

Article

Climate-Adaptive Passive Design Strategies for Near-Zero-Energy Office Buildings in Central and Southern Anhui, China

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Abstract

Driven by the global energy transition and China's dual-carbon targets, Passive ultra-low-energy buildings are a key route for carbon reduction in the construction sector. This study addresses the high energy demand of office buildings and the limited suitability of current efficiency codes in the hot-summer/cold-winter, high-humidity zone of central and southern Anhui. Using multi-year climate records and energy-use surveys from five cities and one scenic area (2013–2024), we systematically investigate climate-adaptive passive-design strategies. Climate-Consultant simulations identify composite envelopes, external shading, and natural ventilation as the three most effective measures. Empirical evidence confirms that optimized envelope thermal properties significantly curb heating and cooling loads; a Huangshan office-building case validates the performance of the proposed passive measures, while analysis of a near-zero-energy demonstration project in Chuzhou yields a coordinated insulation-and-heat-rejection scheme. The results demonstrate that region-specific passive design can provide a comprehensive technical framework for ultra-low-energy buildings in transitional climates and thereby supporting China's carbon-neutrality targets.

Keywords: passive office buildings; climate-adaptive design; thermal performance; central and southern Anhui; building envelope optimization; nearly zero-energy buildings



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1. Introduction

With the intensification of global energy crises and climate change, reducing building energy consumption and achieving carbon neutrality have become focal points of international attention [1]. The building sector, as a significant source of energy consumption and carbon emissions, possesses enormous potential for energy conservation. Passive ultra-low energy buildings significantly reduce buildings' dependence on active heating and cooling systems through optimized building envelopes, enhanced airtightness, and passive energy-saving technologies, representing an important approach to achieving building energy efficiency. Countries such as Germany and Sweden have achieved remarkable results in passive building technology development and standard formulation, while China, driven by its "dual carbon" goals, is also accelerating the popularization of ultra-low energy buildings. According to the "Work Plan for Accelerating Building Sector Energy Conservation and Carbon Reduction," by 2025, all newly constructed urban buildings in China will

fully implement green building standards and increase the proportion of ultra-low energy buildings, which places higher demands on building energy-saving technologies [2,3].

In 2012, Sweden issued the world's first passive ultra-low energy building design standard, the "*Swedish Zero Energy and Low Energy Passive Building Standard*", which clearly stipulates heating and cooling loads, indoor comfort indicators, and other specifications, providing reference for other countries to develop relevant standards [4]. Professor Manfred Hegger, in his published book "*Active Buildings: From Passive to Positive Energy Houses*", proposed that active buildings should be developed on the foundation of passive buildings, generating more energy while meeting self-consumption needs through measures such as solar energy, bioenergy, wind energy, geothermal energy, and wastewater heat recovery [5]. James Mary O'Connor conducted detailed research and analysis on passive design of overall building layout, building thermal performance design, passive building modeling, building structure, and passive strategies [6]. Holder, in "*German Passive House Design and Construction Guidelines*", introduced passive house construction and key technologies from both theoretical and practical perspectives, providing numerous data charts and building images that have made important contributions to the advancement of passive house technology [7].

In 2016, the 20th International Passive House Conference opened in Darmstadt, Germany, signaling that European passive house construction had begun to advance toward the era of "Passive House+." This concept builds upon the classic passive house foundation with even greater energy efficiency and increased utilization of renewable energy sources such as photovoltaic roofing, while reducing heating and cooling energy consumption by 90% and bringing the consumption of fossil fuels and coal to near zero [8–10].

Currently, domestic and international scholars have conducted extensive research in the field of passive buildings, encompassing various building energy conservation technologies.

Building envelopes, as the physical boundary between indoor and outdoor environments, directly impact building energy consumption and indoor comfort [11]. Li Baofeng [12] studied how building skins in hot summer/cold winter regions can be adjusted according to regional and seasonal requirements to meet energy conservation needs under different climate conditions. Through experimentation, he analyzed the disadvantages of conventional shading measures and the potential for selecting different shading forms for different seasons. Xin Fu [13] utilized Design Builder software to conduct dynamic energy consumption simulations of passive residential buildings' airtightness and external wall insulation systems in hot summer/cold winter regions, concluding that improving building airtightness and external wall insulation can effectively reduce annual heating and cooling loads, with heating loads being more significantly affected than cooling loads. He proposed using the ratio of heating to cooling (r) as an important indicator in passive residential building energy efficiency evaluation, to reasonably select ventilation strategies and wall heat transfer coefficients. Moradibistouni, M., Vale [14] et al. used life cycle analysis methods to assess the environmental impact of different insulation materials on a near-zero energy residential building in Wellington, New Zealand, exploring the effects of building envelope insulation thickness and material selection on the building's environmental footprint.

Solar energy, as the most abundant renewable energy source, plays a key role in passive building design. Current research not only focuses on traditional passive solar heating technologies but also emphasizes the synergistic use of solar energy with other systems [15–17]. Voznyak O. [18] developed a novel building-integrated solar collector that doubles as cladding; by comparing a Grafplast PDA rubber-graphite coating with conventional materials and optimizing tube diameter (optimal $\varnothing$ 0.016 m), the team raised collection efficiency by 8%. The experiment also evaluated the effects of tube spacing

and heat-transfer fluid velocity. Haider Albayyaa and Dharmappa Hagare [19] modelled two types of double-storey, four-bedroom detached houses in Sydney and quantified how passive-solar and energy-efficient designs—and various wall and floor systems—affect total energy required for thermal comfort; high-thermal-mass materials reduced winter heating demand by 37% and 36%, respectively. Through longitudinal tests in a humid subtropical climate, Talha T. [20] revealed that building-integrated, unglazed, transmissive solar collectors (TSCs) show significant temperature fluctuations at low ambient temperatures; roof installation yields 5–18% more heat than façade installation, and optimal orientation adds another 3–13% efficiency.

Building thermal environment regulation is a key link connecting energy conservation goals with human comfort needs. Modern passive buildings emphasize achieving thermal environment regulation through the building design itself rather than relying on mechanical equipment. Research in this field exhibits multi-scale and multi-objective characteristics [21,22]. Studying extreme hot-dry Turpan Basin conditions through measurement and simulation, Zhang L. [23] found that shading and ventilation in drying rooms markedly lower roof inner-surface temperatures and improve summer comfort; among four geometric parameters, the perforated-wall area ratio proved most critical, as increasing it raises solar heat gains on the roof and thus interior temperatures. Jing Ma [24] et al., through studying the thermal environment of enclosed balconies common in residential buildings, designed a passive solar residential building that optimizes building details and utilizes passive solar energy to provide auxiliary heating in winter and cooling in summer, giving the indoor microclimate more thorough and reasonable modification. Enliang Zhao [25] et al. conducted simulations and field measurements on two passive residential buildings in cold regions of China with nearly identical geographical locations, architectural forms, and floor plans, exploring the contribution of solar heat gain as a passive strategy to indoor thermal comfort and the importance of establishing passive houses in cold regions of China.

In hot summer/warm winter regions, reasonable natural ventilation design can effectively promote indoor-outdoor air exchange, reduce air conditioning energy consumption, and improve air quality and thermal comfort; while scientific external shading systems can significantly reduce solar radiation heat gain, lower building cooling loads, avoid glare, and optimize indoor light environments. The synergistic effect of these two approaches not only greatly enhances building energy efficiency but also shapes passive energy-saving strategies adapted to regional climates, serving as core means for achieving sustainable building design. Especially against the current global background of energy conservation and emission reduction, optimizing the integrated application of natural ventilation and shading technologies has become a key direction in green building development. Several scholars have conducted related research on this topic [26–28].

Myroniuk K. [29] experimentally verified a Trombe-wall passive-ventilation system in modular housing, determining optimum air-gap thickness (100 mm) and outlet area (0.056 m^2) to deliver $120 \text{ m}^3/\text{h}$ airflow; the authors noted that façade pressure coefficients still require study. Saelens D. [30] assessed natural-ventilation strategies and energy performance in office buildings with double-skin façades. Through monitoring and multi-objective optimization, Liu Y. [31] confirmed that in Guangzhou residential buildings daylighting cuts lighting energy by $3.3 \text{ kWh}/(\text{m}^2 \cdot \text{yr})$, while natural ventilation reduces room-level air-conditioning energy by $4.7\text{--}26.9 \text{ kWh}/(\text{m}^2 \cdot \text{yr})$; global sensitivity analysis identified roof albedo, insulation thickness, and window-to-wall ratio as dominant variables, and optimized top-floor designs saved up to $52.3 \text{ kWh}/(\text{m}^2 \cdot \text{yr})$ in total. Baldinelli G. [32] explored the energy benefits of combining double-skin façades with movable shading in warm climates.

Anhui Province, as a transitional zone between hot summer/cold winter and cold climate regions, faces unique challenges in building energy conservation. The central and southern Anhui region has a complex climate characterized by hot, humid summers and cold, humid winters. Traditional buildings in this region have relatively high energy consumption, and existing energy-saving standards (such as the 75% energy-saving standard implemented in Hefei, Wuhu, and other areas) are still insufficient to meet the deep emission reduction requirements under carbon neutrality goals [33,34]. Although Anhui Province has revised its “Public Building Energy Conservation Design Standard” and “Residential Building Energy Conservation Design Standard”, research on climate adaptability for passive office buildings remains relatively scarce. Office buildings, as an important type of public building, have energy consumption characteristics that differ significantly from residential buildings, creating an urgent need to explore appropriate passive design strategies in combination with regional climate characteristics [35–38].

This study therefore concentrates on passive buildings in central and southern Anhui. Based on regional climatic characteristics and measured data, we adopt a “climate analysis–strategy screening–field verification–demonstration” workflow. Using Climate Consultant, we generate bioclimatic charts to quantify the applicability of passive measures and reveal synergistic optimization mechanisms for envelope thermal performance. We then conduct a detailed analysis of an existing office building in Huangshan and survey a nearly zero-energy building in Chuzhou, systematically evaluating envelope performance and indoor-environment control. The outcomes provide theoretical and practical guidance for ultra-low-energy buildings in the region, offering a climate-adaptive, carbon-neutral solution for transition-zone ULEBs and supporting China’s dual-carbon goals in the building sector.

2. Regional Climate Research of Central and Southern Anhui

The central and southern Anhui region is a typical hot-summer and cold-winter climate zone, requiring resistance to severe cold in winter and protection from summer heat. The building envelope—comprising external walls, roof, and doors and windows—is the key interface for heat exchange between the indoor and outdoor environments. The energy use associated with the envelope accounts for a large share of a building’s total energy consumption, alongside its thermal insulation and heat-insulating performance, directly determines the building’s energy demand. In most buildings in China, the envelope still fails to meet effective energy-saving standards because its thermal insulation and heat-insulation performance is inadequate, leading to excessive energy consumption. By adopting effective energy-saving measures, building energy use can be significantly reduced and energy-use efficiency improved. Therefore, improving the energy performance of the envelope is of paramount importance to realizing building energy conservation.

