastal city post station and 52 at the city block post station, amounting to 152 roofs and an installed capacity of approximately 36.48 kWp.

In addition, this project uses a high-pressure liquid-cooled battery prefabricated cabin for energy storage to meet the building's nighttime electricity needs. According to design specifications, the daily stored electricity is generally twice the daily generated electricity. Therefore, the maximum storage capacity of this project is 80 kWp. The parameters of the energy storage system are in Table 1.

(2) Calculation of power generation

This project, using Meteonorm meteorological data, determined that the annual average total solar radiation in Sanya City, Hainan Province, is 6142.55 MJ/m^2, with an annual average of 1706.4 peak sunshine hours. Figure 6 illustrates the sun's path across the sky relative to a tilted plane with a 17° inclination facing true north (azimuth 0°). The vertical axis represents the sun's height above the horizon, while the horizontal axis shows its azimuth, or compass direction. The yellow area indicates the sun's trajectory throughout the day, with specific time labels marking the sun's position at different hours. The red line shows when the sun is visible in front of the plane, while the blue line represents times when the sun is below the plane's horizon.

The annual power generation and its attenuation of a rooftop photovoltaic system over 25 years were simulated using the PVSYST 7.2 photovoltaic simulation software. PVSYST 7.2 is a widely used PV simulation software designed for the analysis, design, and optimization of solar energy systems. It allows users to model and simulate various types of solar PV systems, including grid-connected, stand-alone, and hybrid systems.

Table 1. Summary of energy storage system parameters.

Parameter	Details
Rated Power	80 kWp
Battery Capacity	Approximately 200–300 kWh
Operating Voltage Range	600–1000 v DC
Battery Type	Liquid-cooled lithium-ion battery
Battery Life	10–15 years or 5000–7000 cycles
Cooling Method	High-pressure liquid cooling system
Operating Temperature Range	−20 °C to 45 °C
System Efficiency	90–95% (including cooling and inverter losses)
Response Time	<200 ms
Control System	Integration with grid or building management systems (BMS)
Prefabricated Cabin Dimensions	Standard 40 ft container
Weight	15 tons

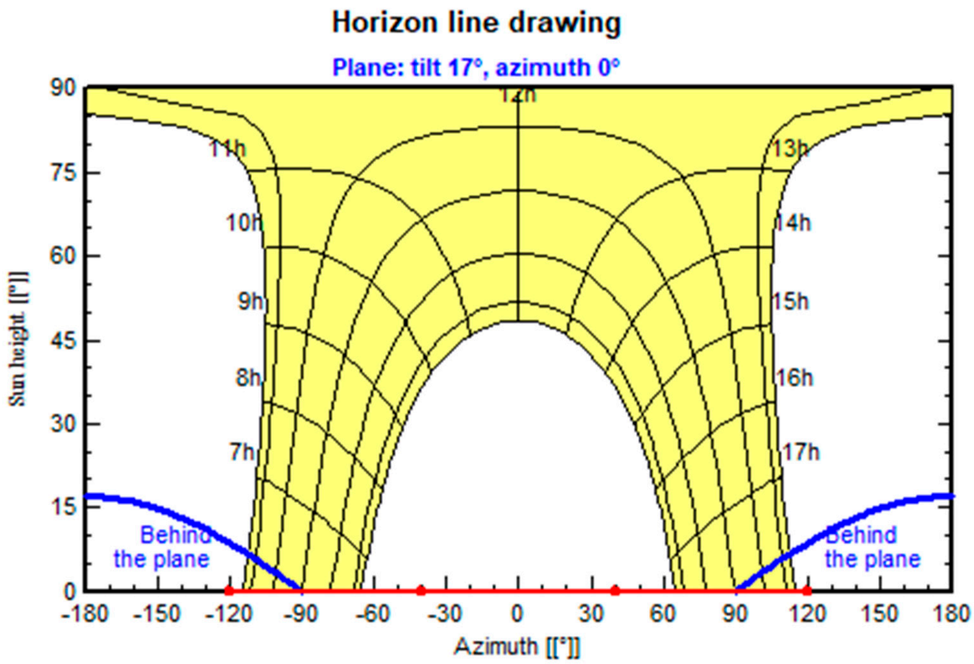

Figure 6. Solar path in relation to the horizon at a specific location.

Table 2 shows the rooftop power generation of coastal city post stations. In the first year, the system generated 30,500 kWh of electricity, which gradually declined at a rate of 0.4% each year until the 25th year, when the power generation decreased to 27,700 kWh. The cumulative total power generation over 25 years is 727,558 kWh, with an overall attenuation ratio of 14.60%.

Similarly, Table 3 shows the rooftop power generation of city block post stations. In the first year, the system generated 15,900 kWh of electricity, which gradually declined at a rate of 0.4% each year until the 25th year, when the power generation decreased to 14,400 kWh. The cumulative total power generation over 25 years is 379,064 kWh, with an overall attenuation ratio of 14.60%.

From the data in Tables 1 and 2, it can be predicted that the cumulative power generation of this zero-carbon building project during its 25-year lifespan will be approximately

1,106,622 kWh, with an average annual power generation of approximately 44,265 kWh. Due to the main function of the post station in this project being to provide convenient services such as public toilets and shops for urban residents, the electricity consumption is very low. According to estimates, the average annual electricity consumption of each post station is approximately 100 kWh/square meter. The power generation of the rooftop photovoltaic system can meet the electricity demand of the post stations.

Table 2. Roof power generation of coastal city post stations.

