Proceedings of CONF-MCEE 2026 Symposium: Geomaterials and Environmental Engineering
DOI: 10.54254/2755-2721/2026.MH29350

Research on an Energy-Saving Technology Framework Based on Building Climatic Zones Characteristics

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Abstract. In response to the expectations for carbon neutrality and the demand for energy efficiency in the building sector, zero-energy and nearly zero-energy buildings have become key development pathways. This paper employs a literature review and case study analysis methodology. Based on the national standard GB 50178-93, "Standard for Building Climate Zoning," it investigates the application of passive, active, and renewable energy technologies tailored to the climatic characteristics and energy efficiency needs of five typical building climate zones. It proposes an integrated climate-adaptive technology framework that combines these three elements. The article further identifies current challenges in material performance and costs and offers recommendations. This study provides theoretical references and practical guidance for the deepening and large-scale promotion of energy-saving practices in Chinese architecture.

Keywords: Building Energy Saving, Building Climatic Zones, Zero-energy Buildings, Passive Technologies, Active Technologies, Renewable Energy Systems

1. Introduction

Global advocacy and aspirations for carbon neutrality have, over the past few decades, prompted the emergence and rapid development of pioneering concepts such as "ultra-low energy consumption buildings," "near-zero energy buildings," and "zero-energy buildings". These concepts not only represent the highest level of building energy efficiency technology but also guide the future direction of architectural development. Urban building and transportation energy consumption typically constitute a significant portion of a city's total energy use. Data indicate that the energy consumption of the building sector can reach up to 40% of total urban energy use [1]. In China, building energy consumption accounts for approximately 28% of the total national energy consumption, with a rising trend due to urbanization and improved living standards [2]. Recently, policies and development frameworks such as Europe's "Fit for 55" policy and China's 14th Five-Year Plan have introduced relevant requirements and targets to regulate energy consumption in the construction industry and achieve carbon reduction goals [3]. Against this backdrop, systematically reviewing and constructing a technology system adapted to China's unique climatic conditions holds significant theoretical and practical importance for guiding building practices and achieving emission reduction targets.

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To address this gap, this paper utilizes literature review and case study methods to conduct a detailed review and evaluation of passive techniques, active techniques, and renewable energy. By selecting and analyzing typical demonstration cases from different climate zones, it empirically examines the climate adaptation strategies and energy-saving effects of various technology combinations in practical applications, thereby constructing a technology selection and application framework based on China's climatic characteristics.

2. Literature review

Building energy efficiency is the core pathway to achieving ultra-low, near-zero, or zero-energy targets. Its measures can be broadly categorized into either a dichotomy of "passive and active strategies" or a trichotomy of "passive techniques, active techniques, and renewable energy" [4]. However, while the dichotomy is logically concise, it can lead to confusion in classifying specific technologies; for instance, there is debate over whether motorized shading systems should be classified as passive or active. The trichotomous method offers clearer categorization, albeit at the expense of enabling direct energy balance calculations for buildings.

Consequently, Jeongyoon et al., who have analyzed global nZEB buildings over the past decade, have further subdivided passive strategies into passive sustainable design and energy-saving techniques, and active strategies into renewable energy and its backup systems [5]. Meanwhile, Feng et al., who have investigated 34 nZEB buildings in hot-humid regions, have proposed overall strategies for passive and active near-zero energy buildings, detailing them into passive design, energy efficiency, and the integration of renewable energy technologies [6]. Empirical research conducted by Walter D. Thomas has demonstrated that technologies such as enhanced building envelope insulation, airtightness, and passive solar heating can significantly reduce building base loads, enabling the remaining energy demands to be met through renewable energy [7].

Based on this theoretical background, to address the existing research's overemphasis on single technologies and the consequent lack of an adaptive framework for China's multiple climatic zones, this paper proposes an energy-saving technology adaptation system based on China's primary building climatic zones, providing a reference for other studies in the field.

