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Green Campus Transformation in Smart City Development: A Study on Low-Carbon and Energy-Saving Design for the Renovation of School Buildings

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Highlights:

What are the main findings?

- The wind environment simulation of the Yezhai Middle School building complex revealed that wind speed exhibits a nonlinear increase with changes in building height, and ground roughness significantly impacts wind speed variations.
- Heat transfer analysis found that using EPS panels and insulation layers in the renovation of Yezhai Middle School's exterior walls can effectively prevent cold air infiltration, reduce ex-ternal heat gain, and achieve approximately 24% energy savings.

What is the implication of the main finding?

- Building simulation software applied in campus renovation can help designers make timely adjustments during the design phase to achieve optimal energy-saving and low-carbon design solutions.
- Through wind environment simulation and exterior wall energy-saving renovations of the Wild Village Middle School complex, scientific basis and practical experience have been pro-vided for low-carbon and energy-saving renovations of other campuses and public buildings.

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Abstract: In the context of increasingly deteriorating global ecological conditions and rising carbon emissions from buildings, campus architecture, as the primary environment for youth learning and living, plays a crucial role in low-carbon energy-efficient design, and green environments. This paper takes the case of Yezhai Middle School in Qianshan, Anhui Province, to explore wind environment optimization and facade energy-saving strategies for mountainous campus buildings under existing building stock renovation. In the context of smart city development, integrating advanced technologies and sustainable practices into public infrastructure has become a key objective. Through wind environment simulations and facade energy retrofitting, this study reveals nonlinear increases in wind speed with building height and significant effects of ground roughness on wind speed variations. Adopting EPS panels and insulation layers in facade energy retrofitting reduces energy consumption for winter heating and summer cooling. The renovated facade effectively prevents cold air intrusion and reduces external heat gain, achieving approximately 24% energy savings. This research provides a scientific basis and practical experience for low-carbon energy retrofitting of other campus and public buildings, advancing the construction industry towards green and low-carbon development goals within the framework of smart city initiatives.

Keywords: smart city development; green campus design; energy efficiency; wind environment simulation; insulation layers; energy retrofitting

1. Introduction

The current frequent occurrences of health problems such as atmospheric pollution, water pollution, and global warming have made it imperative for people to have a healthy and comfortable environment. Public buildings, which cover almost all aspects of residents' lives and serve as the main venues for indoor activities, are one of the important directions for development in China's construction industry. In the context of smart city development, integrating advanced technologies and sustainable practices into public infrastructure has become a key objective. Smart cities aim to enhance the quality of urban living by leveraging technology and data to optimize resources, improve services, and reduce environmental impact [1,2].

Smart building, as a subset of smart environments, requires high support by technological infrastructure that uses data/information. Multiple digital construction technologies have assisted the infrastructure to prepare buildings in becoming smart, such as Building Information Modeling (BIM), the Internet of Things (IoT), and Blockchain technology, which are widely utilized recently as enabling components in the context of smart cities [3].

Achieving low-carbon design is crucial as one of the ultimate goals of smart buildings. Several certifications have been proposed in order to control the energy consumption of the architecture, providing energy performance standards and certification systems, such as Building Research Establishment's Environmental Assessment (BREEAM), Leadership in Energy and Environmental Design (LEED), and German Sustainable Building [4]. For example, in South Korea, Building Energy Efficiency Certificates (BEECs) have been implemented, through which 1648 educational buildings have been certified by conducting the HIPB model in the stimulation [5].

The exploration of innovative solutions in studies coming out reveals that more and more energy-saving technologies are proposed, for example, on insulation materials, building envelopes, and HAVC systems. The studies include the evaluation of the performance of different thicknesses of sisal fiber, which is a sustainable thermal insulation material, resulting in 7 cm being shown as the optimal insulation thickness [6]. Moreover, the utilization of Phase Change Material (PCM) can also enhance a system's efficiency through its latent heat storage capabilities. Optimization algorithms such as the genetic algorithm (GA) and the model predictive control algorithm (MPC) are crucial for enhancing both the efficiency and dependability of building design by refining objective functions within certain constraints [7]. Low-energy passive cooling technologies can be applied to provide excellent thermal comfort with a low energy need which is required for a certain comfort level, which is fulfilled when at least 84% of the recorded hourly temperature measurements remain within the defined comfort limit and its equivalent tolerance range. In a stimulation, the research concluded the alignment of different comfort models with different climate zones which can be applied to educational buildings. Water-based low-energy cooling systems can be applied in all climate zones, using the cool ground for effective cooling, especially in the summer. Thermally Active Building Systems (TABSs) offer high thermal inertia, helping manage peak loads. Using the adaptive comfort model allows indoor temperatures to fluctuate within a comfortable range, reducing the need for energy-intensive cooling. By using combined systems (radiant systems for sensible loads and fan coils for latent loads), various cooling needs of different buildings can be better addressed, achieving efficient energy savings [8]. These technologies collectively pave the way for greener, more energy-efficient buildings, aligning with global sustainability goals and enhancing the overall comfort and functionality of built environments.