Year	Annual Power Generation (10,000 kWh)	Attenuation Ratio (%)	Year	Annual Power Generation (10,000 kWh)	Attenuation Ratio (%)
1	3.05	5	14	2.90	0.40
2	3.04	0.40	15	2.89	0.40
3	3.03	0.40	16	2.87	0.40
4	3.02	0.40	17	2.86	0.40
5	3.00	0.40	18	2.85	0.40
6	2.99	0.40	19	2.84	0.40
7	2.98	0.40	20	2.83	0.40
8	2.97	0.40	21	2.82	0.40
9	2.96	0.40	22	2.81	0.40
10	2.94	0.40	23	2.79	0.40
11	2.93	0.40	24	2.78	0.40
12	2.92	0.40	25	2.77	0.40
13	2.91	0.40	Total	72.7558	14.60

Table 3. Roof power generation of city block post stations.

Year	Annual Power Generation (10,000 kWh)	Attenuation Ratio (%)	Year	Annual Power Generation (10,000 kWh)	Attenuation Ratio (%)
1	1.59	5	14	1.51	0.40
3	1.58	0.40	16	1.50	0.40
4	1.57	0.40	17	1.49	0.40
5	1.57	0.40	18	1.49	0.40
6	1.56	0.40	19	1.48	0.40
7	1.55	0.40	20	1.47	0.40
8	1.55	0.40	21	1.47	0.40
9	1.54	0.40	22	1.46	0.40
10	1.53	0.40	23	1.46	0.40
11	1.53	0.40	24	1.45	0.40
12	1.52	0.40	25	1.44	0.40
13	1.52	0.40	Total	37.9064	14.60

(3) Carbon and other pollutant emissions calculation

According to the "Annual Development Report of China's Power Industry 2020", the energy-saving and emission reduction benefits are estimated based on the coal consumption standard of 0.328 kg/kWh, carbon dioxide emissions of 0.997 kg/kWh, sulfur dioxide emissions of 0.03 kg/kWh, nitrogen oxide emissions of 0.015 kg/kWh, and smoke emissions of 0.272 kg/kWh for thermal power plants with a capacity of 6000 kW or more nationwide. The calculation results are shown in Table 4. This project can reduce 44.1322 tons of carbon dioxide emissions annually. Within a lifespan of 25 years, a total of 1103.3051 tons of carbon dioxide emissions can be reduced.

Table 4. Carbon and other pollutant emissions calculation.

Project	Save Standard Coal (Ton)	Reduce CO_2 Emissions (Ton)	Reduce SO_2 Emissions (Ton)	Reduce N_XO_X Emissions (Ton)	Reduce Smoke and Dust Emissions (Ton)
Per year	14.5189	44.1322	1.3280	0.6640	12.0401
25 year total	362.9730	1103.3051	33.1988	16.5994	301.0020

6.3. Research Result

The results demonstrate the effectiveness of the integrated multi-system approach in significantly reducing the carbon footprint of zero-carbon buildings. The annual reduction of 44.13 tons of CO_2 and the cumulative 1103.31 tons over 25 years highlight the long-term sustainability and environmental benefits of these technologies. This substantial reduction, achieved primarily through the integration of photovoltaic systems and energy-efficient building designs, underscores the practicality of these solutions in mitigating climate change. Additionally, this outcome illustrates that even with a single zero-carbon technology used, the proposed systems can make a meaningful impact on reducing operational carbon emissions in buildings. The results also suggest the scalability of this approach, making it applicable to a wide range of building projects, thus contributing to national and global carbon neutrality goals.

7. Research Significance

7.1. Theoretical Significance

This research introduces the integration of multifunctional envelope systems, PEDF systems, and regional energy station systems, providing an innovative theoretical framework for the field of zero-carbon buildings and addressing the gap in the existing research where these systems are studied in isolation. The methodology systematically explores the potential for achieving zero carbon emissions in buildings through the synergistic interaction of multiple systems, thereby advancing the theoretical development of zero-carbon building construction methods.

7.2. Practical Significance

The multi-system integration method proposed in this study not only effectively achieves zero carbon emissions in buildings, contributing to the realization of carbon neutrality goals, but also offers high replicability and scalability. It has been successfully applied in the zero carbon post station project in Yazhou Bay, Sanya, Hainan, providing valuable experience for similar projects in other regions. This method balances significant environmental benefits with economic feasibility, offering practical guidance for the development of future smart cities and the widespread adoption of sustainable building technologies.

8. Conclusions

This research presents a comprehensive multi-system integration that combines multifunctional envelope systems, PEDF systems, and regional energy station systems to address the challenge of achieving zero-carbon buildings. This innovative framework bridges the research gap where these technologies have typically been studied in isolation and offers a scalable solution for sustainable architecture. The methodology was successfully implemented in the zero-carbon post station project in Yazhou Bay, Sanya, where it demonstrated practical feasibility. Carbon emission calculations revealed a reduction of 44.13 tons of CO_2 annually, totaling 1103.31 tons over 25 years, primarily due to the rooftop photovoltaic systems.

Despite these positive results, significant challenges remain for zero-carbon buildings. Resource limitations, high initial costs, and the complexity of integrating various technologies, such as energy storage and smart management systems, pose barriers to wider adoption. Moreover, geographic and climatic variability can influence the effectiveness of certain technologies, such as renewable energy generation and storage. These factors demand flexible and localized solutions, which complicates standardization and scalability. Future research will focus on the intelligent energy management system and adapting all of these technologies to diverse resource conditions and climates, while further validating through case studies. Addressing these challenges is crucial to enhance the global applicability of zero-carbon building solutions and contribute to the broader goal of carbon neutrality.

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Conflicts of Interest: Author Jiaji Zhang and Shize Yang are employed by the company Hainan Yourui Cohesion Technology Co., Ltd. Author Yuting Lin is employed by Sanya Yazhou Bay Science and Technology City Management Bureau. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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