A quantitative analysis of the geographic and climatic characteristics of the central and southern Anhui region was carried out, and passive building technologies appropriate to the region were derived. Further surveys of the current status of building energy consumption in the region were conducted, and experimental studies were performed. Thermal insulation retrofits were applied to the envelope (external walls, roof, and doors and windows) of a typical building, and the building’s energy consumption before and after the retrofit was analyzed. The results further verify that enhancing the envelope’s thermal performance in subsequent building practice—such as adding external wall insulation, improving door and window airtightness, and optimizing roof insulation and heat-insulation design—can effectively reduce envelope-related energy consumption. By simultaneously considering the regional climatic characteristics and the present situation of building energy use, near-zero-energy buildings (NZEBS) that are better adapted to the

climate of central and southern Anhui can be created, achieving both energy savings and indoor comfort.

2.1. Quantitative Analysis of Climate Characteristics in Central and Southern Anhui Region

Anhui Province is located in the central-eastern part of China, with geographic coordinates of $114^{\circ}45'–119^{\circ}45'$ E and $29^{\circ}24'–34^{\circ}38'$ N. The province spans three major water systems—the Yangtze River, Huai River, and Xin'an River—and lies in a transitional zone between northern and southern China.

The narrow strip between the Yangtze and Huai Rivers is known as the Jianghuai region and constitutes central Anhui. Areas south of the Yangtze River and north of the Huai River are referred to as southern and northern Anhui, respectively. Southern Anhui comprises Chizhou, Huangshan, Xuancheng, and parts of Tongling, Wuhu, and Ma'anshan; central Anhui covers Hefei, Lu'an, Chuzhou, and Anqing; northern Anhui mainly includes the six prefecture-level cities of Fuyang, Huainan, Suzhou, Huaibei, Bengbu, and Bozhou.

Figure 1 presents the province's topography. With the Huai and Yangtze Rivers as boundaries, the purple-red area in the middle denotes central Anhui, the upper zone northern Anhui, and the lower zone southern Anhui. From a natural-geography standpoint, the land south of the Yangtze belongs to the southern region, whereas the Jianghuai belt and all territory north of the Huai River belong to the northern region; agriculturally, the Huai River provides a similar dividing line.

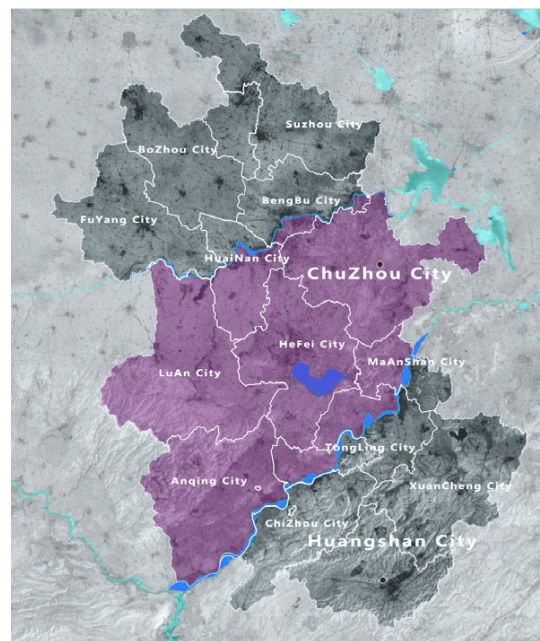


Figure 1. Topographic map of Anhui Province.

Anhui lies within the hot-summer/cold-winter zone and serves as a transition between the warm-temperate and subtropical belts. North of the Huai River, the climate is warm-temperate, semi-humid monsoon, while, south of it, the climate is subtropical humid monsoon. Four distinct seasons are experienced: warm springs with occasional “late-spring cold snaps,” rainy summers, clear and cool autumns, and humid, chilly winters. Precipitation varies sharply with the monsoon, making the province one of China’s most pronounced monsoon areas. Spring and autumn function as brief transition periods; the frost-free season lasts 200–250 days. Average annual temperatures range from 14°C to 17°C ; January averages -1°C to -4°C , and July averages 28°C to 29°C . Total annual precipitation ranges from 773 mm to 1670 mm, with summer rainfall accounting for 40–60%

of the total. Figure 2 shows annual precipitation from 2000 to 2023. The province's flood season runs from May to September, delivering 600–1100 mm of rainfall; central and southern Anhui record particularly abundant totals of 800–1600 mm.

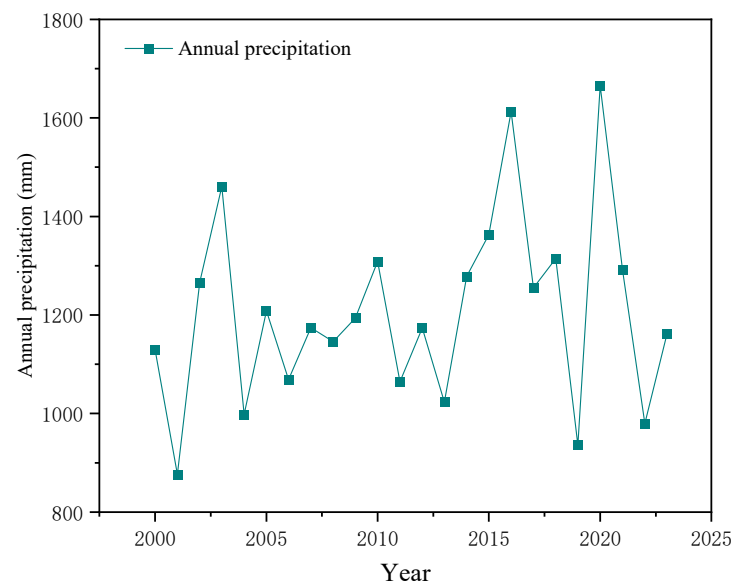


Figure 2. Precipitation in Anhui Province from 2000 to 2023.

2.2. Analysis of Meteorological Data for Typical Cities in the Central and Southern Anhui Region from 2014 to 2023

This study selects five typical cities in the central and southern Anhui region—Hefei, Chuzhou, Anqing, Wuhu, and Huangshan—together with the globally renowned Huangshan Scenic Area. Meteorological data from 2014 to 2023 were compiled to analyze temperature, humidity, wind speed, and solar radiation characteristics.

The region experiences high summer temperatures and low winter temperatures. As shown in Figure 3, the average temperature of the hottest month is about 29 °C, whereas that of the coldest month is roughly 3–5 °C, which is typical of a subtropical monsoon climate. Both insulation and heat-isolation measures are therefore required. Across the five cities, the coldest-month average temperature is 4.39 °C and the hottest-month average is 28.92 °C. The coldest-month averages differ markedly, with a maximum disparity of 1.62 °C, whereas hottest-month averages are much closer. Values for the Huangshan Scenic Area are only −1.45 °C and 18.43 °C because of the higher elevation, so greater emphasis on thermal insulation is needed for tourist facilities on the mountain. The annual temperature range in these cities averages 23–26 °C; such a large range leads to frequent use of HVAC systems and consequently higher energy consumption. The mean annual range for the five cities is 24.53 °C, making increased thermal storage capacity an effective passive-design strategy to mitigate winter overcooling and enhance indoor comfort.

Regarding humidity, summers are very humid, with relative humidity reaching 100%, and even in winter it normally stays around 60%. Figure 4 presents the average relative humidity for the coldest and hottest months. Owing to abundant waterways, humidity is relatively high: in the hottest month, the five-city average is 80.08%, and, in the coldest month, 71.57%. High humidity raises perceived temperatures, increases summer air-conditioning energy use, and affects indoor comfort.

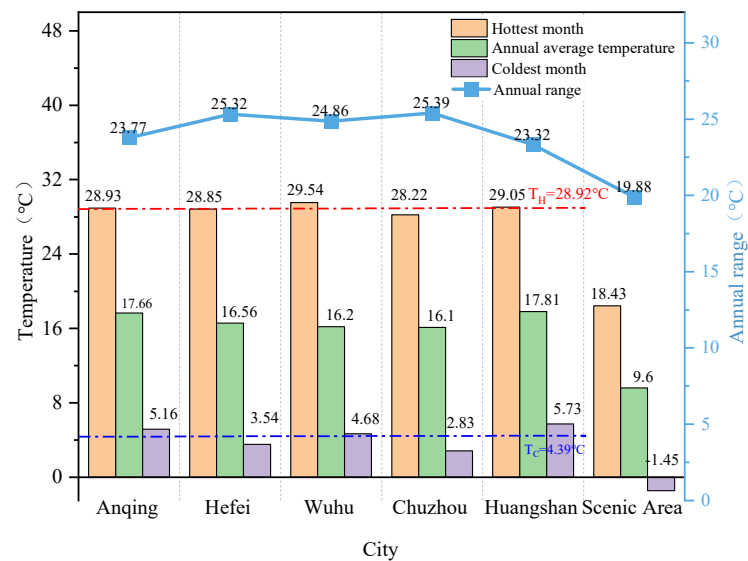


Figure 3. Analysis of annual average temperature in typical cities of the central and southern Anhui region from 2013 to 2024.

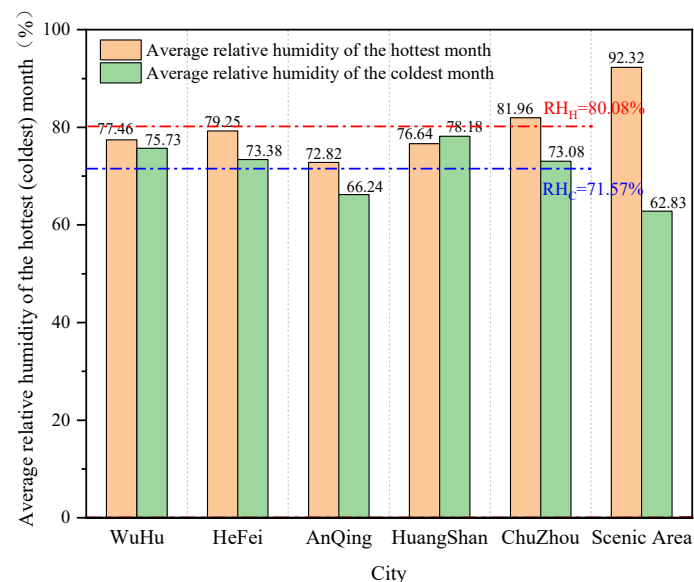


Figure 4. Average relative humidity in the coldest and hottest months in typical cities of the central and southern Anhui region.

Figure 5 depicts diurnal temperature and humidity variations in Hefei on the 2023 summer and winter solstices. Daytime temperatures exceed nighttime values, while humidity shows the opposite pattern. Summer humidity peaks near 100% and falls to about 55%, with temperatures between 25 °C and 33 °C. In winter, predawn humidity is ~70% and afternoon humidity ~30%, with temperatures ranging from −10 °C to 1 °C. Clearly, the region is humid year-round and experiences hot summers and cold winters.

Prevailing winds are mainly southeasterly and southerly, with speeds of Beaufort force 2–3 ($\approx 5\text{--}10\text{ km/h}$, i.e., $1.39\text{--}2.78\text{ m/s}$). Figure 6 shows average wind speeds in the coldest and hottest months. Wind at the Huangshan Scenic Area is markedly stronger than in the cities, but this study concentrates on urban conditions. The five-city average wind speed is 2.1 m/s in the hottest month and 1.96 m/s in the coldest month. Slightly lower winter wind speeds affect natural-ventilation effectiveness; suitable design can capitalize on natural ventilation to reduce mechanical ventilation, save energy, and improve comfort.