Through statistical analysis of public building types, it is found that the number of schools/kindergartens accounts for about 40% of the total, indicating a greater demand for campuses in the future. Schools, especially primary and secondary schools, are places where young people live and study for long periods. The architectural experience and campus environment not only demonstrate but also directly affect the work efficiency and learning effectiveness of teachers and students, as well as the cultivation of green and low-carbon lifestyle concepts among students. Therefore, against the backdrop of stock renewal, it is of great significance to choose energy-saving technologies with good enthusiasm and market maturity, especially for the facade of secondary school buildings [9,10].

In recent years, research on low-carbon energy-saving strategies for campus buildings has focused on energy efficiency and retrofitting, integration of renewable energy, green campus design, and low-carbon education and behavior change. In the field of energy efficiency and retrofitting, Olsen D. J. et al. discussed the planning and implementation strategies for low-carbon campus energy centers [11]; Chung M. H. and Rhee E. K. analyzed the energy-saving potential of existing buildings through field surveys of campus buildings in South Korea [12]; Soares N. et al. studied practical cases of improving energy efficiency in higher education buildings [13]; Liu Q. and Ren J. proposed energy-saving design strategies for Chinese university buildings through green performance analysis. Di Stefano J. evaluated the potential for Melbourne University to improve energy efficiency and reduce carbon dioxide emissions by upgrading lighting systems [14]; Ashrafian T. conducted a comprehensive analysis of the energy, cost, and comfort factors involved in improving the energy efficiency of school buildings in the context of climate change [15].

In the field of renewable energy integration, Shea R. P. et al. explored how the University of Dayton transitioned to a carbon-neutral campus through full electrification and renewable energy [16]; Hurwitz Z. L. et al. studied the economic efficiency and carbon emissions of multi-energy systems in buildings [17]; Bhavsar R. et al. showcased the practice of achieving zero energy and zero carbon emissions at Mohawk College through efficient and renewable energy technologies [18].

In the field of green campus design, Gui X. et al. examined the impact of academic calendars on university energy consumption [19]; Zheng N. et al. combined ecological footprint evaluation and machine learning to study the construction of low-carbon campuses in China [20]; Fonseca P. et al. discussed various schemes for achieving near-zero energy consumption on university campuses [21]. Luo X. et al. proposed an evaluation model and selection strategy for carbon reduction technologies for campus buildings in China's Yangtze River Delta region to reduce carbon emissions through optimized design and technology choices [22].

In the field of low-carbon education and behavior change, Roy R. et al. compared the environmental impacts of campus education and remote education, finding that remote education significantly reduces energy consumption and carbon emissions [23]; Guerrieri M. et al. quantitatively assessed the role of university campuses as small urban models in the low-carbon transition [24].

Despite significant progress in the practice and exploration of low-carbon campuses, many challenges still need to be solved. Yoshida Y. et al. introduced Osaka University's strategies and challenges in achieving a sustainable campus [25]; Mytafides C. K. et al. discussed the challenges of achieving zero-energy buildings under specific climate conditions [26]; Mustaffa N. K. et al. explored the driving factors, challenges, and strategies in achieving a low-carbon campus at the University of Technology, Malaysia [27].

Additionally, several papers have presented case studies demonstrating the practices of higher education institutions worldwide in building low-carbon campuses. Sesana M. M. et al. described practical cases of building energy-efficient renovations on Italian university campuses [28]; Kourgiozou V. et al. systematically reviewed the practices of the UK higher education sector in achieving net-zero carbon emissions [29]; Del Borghi A. et al. showcased the design and renovation practices of carbon-neutral campus buildings in Europe and the United States [30].