3. Introduction to core principles of building design

3.1. Introduction to core passive principles

Passive energy-saving techniques are the cornerstone of achieving ultra-low energy consumption in buildings. The core of these techniques lies in maximizing the use of natural conditions to achieve indoor comfort through the building's own design and material selection, rather than relying on mechanical equipment. Research indicates that heat loss through heat transfer via the building envelope can account for up to 75% of total building energy consumption. Therefore, the focus of passive techniques is on optimizing the building envelope, with main technical directions as follows [8].

For wall and roof insulation, the emphasis is on applying high-performance insulation materials to enhance the thermal resistance of the envelope. The performance of traditional materials is being further improved. For instance, incorporating graphite particles into EPS can reduce its thermal conductivity to below 0.030 W/(m·K) and enhance its infrared reflection capability, allowing for approximately a 20% reduction in thickness to achieve equivalent performance. New materials like Thermoset Modified Polystyrene Board (TPS) achieve higher fire resistance ratings through

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chemical modification and serve as core insulation materials in TPA insulated decorative finished panels. Ultra-thin Vacuum Insulation Panels (VIP), with extremely low thermal conductivity (only 1/10 to 1/5 of that of traditional materials), are suitable for building energy retrofit projects or space-constrained areas [9].

Integrated insulation and decorative systems involve pre-fabricating insulation and finishing layers for one-time on-site installation, effectively addressing issues associated with traditional thin plaster systems, such as cracking and detachment, as well as the complexity of construction procedures [10, 11]. Autoclaved aerated concrete (AAC) blocks, as a new wall material, combine structural enclosure and insulation functions [12]. Their lightweight, fire-resistant, and easy-to-process characteristics allow them to meet energy-saving requirements directly in regions with hot summers and cold winters, thus eliminating the need for additional external insulation.

External windows and doors represent weak points in the building envelope's energy performance. Passive buildings require these components to possess both high thermal insulation properties and controllability. Passive windows typically use multi-chamber plastic frames or thermally broken aluminum alloy frames filled with efficient foam insulation. Glazing commonly employs triple-pane insulating glass units with double Low-E coatings filled with inert gas (e.g., argon), or even composite vacuum glazing [13].

3.2. Introduction to active principles and renewable technologies

Active energy-saving technologies, while meeting building comfort demands, significantly reduce fossil fuel consumption and operating costs by employing high-efficiency mechanical equipment and integrating renewable energy systems.

3.2.1. High-efficiency heat recovery ventilation systems

These systems primarily use heat recovery units to pre-cool or pre-heat fresh air via duct systems, thereby regulating the temperature of fresh air temperature, reducing building heating and cooling loads, and improving the efficiency of the ventilation system. Relevant studies indicate that when the sensible heat efficiency of a heat recovery unit reaches 70%, building heating energy consumption can be reduced by nearly half, making it one of the key technologies for achieving ultra-low energy consumption buildings [14].

Based on their energy recovery method, fresh air heat recovery units can be categorized into sensible heat recovery units and total (enthalpy) heat recovery units. Sensible heat recovery units only transfer sensible heat and are therefore suitable for arid climate regions. Total heat recovery units can transfer both sensible and latent heat, making them thus more suitable for humid climate regions [15].

3.2.2. Building-integrated photovoltaics

Beyond the energy-saving potential inherent in the building envelope itself, integrating or attaching photovoltaic systems, which are referred to as Building-Applied (BA) or Building-Integrated (BI) PV systems, can meet building energy demands and reduce peak electrical loads [16].

PV systems come in various forms. For example, Semi-Transparent Photovoltaics (STPV) can be used in windows, thereby reducing solar heat gain while generating electricity; and Photovoltaic Shading Devices (PVSD), such as PV louvers and PV awnings, can generate electricity while simultaneously controlling solar radiation [17]. The power generation capacity of Building-

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Integrated Photovoltaic (BIPV) systems varies depending on climate type, building requirements, their intrinsic properties, and installation methods. Research shows that China possesses abundant wind and solar resources, with the potential of wind and PV technologies far exceeding the installed capacity required to meet carbon neutrality scenarios [18].