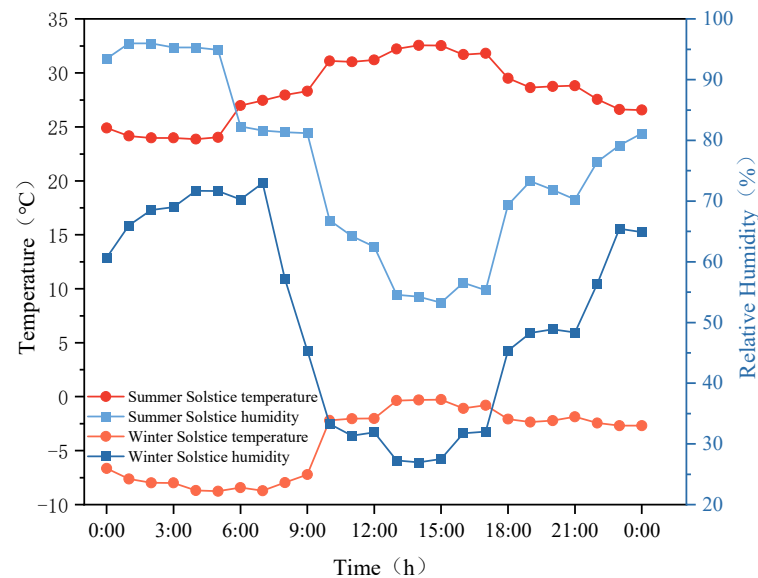


Figure 5. Temperature and humidity changes in Hefei on summer and winter solstice days.

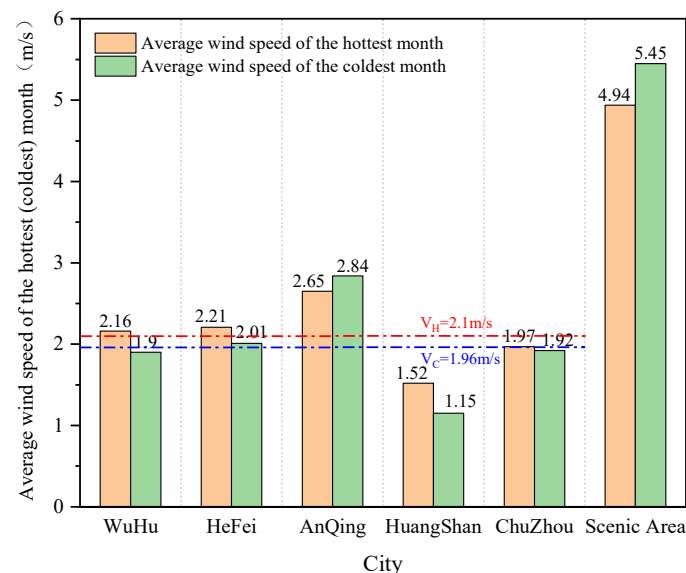


Figure 6. Average wind speed in the coldest and hottest months in typical cities of the central and southern Anhui region.

Figure 7 illustrates solar-radiation intensity for the coldest and hottest months. Summer radiation greatly exceeds winter values and is similar among the five cities: the hottest-month average is 217.66 W/m^2 , and the coldest-month average 123.98 W/m^2 (56.96% of the summer value). Consequently, solar energy can be fully exploited in summer, whereas winter requires supplementary energy sources. Envelope design should therefore emphasize summer heat insulation and winter thermal insulation for heating. Figure 8 gives the solar-radiation profile for Hefei on the 2023 summer and winter solstices: both duration and intensity are greater in summer. Peaks occur at $\sim 11:30 \text{ a.m.}$ in winter and $\sim 2:00 \text{ p.m.}$ in summer, with a difference of 451.84 kJ/m^2 between the two peaks.

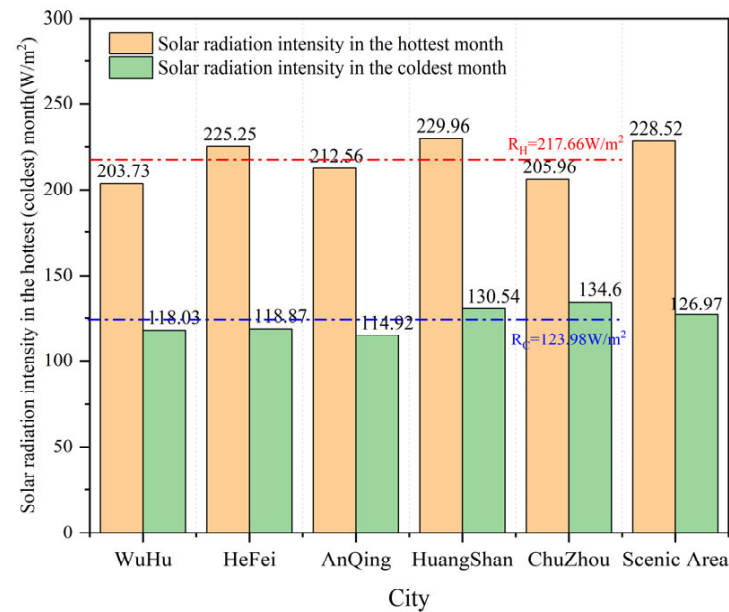


Figure 7. Solar radiation intensity in the coldest and hottest months in typical cities of the central and southern Anhui region.

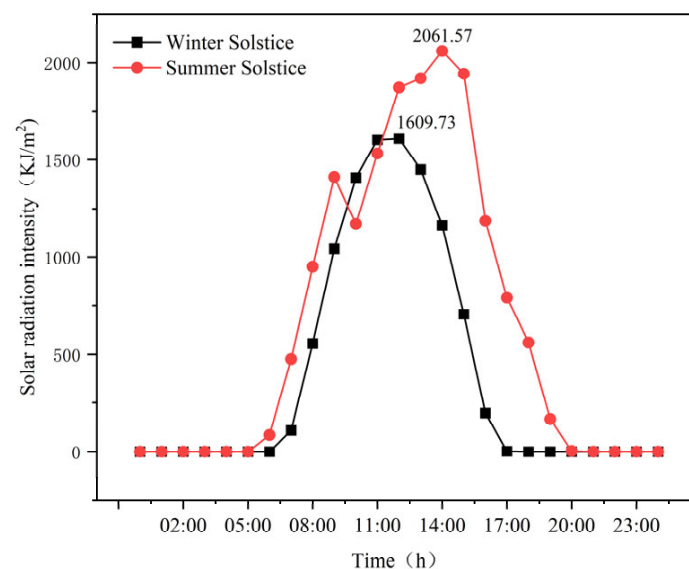


Figure 8. Solar radiation changes in Hefei on summer and winter solstice days.

3. Research on the Applicability of Passive Energy-Saving Technologies

3.1. Thermal Comfort Model

This paper uses the climate analysis software Climate Consultant 6.0 to analyze climate data from typical cities during representative time periods from 2009 to 2023 [39,40], determining the applicability of different passive strategies in typical cities through bioclimatic charts.

This study adopts the adaptive model in the *ANSI/ASHRAE Standard 55-2020* [41] as the core framework for thermal comfort evaluation, while retaining the steady-state framework of *ASHRAE Fundamentals 2005* [42] to preserve data continuity and enable method-to-method comparison. Aligning the two models with the local climate and passive-design goals provides a scientific tool for localizing China's near-zero-energy building (NZEB) standards.

ASHRAE Fundamentals 2005 is built on the steady-state PMV model, which determines comfort with fixed parameters and is, therefore, appropriate for fully air-conditioned spaces. *ANSI/ASHRAE 55-2020*, by contrast, employs a dynamic adaptive model that shifts comfort thresholds according to outdoor climate and occupant behavior, making it better suited to naturally ventilated, energy-saving scenarios. The calculation procedure is as follows:

(1) Adaptive comfort equation

For naturally ventilated spaces, *ANSI/ASHRAE 55-2020* evaluates thermal comfort by dynamically adjusting the adaptive comfort zone:

$$T_{\text{comf}} = T_{\text{op}} \pm \Delta T_{\text{adaptive}}$$

where the following is true:

T_{comf} : Adaptive comfort temperature (°C)

T_{op} : Monthly mean outdoor temperature (°C)

$\Delta T_{\text{adaptive}}$: Behavior-driven temperature offset (+3 °C in summer, −3 °C in winter)

Because the comfort boundary is recalibrated with real-time outdoor data, Equation (1) reflects transitional-climate conditions—such as those in south-central Anhui—far more accurately than the fixed 26–28 °C summer threshold prescribed by *ASHRAE 2005* [42].

Climate Consultant can directly read climate files in EPW format—the data structure employed by the EnergyPlus simulation engine. It converts the raw hourly records of thousands of stations worldwide into dozens of intuitive graphics, helping users organize and visualize climatic information in an easy-to-understand way. Its purpose is to reveal subtle climatic attributes and their impact on building form, enabling designers to create more energy-efficient and sustainable architecture.

According to heat production and loss per unit body-surface area, the human heat-balance equation can be written as Equation (1):

$$M - W - C - R - E - S = 0 \quad (1)$$

where the following is true:

M = Metabolic rate (58.2 W/m² for sedentary activity);

W = Mechanical work (generally 0 W/m² for routine activities);

C = Convective heat loss from the body surface (W/m²);

R = Radiative heat loss from the body surface (W/m²);

E = Latent heat loss by respiration and perspiration (W/m²);

S = Body heat-storage rate (W/m², zero at thermal equilibrium).

Under steady-state conditions, the thermal comfort equation becomes Equation (2):

$$\begin{aligned} (M - W) = & f_{cl} h_c (t_{cl} - t_a) + 3.96 \times 10^{-8} f_{cl} [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] \\ & + 3.05 [5.733 - 0.007(M - W) - P_a] + 0.42(M - W - 58.2) \\ & + 0.0173M(5.867 - P_a) + 0.0014M(34 - t_a) \end{aligned} \quad (2)$$

where the following is true:

f_{cl} = Clothing area factor;

t_a = Air temperature (°C);

t_{cl} = Clothing surface temperature (°C);

$\bar{t}_r$ = Mean radiant temperature (°C);

h_c = Convective heat-transfer coefficient (W/m² K^{−1});

P_a = Water-vapor partial pressure (kPa).

Thermal sensation is expressed by the predicted mean vote (PMV). Combining Equation (2) with additional parameters yields Equation (3), which correlates PMV with

indoor air temperature T_a , relative humidity RH, outdoor temperature T_{out} , mean radiant temperature T_{rad} , air velocity V_a , metabolic rate M , and clothing insulation Clo:

$$PMV = [0.303\exp(-0.036M) + 0.0275] \quad (3)$$

and the associated predicted percentage of dissatisfied (PPD) is given by Equation (4):

$$PMV = [0.303\exp(-0.036M) + 0.0275] \times \left\{ \begin{array}{l} M - W - 3.05[5.733 - 0.007(M - W) - P_a] - 0.42(M - W - 58.2) - 0.0173M \\ (5.867 - P_a) - 0.0014M(34 - t_a) - 3.96 \times 10^{-8} f_{cl} [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] \\ - f_{cl} h_c (t_{cl} - t_a) \end{array} \right\} \quad (4)$$

In essence, the ASHRAE thermal comfort model links environmental variables and personal factors through a multi-parameter empirical formulation that balances underlying physical mechanisms with experimental validation, providing a standardized tool for building-thermal-environment design and assessment.