In the field of practical case studies, there are relatively few research papers on green campus buildings domestically, and most projects belong to the new building design sector. As the era of stock buildings arrives, more and more old buildings will need renovation. Therefore, the design strategies for green, low-carbon energy-saving renovations in campus buildings are also directions that need more attention. This paper takes the renovation project of a secondary school campus in Anhui Province as the research object. It summarizes the strategies for low-carbon energy-saving facade renovations suitable for mountain campus buildings in China's hot summer and cold winter regions through simulation analysis of the wind environment and energy-saving facade renovations of the renovated building complex. This study can provide some references and supplements for green, low-carbon energy-saving renovations for campus renovation projects.

2. Materials and Methods

2.1. Yezhai Middle School

2.1.1. Overview of Yezhai Middle School

The Qianshan Yezhai Middle School Campus Expansion and Upgrade Project is located in Tianzhushan Town, Qianshan City, Anhui Province. The construction scope includes the main campus of Yezhai Middle School and its west and north sides. It encompasses the original site of Tianzhushan Central Primary School allocated by the government and the former Yezhai mining supply station site, totaling 23.27 mu (approximately 1.56 hectares). Additionally, it involves the requisition of 78 mu (approximately 5.23 hectares) of collective mountain ponds, terraces, and flower beds in Fengjing Village (Figure 1). Through the implementation of the project, the area of the Yezhai Middle School campus will increase by approximately 100 mu (approximately 6.7 hectares).

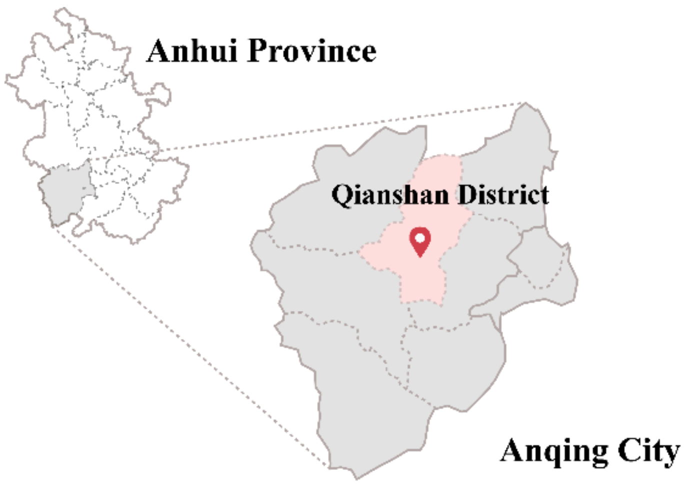


Figure 1. Location map of Yezhai Middle School.

The surrounding living facilities and public information platforms of the project are well equipped. The road, power supply, water supply and drainage, greening, and lighting systems are well established. The project site is conveniently connected to various towns and townships under the jurisdiction of Qianshan City via National Highway 318 and provincial and county roads. The site is 8 km away from downtown Qianshan, providing easy access for the transportation of building materials and other goods.

The terrain of the entire project area gradually descends from north to south, with Tianzhushan Mountain to the back and Qianshui River to the south, offering an excellent ecological environment. The site is adjacent to Jingzhong Road in the south and connects to the existing campus in the east. The surrounding land is mainly used for residential and commercial purposes, showcasing obvious location and resource advantages.

After evaluating the original buildings of Yezhai Middle School, the structures that are aged and do not meet modern usage requirements are identified for demolition. These buildings will undergo renovation and additional construction. The project is mainly divided into two phases: the West Campus and the Main Campus. The new construction mainly focuses on the West Campus (Figure 2).