3.2.3. Ground Source Heat Pumps

Ground Source Heat Pumps (GSHP) are efficient renewable energy systems for building applications. GSHP systems utilize soil, groundwater, or surface water as heat sources/sinks, thereby offering sustainability and environmental benifits. In recent years, the application of GSHPs in China has grown rapidly. Ground-Coupled Heat Pump (GCHP) systems account for a 95.09% market share [19]. Current research indicates that the thermal performance and economic benefits of GSHP systems are notably significant.

4. Typical climate zones and application of ultra-low energy technology

4.1. China building climate zoning standard

China's vast territory features complex and diverse climates. To provide scientific guidance for building design, the Ministry of Construction of the People's Republic of China established the standard "Building Climatic Zoning" (GB 50178-93), which classifies the country's building climatic zones into seven primary zones through a combination of comprehensive analysis and consideration of dominant factors. It uses average January and July temperatures and average July relative humidity as primary indicators, and annual precipitation and average annual temperature days as supplementary indicators. This paper focuses on the key differences in building energy-saving requirements across typical climatic conditions, selecting five of the most representative climatic zones for in-depth analysis of energy-saving needs.

4.2. Analysis of characteristics and building energy efficiency examples in each climate zone

4.2.1. Building climate zone I (severe cold region)

The climate in this zone features long, harsh winters and short, cool summers, with significant annual temperature differences (30-50°C); a long freezing period, deep frozen ground, heavy snowfall, substantial solar radiation, abundant sunshine, and strong winter winds. In January, the average temperature drops to -31 to -10°C, with more than 145 days recording an average daily temperature of ≤5°C. For this region, the core of building energy conservation lies in mitigating massive heat loss caused by extreme cold in winter. The focus of passive technologies is to adopt the highest standard of insulation measures and fully utilize passive solar heating. Active technologies and renewable energy systems emphasize the use of efficient heating systems, effective fresh air heat recovery, and the application of solar photovoltaic systems. A typical example is the "Jinyuan Forest Town" (Harbin), which employs graphene extruded board walls, high-performance passive windows with triple-glazed, two-chamber high-transmittance, single-silver double Low-E processes, as well as airtight treatment, combined with heat recovery fresh air systems and low-temperature air source heat pumps [20].

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4.2.2. Building climate zone II (cold region)

This region is characterized by long, cold, dry winters; plains experience hot and humid summers, while plateau areas have cooler summers; a large annual temperature range (26-34°C); short springs with frequent strong winds and dust storms. The core challenge is the dual demand for winter heating and summer cooling, alongside insulation requirements. Therefore, passive techniques must balance insulation and shading, with widespread adoption of operable external shading systems. Active technologies require the deployment of high-efficiency heating and cooling systems (e.g., air-source/ground-source heat pumps) and ventilation heat recovery. Solar energy application holds high value. For example, the Wanhua Talent Center (Yantai) project primarily employed passive measures such as PIR foam-injected integrated insulation walls and fiberglass reinforced polyurethane energy-efficient windows. These were integrated with a ground-source heat pump unit, a solar water heating system, and rooftop PV systems, forming a multi-pronged optimized solution [21].

4.2.3. Building climate zone III (hot summer & cold winter region)

This region's climate is characterized by hot, humid summers, cold, damp winters, a small diurnal temperature range, high annual precipitation, and relatively low sunshine hours, a plum rain season, often with heavy rain and storms, and frequent typhoons in summer and autumn. Besides insulation, dehumidification and moisture control are major technical priorities. Passive techniques need to enhance the thermal performance and moisture resistance of the envelope, while emphasizing ventilation and moisture control design, as well as operable external shading. Active technologies can include temperature- and humidity-independent control (THIC) AC systems, high-efficiency dehumidifying fresh-air systems, and high-efficiency heating/cooling equipment. The Shanghai Jianke Xuhui Science Park Jianke Center applied passive techniques, including UHPC exterior walls, integrated shading systems, roof VIPs, and triple-pane IGU with argon fill, featuring double-silver low-E exterior windows, combined with façade PV power generation to address this challenge [22].