3.2. Bioclimatic Sphere and Strategy Selection Method

Table 1 shows the analysis of comfort time proportion for passive strategies in cities of central and southern Anhui region. The applicability of various passive design strategies are evaluated through “effective time ratio” (the ratio of applicable hours for each design strategy to total annual hours). Considering that climate parameters of the Huangshan Scenic Area, such as wind speed and temperature, differ significantly from urban areas, it was not included in the variance calculation. Table 2 displays the effective time ratios and applicability evaluation results for different cities. According to Table 1, among the various passive strategies in central and southern Anhui region, the most effective strategy for winter is improving the utilization rate of indoor heat gain, while the most important cooling strategies for summer are shading and ventilation, which can effectively reduce indoor temperature. The applicability of mechanical ventilation and natural ventilation varies significantly between cities, requiring flexible selection and analysis based on specific urban climate and building characteristics. Meanwhile, building thermal mass, evaporative cooling, and wind protection strategies show lower applicability in this region, possibly due to climate characteristics or regional differences limiting their effectiveness. Finally, passive design strategies related to building envelopes (such as enhancing thermal performance of exterior walls and roofs) demonstrate higher applicability, effectively improving building energy efficiency and comfort. Therefore, the research results indicate that adopting appropriate passive design strategies is crucial for building energy conservation and comfort under the climate conditions of central and southern Anhui region.

Table 1. Analysis of comfort time proportion (%) for passive strategies in cities of the central and southern Anhui region.

Strategy	Anqing	Hefei	Wuhu	Huangshan	Average	Variance	Huangshan Scenic Area
Comfort zone	5.1	5.8	5.2	7.0	5.78	0.76	4.9
Shading (A)	14.1	15.0	14.2	15.3	14.65	0.35	12.8
Building thermal mass (B)	2.7	3.4	2.4	3.2	2.93	0.21	2.0
Thermal mass + night ventilation (C)	3.0	3.9	2.7	3.6	3.30	0.30	2.6
Direct evaporative cooling (D)	2.1	3.1	2.0	2.5	2.43	0.25	1.5
Indirect evaporative cooling (E)	2.8	3.6	2.5	2.9	2.95	0.22	2.0

Table 1. Cont.

Strategy	Anqing	Hefei	Wuhu	Huangshan	Average	Variance	Huangshan Scenic Area
Natural ventilation (F)	11.0	10.5	12.2	7.6	10.33	3.81	7.0
Mechanical ventilation (G)	10.5	9.6	11.7	4.5	9.08	10.04	6.7
Internal heat gains (H)	22.4	19.1	21.2	23.6	21.58	3.68	23.2
Passive solar gains + lightweight envelope (I)	8.2	9.3	9.2	9.4	9.03	0.31	8.8
Passive solar gains + heavyweight envelope (J)	5.1	5.8	5.2	6.9	5.75	0.68	5.1
Wind protection (K)	0.0	0.0	0.1	0.0	0.03	0.0025	4.9
Total	44.3	42.6	47.9	44.7	44.14	–	41.2
Passive design potential	39.2	36.8	42.7	37.7	38.54	–	36.3

Table 2. Effective time ratio a (%) of passive calculation for each city.

Effectiveness	Anqing	Hefei	Huangshan	Wuhu	Huangshan Scenic Area
Very effective ($a > 10\%$)	AFGH	AFH	AH	AFGH	AH
Effective ($10\% \geq a > 5\%$)	IJ	GIJ	FIJ	IJ	FGIJ
Poor ($a \leq 5\%$)	BCDEK	BCDEK	BCDEGK	BCDEK	BCDEK

3.3. Passive Technology Applicability Analysis

Based on Tables 1 and 2 and Figure 9, the following conclusions can be drawn:

- (1) Overall potential and impact of passive design strategies: Simulation results show that by adopting passive design strategies, the central and southern Anhui region can significantly enhance building comfort and energy efficiency. Without any passive design strategies, comfortable time in cities accounts for only 5.78% of the year; however, after implementing all passive design strategies, the proportion of comfortable time increases to 38.54%, demonstrating the enormous potential of passive design. Among these, the most effective strategy for winter is improving indoor heat gain utilization, emphasizing the importance of building form, insulation level, and airtightness.
- (2) Applicability differences and specific analysis of various strategies: Among the passive design strategies, shading and ventilation are identified as key cooling strategies for summer in all cities in the central and southern Anhui region, effectively reducing indoor temperatures. However, there are significant differences in the applicability of mechanical ventilation. In cities like Anqing and Wuhu, the effective time ratio of mechanical ventilation exceeds 10%, while in Huangshan it is only 4.5%, and in the Huangshan Scenic Area it is 6.7%. This difference mainly stems from Huangshan's special geographical environment and climate characteristics (such as frequent clouds and fog, high humidity, and abundant precipitation). Additionally, building thermal mass, evaporative cooling, and wind protection strategies have lower applicability in this region, possibly because climate characteristics limit their effectiveness. Therefore, the research indicates that different cities' and regions' climate conditions require personalized analysis and flexible application of passive design strategies.
- (3) Regarding passive strategies related to building envelopes, combining two types of envelope structures shows a high proportion of effective time, totaling 14.18%. Their utilization of solar radiation heat gain is closely related to the building itself, and lightweight envelope structures and heavyweight envelope structures perform differently under solar radiation. This is mainly reflected in how they conduct, store, and

release heat. Lightweight envelope materials (such as lightweight concrete, foam concrete, light steel, etc.) typically have lower thermal conductivity. Under solar radiation, the advantage of lightweight envelope structures lies in their good thermal insulation performance, but due to their low heat storage capacity, internal temperatures may fluctuate significantly with external environmental changes. They are suitable for scenarios requiring reduced building weight and rapid construction, and for designs aiming to reduce the impact of high summer temperatures. Heavyweight envelope materials (such as solid brick, thick concrete, etc.) have higher thermal conductivity. Under solar radiation, heavyweight envelope structures can store large amounts of heat, making indoor temperature changes more gradual. However, due to their higher thermal conductivity and poorer insulation performance, indoor temperatures may rise in hot weather. They are suitable for designs requiring high durability and stable temperatures, especially in areas with large day-night temperature differences. According to the results, lightweight envelope structures have a higher proportion of effective time for passive strategies in the central and southern Anhui region because this region has relatively small day-night temperature differences, more scenarios requiring rapid construction, and hotter summers in southern regions, making it suitable for buildings with low heat storage capacity.

- (4) As shown in Table 1, analysis of effective passive strategies for the central and southern Anhui region reveals that in these four cities, the average ‘a’ values for shading and natural ventilation are 14.65% and 10.33%, respectively, while the average ‘a’ values for heating strategies such as indoor heat gain and passive solar radiation heat gain reach 21.58% and 14.78%. This indicates that the central and southern Anhui region must simultaneously address both summer cooling and winter heating demands.
- (5) Adopting appropriate passive technologies can effectively increase comfortable time. As shown in Figure 10, by merely enhancing building envelope performance and implementing effective natural ventilation as passive measures, the comfortable times for Anqing, Hefei, Wuhu, Huangshan, and the Huangshan Scenic Area are 32.4%, 35.3%, 34.4%, 33.6%, and 28.4%, respectively. This demonstrates that improving envelope performance and organizing effective natural ventilation can significantly enhance people’s comfort.

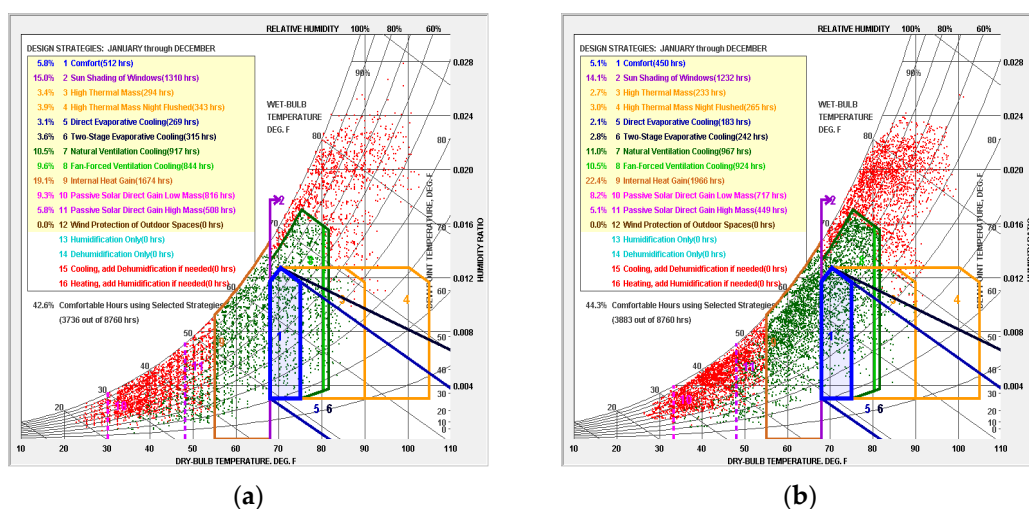


Figure 9. Cont.

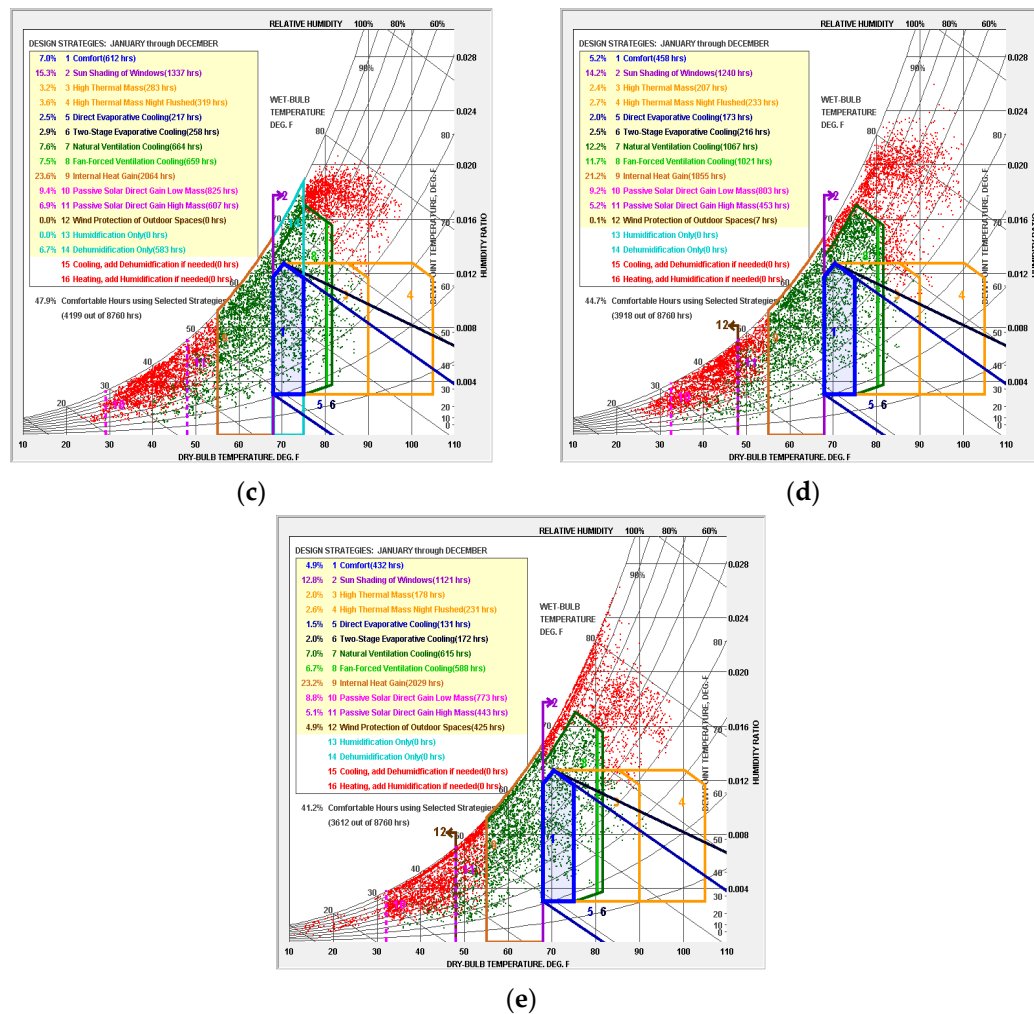


Figure 9. Typical climate analysis for cities in the central and southern Anhui region from 2009 to 2023. (a) HeFei (b) AnQing (c) HuangShan (d) WuHu (e) HuangShan Scenic Area.