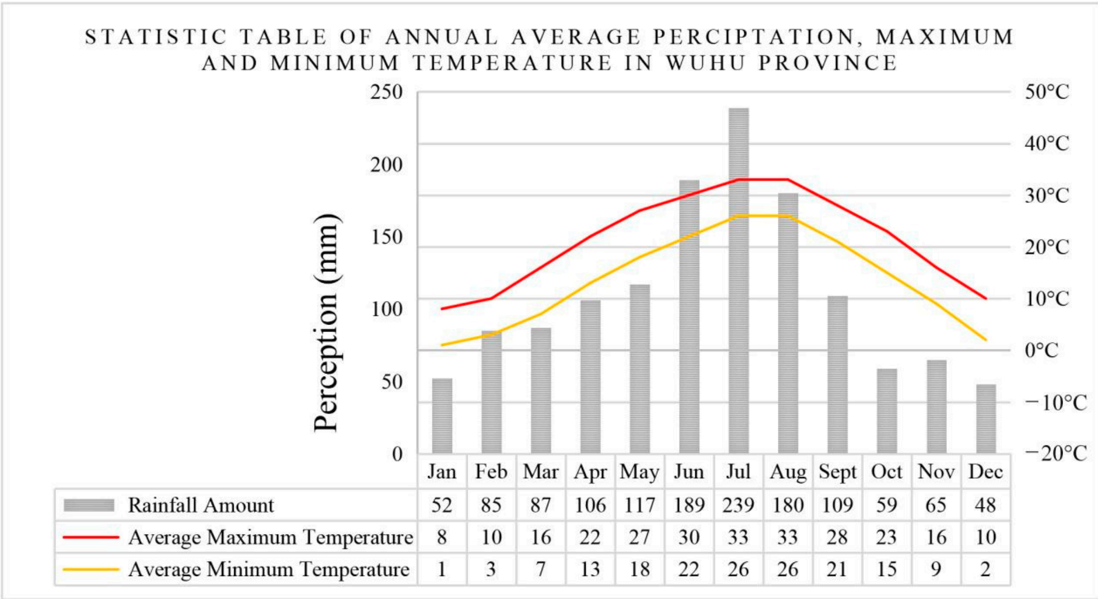


Figure 2. Annual average temperature and precipitation in Qianshan City.

2.1.2. Environmental Analysis

Tianzhushan Town is located in a subtropical monsoon climate zone, with an annual average temperature of approximately 9.5 °C and an average annual sunshine duration of no more than 2000 h. The area experiences foggy days for about 250 to 300 days per year, with a minimum of 200 days. The average annual precipitation is around 1900 mm, with the maximum number of rainy days in a year reaching approximately 150 days. Its characteristic features include distinct seasons, mild climates in spring and autumn, hot summers, and dry, cold winters. The area receives abundant sunlight and ample rainfall, resulting in a relatively long frost-free period. The multi-year average temperature is 16.2 °C [31,32] (Figures 2 and 3). The annual solar radiation in Tianzhu Mountain Town is approximately 154 $MJ/m^2 \cdot d$, exhibiting a seasonal distribution pattern with higher radiation in summer and lower in winter. The solar radiation is highest in July, reaching 17 $MJ/m^2 \cdot d$, and lowest in January, at about 8 $MJ/m^2 \cdot d$.

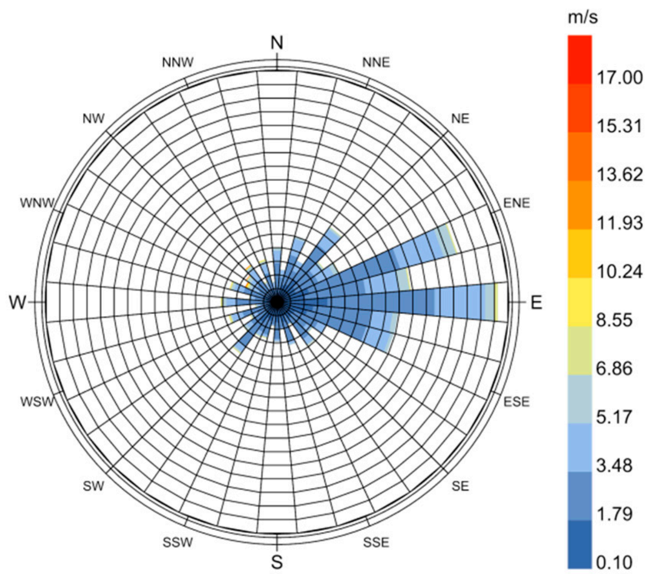


Figure 3. Wind rose diagram showing wind direction and wind speed.

2.2. Methodology

This study focuses on the wind environment and wall insulation as key research subjects based on their critical impact on improving the energy efficiency of campus buildings. The wind environment directly affects the airflow and heat exchange around the building, thereby influencing indoor thermal comfort and energy consumption. As one of the primary measures for building energy conservation, wall insulation can significantly reduce heating energy consumption in winter and cooling energy consumption in summer. Therefore, optimizing the wind environment and wall insulation is of great theoretical and practical significance for achieving the low-carbon energy-saving goals of campus buildings.

2.2.1. Wind Environment Simulation

Wind environment simulation is a technique based on Computational Fluid Dynamics (CFD) methods, which numerically solve airflow in building environments to predict the distribution of wind speed, wind pressure, and flow direction. The main principles include the continuity equation, momentum equation, and energy equation (Appendix A).