4.2.4. Building climate zone IV (hot summer & warm winter region)

This region features long summers without winter, high temperatures, and heavy humidity, with abundant rainfall; tropical storms and typhoons are common in summer and autumn, accompanied by strong winds and heavy rain. The core challenge lies in prioritizing heat insulation, shading, ventilation, and rain protection throughout the year. The core of passive technologies is high-performance insulation, comprehensive movable external shading systems, and enhanced natural ventilation design. Active technologies focus on high-efficiency dehumidifying air conditioning systems and pre-dehumidifying fresh air systems. The potential for solar photovoltaic generation energy is immense. For example, the existing building zero-energy renovation office building by China Construction Science and Technology Co., Ltd. (Huizhou) primarily utilizes rock wool exterior walls, reflective thermal insulation coatings, and double-layer hollow Low-E glass windows, with large-scale applications of cadmium telluride photovoltaic glass and high-efficiency monocrystalline silicon components on the facade and roof [23].

4.2.5. Building climate zone V (temperate region)

This region features mild winters and cool summers, with distinct dry and wet seasons; a small annual temperature range but large diurnal temperature variation; relatively high precipitation and

DOI: 10.54254/2755-2721/2026.MH29350

less sunshine [25]. The core challenge is utilizing passive design to achieve year-round natural comfort. Passive techniques hold the greatest potential, with the possibility of achieving "unplugged" comfort through optimized architectural design. The demand for active technologies is relatively low, requiring only auxiliary equipment. The Zero-Energy Consumption Renovation Project of the Structural Hall at the CSCEC Research Institute in Guizhou (Guiyang) applied integrated insulation decorative panels, installed additional skylights, and utilized high-efficiency VRF systems and total heat recovery ventilation systems, combined with a BIPV system, serving as a model of technology integration for this climate zone [24].

5. Discussion

By summarizing demonstration projects of nearly zero-energy buildings across different climatic zones, this paper validates the approach of integrating passive energy-saving technologies, active energy-saving technologies, and renewable energy systems to achieve nearly zero-energy buildings. However, the transition from demonstration to large-scale promotion still faces several systemic challenges and barriers..

Firstly, high-performance building envelope materials and energy-efficient equipment can result in higher initial construction costs, with studies indicating an increase of 20%-40% compared to conventional buildings. Although life-cycle energy savings are significant, the high initial cost barrier somewhat limits market acceptance.

Concurrently, the performance and long-term reliability of building envelope materials require further improvement and verification. On one hand, Class A fire-rated thermal insulation materials (e.g., rock wool) still have room for improvement in terms of insulation performance, tensile strength, hydrophobicity, and ease of construction [25]. On the other hand, new energy storage materials like Phase Change Materials (PCMs), while performing excellently in laboratories and short-term experiments, require more engineering practice to verify their long-term cycle stability, durability, and actual when integrated into complex envelope assemblies [26].

6. Conclusion

The promotion and development of ultra-low energy/zero-energy buildings are essential pathways for the building sector in China and for the achievement of carbon neutrality. This study systematically examines the characteristics of typical building climatic zones in China and their specific technological applications, while conducting detailed analyses of demonstration projects within these zones. The paper emphasizes the importance of an integrated energy-saving framework built on passive strategies, active energy-saving, and renewable energy systems. However, this study also has certain limitations: it primarily focuses on existing case studies without conducting actual investigations, and it overlooks specific analyses of non-typical climatic zones. Future research is expected to delve deeper, constructing an energy-efficient, comfortable, resilient, and productive building environment, thereby contributing a Chinese solution to global carbon neutrality efforts.

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