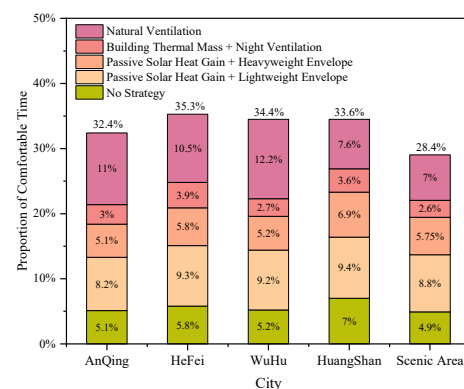


Figure 10. Analysis of effective passive strategies and comfort time in cities of the central and southern Anhui region.

4. Analysis of Indoor Thermal Environment in Huangshan Office Buildings

The central and southern Anhui region is located in a hot-summer and cold-winter climate zone, requiring heating in cold winters and cooling in hot summers, while the spring and autumn seasons have relatively suitable temperatures. To understand the indoor thermal environment of buildings in the central and southern Anhui region and the effect

of nighttime ventilation in summer on the indoor thermal environment, this study analyzes the indoor temperature, humidity, and airflow in two buildings in Huangshan City in the southern Anhui region.

4.1. Test Objects and Data Collection Methods

Two office buildings were selected in Huangshan City, a representative city in southern Anhui, as shown in Figure 11. Data on indoor temperature, humidity, and ventilation wind speed were collected during summer and transitional seasons. The testing period for the Huangshan Office Building was 20–21 August 2020 and 6–7 October 2020, while the testing period for the Shexian County Office Building was 28–30 August 2020.



Figure 11. Facades of an office building in Huangshan and an office building in Shexian County.

The Huangshan Office Building is a 13-story building (49.6 m high), and the Shexian County Office Building is a 6-story building. Measuring points were placed in the fourth-floor conference room and small office of the Huangshan Office Building, as well as in the fourth-floor conference room of the Shexian County Office Building. As shown in Figure 12, four measuring points were arranged in the conference room of the Huangshan Office Building, with points 1, 2, and 4 measuring temperature and humidity, and the anemometer placed at position 3. The small office faces north, with 6–7 temperature and humidity meters placed at the desk and window positions. Figure 13 shows the Shexian County Office Building, with measuring points arranged in the same way as in the Huangshan Office Building. Data collection equipment included portable temperature and humidity meters and anemometers, with equipment parameters shown in Table 3. Figures 14 and 15 show the on-site wind speed and temperature data collection.

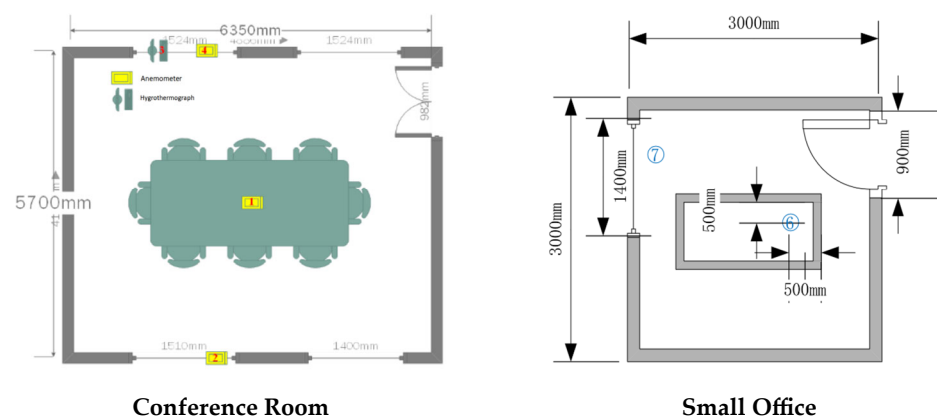


Figure 12. Measurement point layout in the conference room and small room of the Huangshan office building.

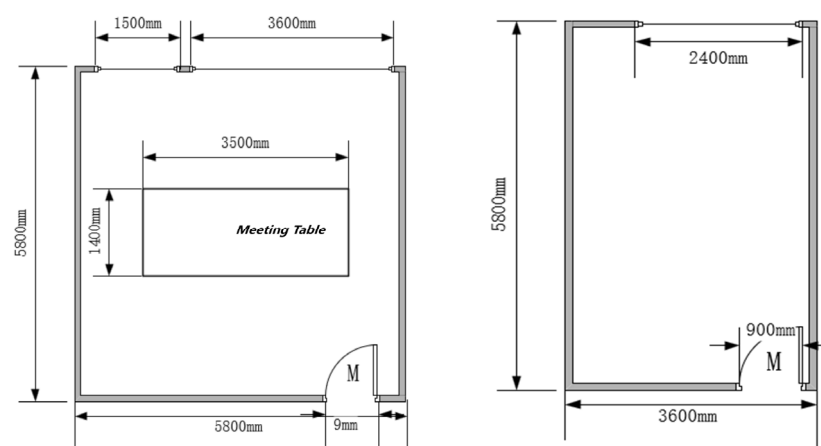


Figure 13. Conference room and north-facing small office in the Shexian construction building.

Table 3. Parameters of indoor environment data collection equipment.

Instrument Name	Instrument Model	Measuring Range	Accuracy
Temperature and humidity meter	TES1361C (Tes, Taipei, China)	Temperature: $-20\text{ }^{\circ}\text{C}$ to $60\text{ }^{\circ}\text{C}$; humidity: 10% to 95% RH	Temperature $\pm 0.8\text{ }^{\circ}\text{C}$; humidity $\pm 5\%$ RH
Anemometer	Kanomax6036 (Kanomax, Shenyang, China)	0.01 to 30 m/s	—



Figure 14. On-site wind speed and temperature sampling (partial).

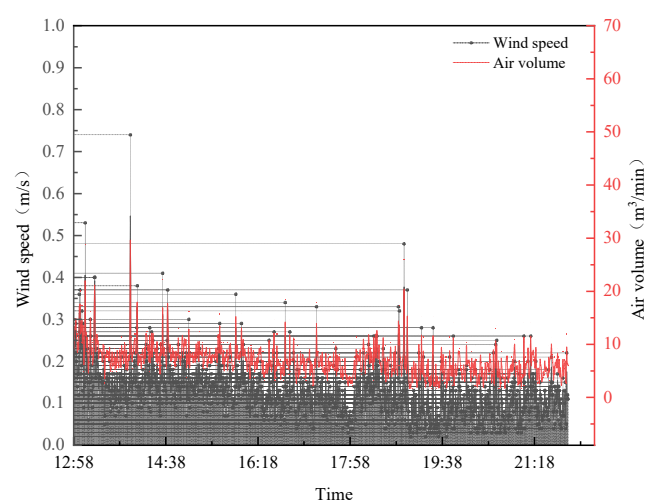


Figure 15. Wind speed and volume chart of the conference room in the Huangshan office building (20th).

4.2. Analysis and Discussion of Measured Data

(1) Indoor Wind Speed Analysis

Figure 15 shows the wind speed and volume chart of the Huangshan Office Building from the afternoon to night on August 20. The discrete nature of natural ventilation is evident, with average wind speeds between 0.1 m/s and 0.2 m/s. The comfortable wind speed for human adaptation is less than 0.25 m/s, which meets human thermal comfort requirements.

Figure 16 shows the real-time wind speed and volume chart of the conference room in the Shexian County Office Building. Between 16:40 and 17:20, the maximum wind speed reached 1.25 m/s. This high wind speed occurred because the door was open, creating a cross-ventilation effect between the door and windows, which is beneficial for accelerating indoor air exchange. After closing the doors and windows, the wind speed oscillated discretely at around 0.15–0.2 m/s, still meeting human comfort requirements.

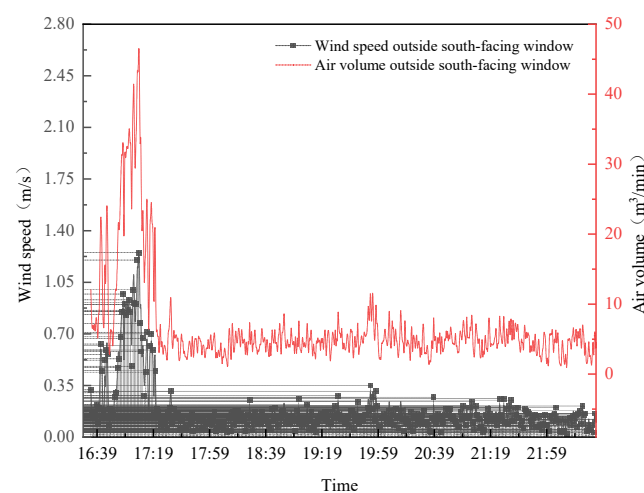


Figure 16. Wind speed and volume chart of the conference room in the Shexian office building (29th).

Based on the measurements from these two office buildings in the southern Anhui region, it is evident that the wind speed from natural ventilation can meet human comfort requirements for air velocity.

(2) Indoor Temperature and Humidity Analysis

The conference table in the Huangshan office building is located in the middle of the room. As shown in Figure 17, daytime outdoor temperatures are significantly higher than indoor temperatures. Around 5:40 PM, a turning point occurs, after which outdoor temperatures gradually decrease, becoming lower than indoor temperatures at night. The measuring point at the conference table, located in the middle of the room, shows a noticeable attenuation compared to outdoor temperatures, with a peak difference of about 2.5 °C. Despite the open-window ventilation environment, indoor temperatures remain relatively stable. From 8:00 AM to 5:00 PM—typically working hours—the room temperature is maintained at 19–21.5 °C, which is within a comfortable range. This indicates that during transitional seasons, opening windows for ventilation can effectively regulate indoor temperature and humidity, meeting people's comfort requirements.

As shown in Figure 18, in the Shexian County office building, daytime outdoor temperatures are higher than indoor temperatures, while nighttime outdoor temperatures are lower than indoor temperatures. The south-facing indoor and outdoor temperatures and the north-facing outdoor temperatures do not differ significantly. In the afternoon and early morning, north-facing temperatures are higher than south-facing temperatures, but the peaks and valleys of south-facing indoor temperatures and north-facing indoor

temperatures differ by 2–4 °C. The figure shows that around 8:00 AM, outdoor temperatures gradually rise, becoming higher than indoor temperatures. Around 6:30 PM, temperatures begin to decrease, remaining lower than indoor temperatures until the next morning. Before 9:00 AM, indoor temperatures generally remain in the range of 27–29 °C, which can satisfy the thermal comfort needs of people engaged in light activity. Therefore, opening windows for ventilation in the evening during late summer and early autumn can effectively remove indoor heat through natural ventilation. Indoor temperatures show a delay and attenuation compared to outdoor temperatures due to the building envelope. The conference table, located in the middle of the office, shows a peak temperature difference of 7 °C compared to outdoor temperatures. Indoor temperatures fluctuate in the range of 27–30 °C, remaining relatively stable. Additionally, due to the sun's angle, north-facing areas reach their highest temperatures at noon but also cool down the fastest at night.

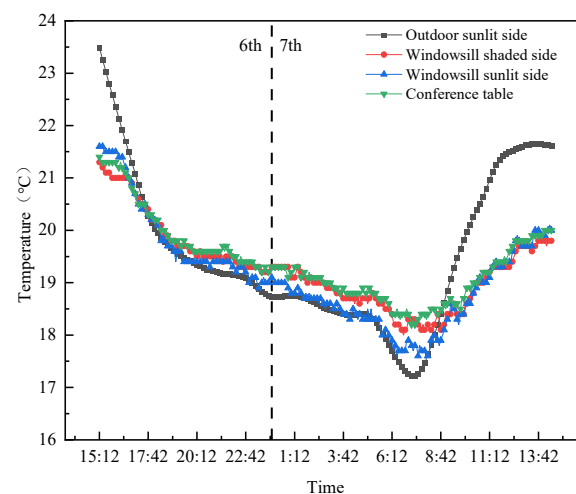


Figure 17. Temperature comparison chart of the conference room in the Huangshan office building (6–7th).

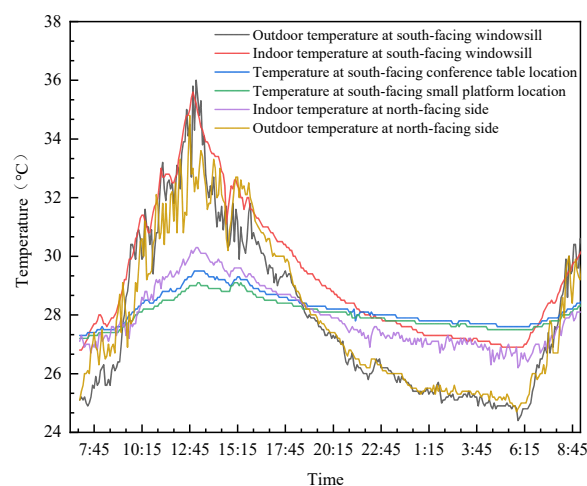


Figure 18. Temperature comparison chart of different positions in the conference room of the Shexian office building (29–30th).

As shown in Figure 19, indoor and outdoor relative humidity trends are consistent, with relative humidity fluctuating in the range of 50–80%. Figure 20 shows that relative humidity fluctuates in the range of 50–90%. This indicates that the southern Anhui region has relatively high humidity in late summer and early autumn which increases both heat and cold sensations in the air.

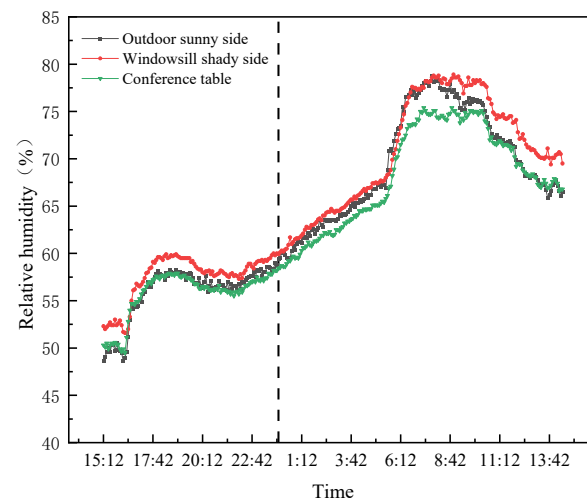


Figure 19. Relative humidity chart of the conference room in the Huangshan office building (October).

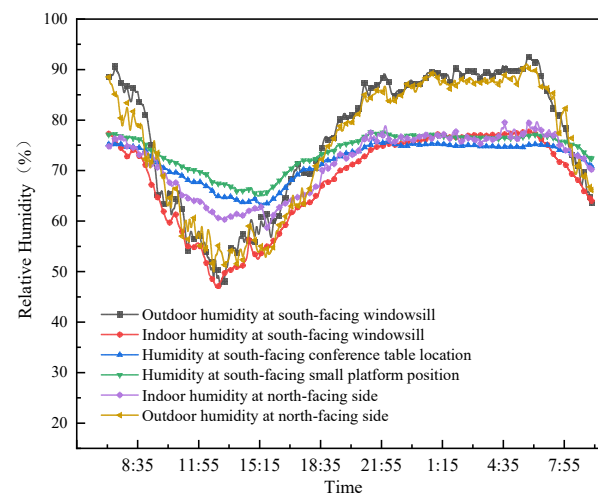


Figure 20. Relative humidity chart of the conference room in the Shexian office building (August).

Through the above research, it can be observed that during summer daytime, outdoor temperatures are higher than indoor temperatures. During both transitional seasons and summer, nighttime outdoor temperatures are lower than indoor temperatures, with suitable wind speeds. Nighttime natural ventilation can improve the indoor thermal environment, meeting human thermal comfort needs while offering significant energy-saving potential.

5. Integration Application and Demonstration Research of Near-Zero-Energy Building in Chuzhou City

Based on the theoretical analysis in the previous sections, this chapter examines the selection of building envelope insulation materials and high-efficiency windows for a near-zero energy demonstration building in Chuzhou City in the central and southern Anhui region. By collecting indoor temperature and humidity data during summer and winter, this chapter analyzes the actual indoor environment of near-zero-energy buildings in the central and southern Anhui region, as well as indoor thermal comfort under summer nighttime natural ventilation conditions. It also comprehensively evaluates the energy-saving and emission-reduction effects of near-zero-energy buildings.

5.1. Project Overview

This project is located in Chuzhou in the central and southern Anhui region. Chuzhou has a hot summer and cold winter climate, with an average temperature of 1–3 °C in the

coldest month (January) and extreme low temperatures reaching $-10\text{ }^{\circ}\text{C}$; the average temperature in the hottest month (July) is $28\text{--}30\text{ }^{\circ}\text{C}$, with extreme high temperatures exceeding $38\text{ }^{\circ}\text{C}$. The four seasons are distinct, with humid and rainy summers and cold, dry winters. The building's appearance is shown in Figure 21, and it is the earliest completed near-zero-energy building in the central and southern Anhui region. The building has a floor area of approximately 260 m^2 , with three floors above ground, a building height of 9.75 m , a floor height of 3.25 m for each floor, and no basement. The building shape coefficient is 0.57 , with window-to-wall ratios of 0.14 on the south side, 0.06 on the north side, 0.10 on the east side, and 0.11 on the west side. The building employs a fully prefabricated structural system, achieving completion of the main three-story structure within 48 h . The entire building integrates a continuous and efficient thermal insulation technology system for the exterior walls, interior walls, roof, and ground floor, as well as energy-efficient door and window systems, high-performance HVAC systems, photovoltaic energy storage, and smart building technologies that represent current advanced green and low-carbon technologies. The engineering parameters are shown in Table 4.



Figure 21. Actual view of a near-zero-energy building.

Table 4. Building envelope construction and thermal parameters.

Envelope Component	Construction Details (Thickness in mm)	U-Value $\text{W}/(\text{m}^2 \cdot \text{K})$
Roof	Reinforced concrete (40) + graphite-enhanced EPS board (SEPS, grade 033, B1) (200) + cement mortar (20)	0.19
Exterior wall	Graphite-enhanced EPS board (SEPS, grade 033, B1) (200) + autoclaved aerated concrete block B07 (100)	0.18
Thermal bridge slab	Graphite-enhanced EPS board (SEPS, grade 033, B1) (200) + reinforced concrete (100)	0.18
Window	Thermally insulated multi-chamber metal frame, $K_f = 5.0\text{ W}/(\text{m}^2 \cdot \text{K})$, frame area 20%; glazing: 5 mm low-e + 16 mm argon warm-edge spacer + 5 mm low-e + 16 mm argon warm-edge spacer + 5 mm tempered	1.00
Floor	Extruded polystyrene board (XPS) (50) + reinforced concrete (100.0 mm) + 1.5 mm PE film + 12 mm wood flooring	0.45

Based on the climate characteristics of the central and southern Anhui region, the project applies a series of key near-zero-energy building technologies: the structure uses fully prefabricated dry connections for rapid assembly; the exterior envelope applies graphite polystyrene board insulation technology and energy-efficient door and window systems to achieve efficient thermal insulation. The specific construction methods for the building envelope are shown in Table 4. Indoor spaces use heat pump-type environmental

integrated machines to create a constant-temperature and humidity living environment; integrated BIPV (Building Integrated Photovoltaics) + direct flexible energy storage technology achieves building energy supplementation and efficiency; and a smart building system centered on intelligent energy consumption monitoring and management enables intelligent control and operational maintenance throughout the building's lifecycle.

5.2. Testing and Analysis of Indoor Thermal Environment

China's latest "Technical Standard for Near-Zero-Energy Buildings" GB/T 51350-2019 stipulates that the indoor temperature in near-zero-energy buildings in summer should not exceed 26 °C, and the relative humidity should not exceed 30% to meet the requirements for a healthy and comfortable indoor environment. Meanwhile, the insulation effect of the building envelope in winter without active equipment is also important. This indoor environment test mainly controls the operation of indoor equipment to study changes in the indoor thermal and humidity environment while further verifying the thermal insulation performance of the building envelope. The Chuzhou near-zero-energy demonstration project employs a 200 mm SEPS insulation layer, low-e triple glazing with double cavities, and an intermittent-ventilation strategy. Field measurements in August 2023 showed that these measures maintained indoor temperatures between 22 °C and 27.5 °C, thus meeting the GB/T 51350-2019 summer requirement of ≤ 26 °C during occupied, air-conditioned hours. While the air-conditioning was running, temperatures remained steady at 22–23 °C; after shutdown, the nighttime swing was limited to just 4.6 °C, well below the standard limit. This performance stems from an envelope whose heat-transfer coefficients are more than 60% lower than those of conventional buildings (roof: 0.18 W/(m²·K)) together with a favorable dynamic thermal response that effectively attenuates outdoor heat.

5.2.1. Measurement Point Layout and Data Collection

This paper primarily collected data on the indoor thermal environment of the near-zero-energy building in summer and winter. The indoor system operation schedule and door and window opening times are shown in Tables 5 and 6, respectively. The main test equipment used is shown in Table 7.

Table 5. Indoor temperature and humidity collection working conditions in summer.

Collection Condition	Test Period	Specific Setup
S1	2023-08-19 09:30–17:00	Only second-floor system running; windows and doors closed
S2	2023-08-19 17:00–2023-08-20 06:00	System off; second-floor windows open from 19:00 to 06:00
S3	2023-08-20 06:00–17:45	System off; windows and doors closed
S4	2023-08-20 17:45–19:45	System off; first-floor windows open
S5	2023-08-20 19:45–2023-08-21 06:00	System on; windows and doors closed
S6	2023-08-21 06:00–08:00	System off; windows and doors open on first and second floors
S7	2023-08-21 08:00–09:00	System off; windows and doors closed

Table 6. Indoor temperature and humidity collection working conditions in winter.

Collection Condition	Test Period	Specific Setup
W1	2024-01-09–2024-01-10 08:00	Windows and doors closed; system off
W2	2024-01-10 08:00–18:00	All windows and doors open
W3	2024-01-10 18:00–2024-01-11 18:00	Windows and doors closed; system on for two hours then off
W4	2024-01-11 18:00–2024-01-12 08:00	Second-floor windows open; system off
W5	2024-01-12 09:20–12:00	System running (setpoint: 22 °C, 50% RH)

Table 7. Measurement equipment list.

Instrument Name	Instrument Model	Measuring Range	Accuracy	Measurement Frequency
Temperature and humidity meter	TES1361C (TES, Taipei, China)	Temperature: −20 °C to 60 °C; humidity: 10% to 95% RH	Temperature ± 0.8 °C; humidity $\pm 5\%$ RH	Every 10 min
Anemometer	Kanomax 6036 (Kanomax, Shenyang, China)	0.01 to 30 m/s	$\pm 3\%$	—
Solar radiation sensor	TES-1333R (TES, Taipei, China)	0 to 2000 W/m ²	$<\pm 3\%$	—

(1) Summer Measurement Point Layout

The near-zero-energy building has three floors, with air conditioning equipment installed on the first and second floors, while the third floor has no air conditioning outlets. A total of seven measurement points were arranged: one outdoor and six indoor. Points 1–4 were on the first floor, points 5 and 6 were on the second and third floors, respectively, and point 7 was on the outdoor terrace of the second floor for measuring outdoor temperature and humidity. This test conducted temperature and humidity measurements at the same horizontal plane, based on a seated human height of 1 m, taking the middle position of the human sitting posture, with measurement points placed at a height of 0.5 m from the floor on each level. Considering temperature and humidity variations across floors, points 3, 5, and 6 were placed at the same position on each floor. When arranging indoor points, the temperature and humidity changes at transparent building envelope structures were considered, with points 2 and 4 placed on the first floor. Wind speed measurements were placed at the west window of the second floor. The arrangement of each measurement point is shown in Figure 22a–c.

(2) Winter Measurement Point Layout

For winter testing, a total of seven measurement points were arranged as shown in Figure 23: one outdoor and six indoor points. Points 1–2 were on the first floor, points 3–5 were on the second floor, point 6 was on the outdoor terrace of the second floor for measuring outdoor temperature and humidity, and point 7 was on the third floor. To measure temperature variations at different heights on the same floor, and considering that people prefer lower limb temperatures to be higher than head temperatures in winter, point 3 was placed 0.3 m from the ground, and point 4 was 1.1 m from the ground.

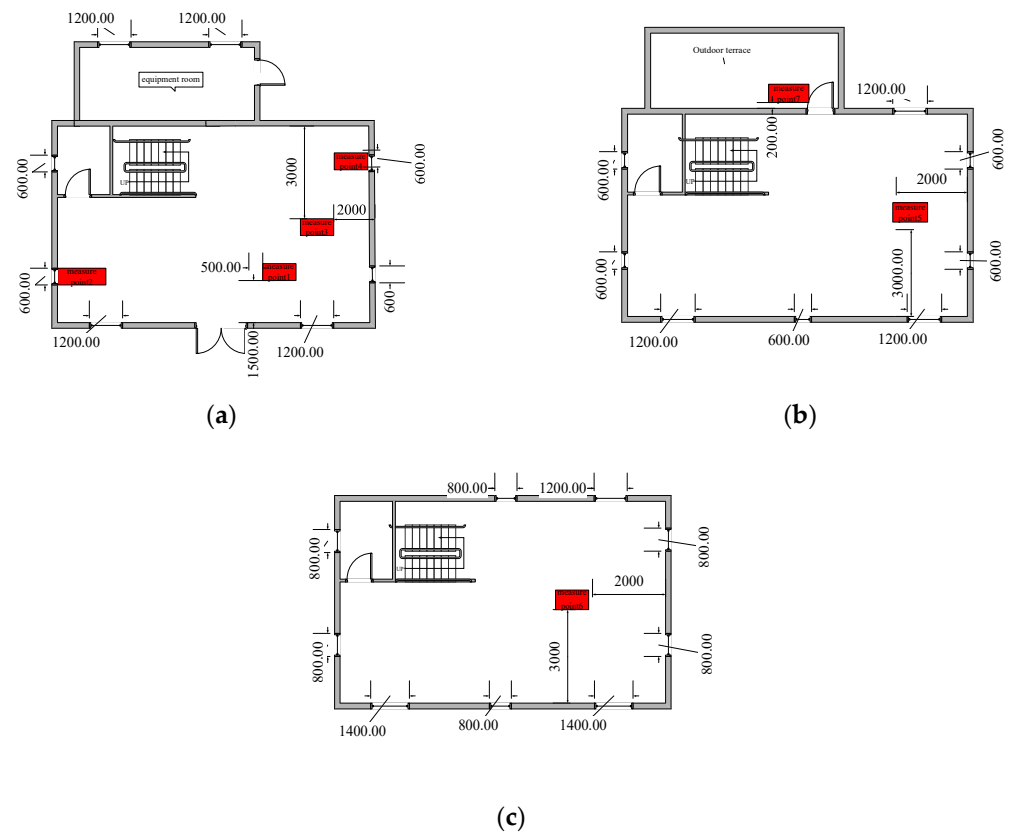


Figure 22. Measurement point layout for summer testing in the near-zero-energy demonstration building. (a) First-floor measurement point layout. (b) Second-floor measurement point layout. (c) Third-floor measurement point layout.

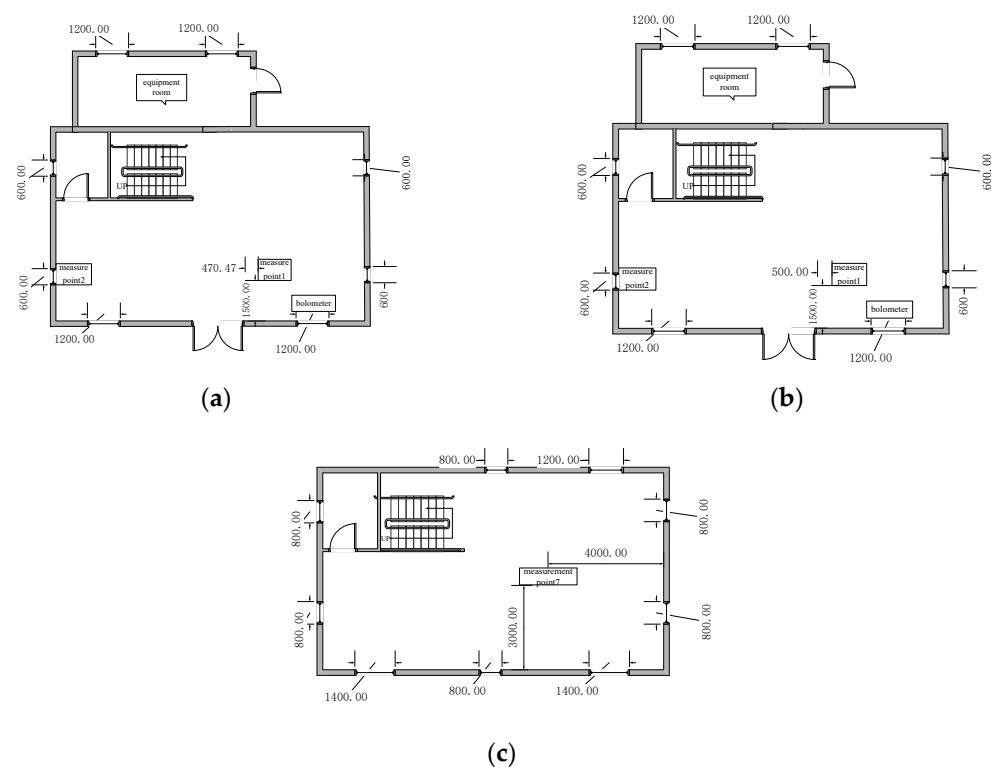


Figure 23. Measurement point layout for winter testing in the near-zero-energy demonstration building. (a) First-floor measurement point layout. (b) Second-floor measurement point layout. (c) Third-floor measurement point layout.

5.2.2. Dynamic Response Characteristics of Indoor Temperature and Humidity

(1) Summer Indoor Temperature and Humidity Analysis

As shown in Figure 24, the building's insulation system is very stable. With doors and windows closed, the indoor thermal environment changes minimally with outdoor temperature fluctuations, indicating good insulation performance. Only on the evening of the 20th through the 21st was the system turned on, with the temperature set to 22 °C. The first and second floors responded quickly to temperature changes, while the third floor, having no air outlets, showed minimal adjustment effect from the HVAC system. Before the air conditioning was turned on, due to the first-floor windows being open and the outdoor temperature being higher than indoors, there was a noticeable temperature increase. As ventilation increased, the indoor temperature gradually decreased. After ventilation, the first-floor temperature was higher than the second-floor temperature, but 30 min after the air conditioning was turned on, the first-floor temperature merged with and gradually became lower than the second-floor temperature.

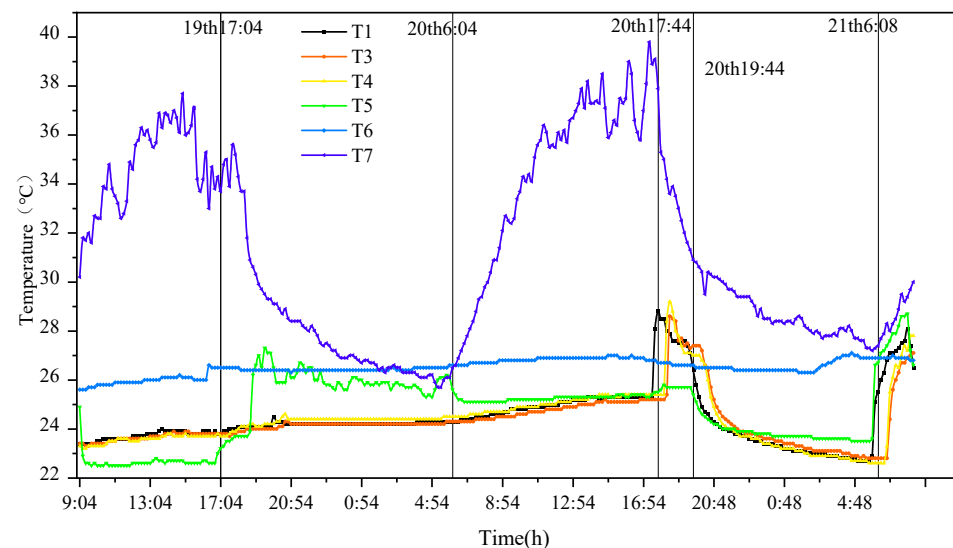


Figure 24. Indoor temperature of near-zero-energy demonstration building in summer.

As shown in Figures 25 and 26, with first-floor windows open, the temperature changes on the second and third floors were not significant. After the environmental control system was turned on, the temperature at point 3 decreased the fastest. Around 21:00, the temperatures of the first and second floors intersected, with temperature showing a positive correlation with floor height. The first-floor temperature was the lowest, with a temperature difference of 3.6 °C between the first and third floors at 6:00 on the 21st. With the system on, temperature regulation effects were evident on the first and second floors, while the third floor, without air outlets, showed minimal indoor temperature regulation effect.

As shown in Figure 27, the temperature changes after opening and then closing windows followed by system operation maintained indoor temperatures in the range of 23–28 °C, meeting human thermal comfort requirements. Outdoor temperatures rose from 28 °C to above 30 °C between 6:00 and 8:00. After opening windows, the temperatures at points 3 and 5 increased by 3 °C within 20 min, with virtually consistent trends and a temperature difference with the outdoors of about 1.5 °C, while the third-floor temperature remained stable. At 8:00, the HVAC system was turned on, and point 3 decreased by 1.8 °C within 2 h, point 5 decreased by 2.7 °C within 2 h, while point 6 temperature fluctuated within 0.2 °C.

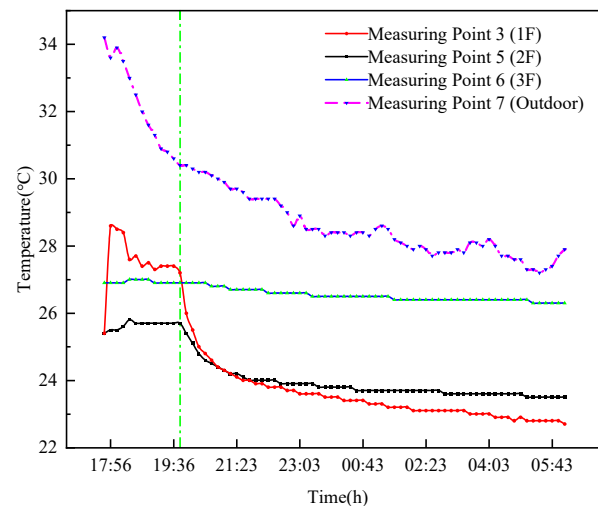


Figure 25. Temperature changes at each floor from 18:00 on the 20th to 6:00 on the 21st.

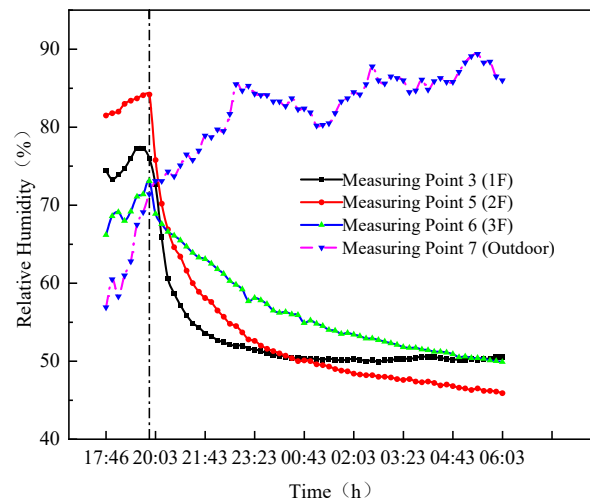


Figure 26. Humidity changes at each floor from 18:00 on the 20th to 6:00 on the 21st.

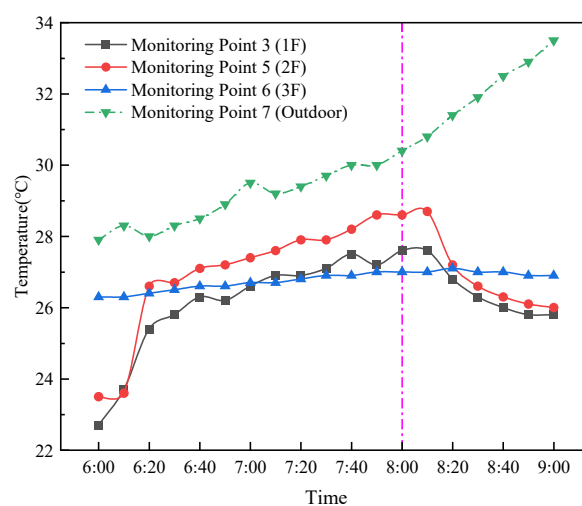


Figure 27. Temperature changes at each floor from 6:00 to 9:00 on the 21st.

As shown in Figure 28, humidity increased instantly after opening windows at 6:00. The humidity at points 3 and 5 reached 85% within 20 min, approaching the outdoor humidity level. The relative humidity at point 6 increased from 50% to 65% within 20 min

after the humidity at points 3 and 5 increased, and then stabilized. After closing windows at 8:00 in the morning, outdoor humidity decreased significantly, while the humidity changes at various indoor points were minimal.

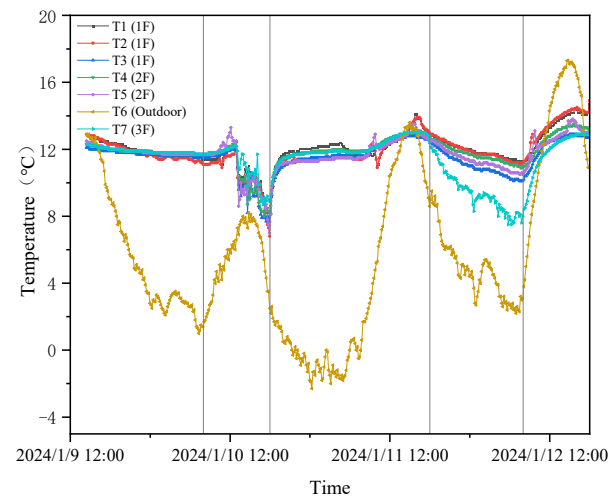


Figure 28. Humidity changes at each floor from 6:00 to 9:00 on the 21st.

(2) Winter Indoor Temperature and Humidity Analysis

As shown in Figures 29 and 30, the winter temperature and humidity change curves reveal significant outdoor temperature and humidity variations. Outdoor temperatures fluctuated between -2°C and 10°C , with humidity in the range of 30–90%, while indoor temperatures were between 9°C and 15°C , with humidity in the range of 30–65%. Opening windows for ventilation had a significant impact on indoor temperature and humidity. With windows closed and the HVAC system off, temperature fluctuated around 13°C and humidity around 55%. The figure shows that on the 10th, daytime temperatures decreased significantly. During this test phase, the HVAC system was turned on for 2 h in the evening of the 10th, causing the indoor temperature to rise instantly. Even after the system was turned off, indoor temperatures remained stable and consistently higher than outdoor temperatures. With the HVAC system operating on the 12th, temperatures rose rapidly. This demonstrates the significant effectiveness of the demonstration building's envelope insulation performance.

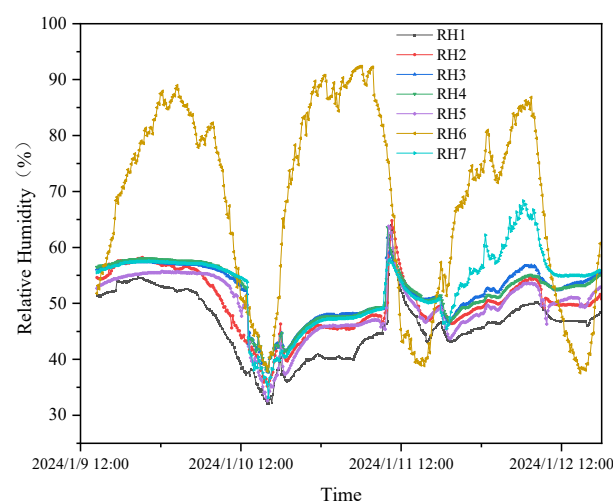


Figure 29. Temperature change curves during winter testing.

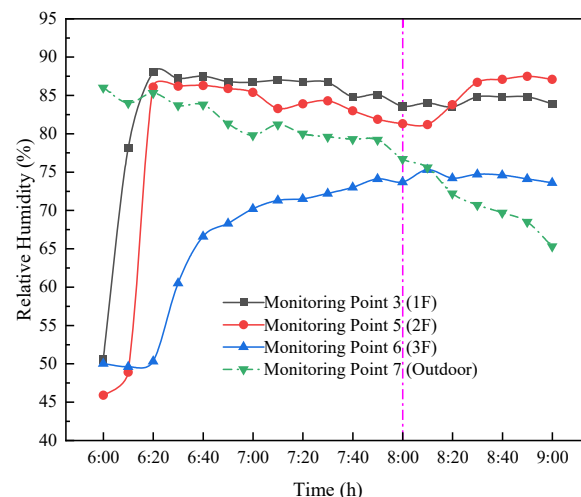


Figure 30. Humidity change curves during winter testing.

6. Conclusions

The regional characteristics of central and southern Anhui were examined in detail, and climate indicators (temperature, humidity, wind speed, solar radiation) for five typical cities and one world-famous scenic area were quantitatively analyzed. Building energy surveys were then used to assess the current situation. The main findings are as follows:

- (1) Central and southern Anhui has a typical hot-summer and cold-winter climate with high year-round humidity. These conditions significantly increase building energy demand, so the thermal performance of the building envelope must be specifically optimized.
- (2) Using climate data from 2009 to 2023 and the Climate Consultant software, four typical cities were evaluated for passive-technology suitability. Envelope measures that combine lightweight and heavyweight materials account for 14.18% of the effective strategy time, while shading and ventilation contribute 14.03% and 10.18%, respectively. Under the regional climate, these three strategies improve energy efficiency and indoor thermal comfort, providing scientific and practical guidance for designing nearly zero-energy buildings.
- (3) The envelope of the near-zero-energy demonstration building shows strong thermal-environment control. In summer, with doors and windows closed, indoor temperatures remain stable despite outdoor fluctuations. When the HVAC system starts, the first- and second-floor temperatures converge within 30 min, whereas the third floor (no supply outlet) lags, with a 3.6 °C difference—highlighting the need for zoned control. With natural-ventilation strategies, opening windows raises indoor temperature by 3 °C and humidity by 35% within 20 min; after closing windows, HVAC lowers temperature by 1.8–2.7 °C within 2 h and keeps humidity fluctuations within $\pm 5\%$. In winter, with windows closed and HVAC off, indoor temperature holds at 13 °C (outdoors -2 to 10 °C) and humidity at 55%. Two hours after HVAC shutdown, indoor temperature is still 4–6 °C higher than outdoors, demonstrating excellent thermal inertia. Optimizing envelope performance, layered temperature control, and ventilation timing can balance energy use and comfort in both seasons, underpinning ultra-low-energy building technology in transitional climates.
- (4) Future research should prioritize building higher-precision regional climate–building-energy coupling models to support design decisions scientifically. Key challenges include improving material durability under high-humidity conditions and establishing standardized retrofit systems for existing buildings. Nevertheless, coordinated innovation in advanced materials, intelligent controls, and renewable-energy

systems is expected to deliver a triple breakthrough—higher energy performance, smarter operation, and cost optimization—for nearly zero-energy buildings in central and southern Anhui. These advances will ultimately produce a replicable technical framework that comprehensively supports the region’s low-carbon transition in the construction sector.

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