In this study, we used Ecotect software to simulate and analyze the wind environment of the Yezhai Middle School building complex. Ecotect's user interface is intuitive and easy to operate, making it suitable for simulation analysis in the early stages of architectural design. Its outstanding visualization capabilities allow simulation results to be presented through clear graphics and charts, enabling architects and non-technical personnel to understand the analysis results intuitively. This intuitiveness is well suited for rapid concept validation and scheme optimization in the initial design phase.

Additionally, Ecotect has relatively low computational resource requirements, allowing it to run smoothly even on hardware with lower specifications. This specialty is particularly important for small projects with limited resources, as it provides sufficiently accurate simulation results without expensive hardware.

Although there are currently many more detailed and professional building simulation software options on the market, such as EnergyPlus 8.4, OpenStudio, and IES VE, which offer higher precision and a more comprehensive range of functionalities, Ecotect still has significant advantages in terms of flexibility and ease of use in the early design stages. For this study, Ecotect provided the capability for rapid iteration and multi-aspect performance evaluation, which played a crucial role in optimizing the preliminary design and supporting decision making.

Therefore, although Ecotect is no longer being updated, its core functions remain reliable, and it is still widely used in some preliminary studies. It is also a key reason for choosing it as the simulation tool—it can provide sufficient information in the early stages to ensure the smooth progress of the study and lay the foundation for more in-depth and refined analysis in the future. In future research, we will use more advanced software to validate and refine the results.

In practical applications, the process begins with geometric modeling of the building using SketchUp, followed by partitioning the geometric model into appropriate computational grids using CFD software. Setting boundary conditions involves specifying inlet wind speeds, outlet pressures, and wall boundaries, selecting an appropriate CFD solver, and configuring computational parameters. Iteratively solving these equations yields wind speed, pressure, and temperature field distributions. Post-processing tools are then used to analyze wind speed and direction distributions at different height sections, assessing the impact of building design on the wind environment (Figure 4).

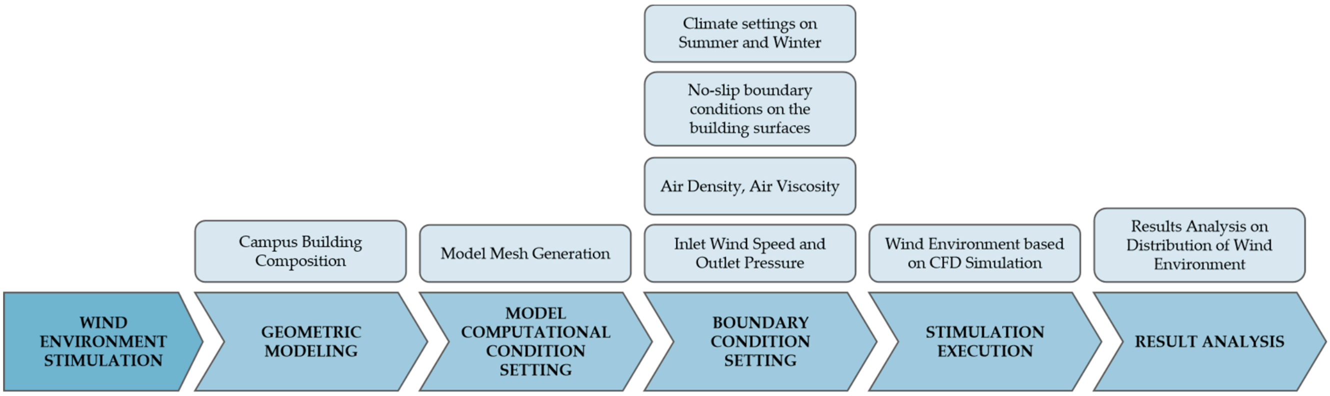


Figure 4. The flowchart of wind environment simulation.

In this study, we meticulously designed the CFD model's mesh generation to ensure the simulation results' accuracy and stability. First, an unstructured grid was adopted. This type of mesh can flexibly adapt to the complex geometry of buildings, particularly excelling at capturing fluid behavior around building edges and corners. The minimum cell size was set to 0.05 m for fine simulations in critical areas. In comparison, the maximum cell size was increased to 0.5 m in regions where flow changes are more gradual to enhance computational efficiency.

To accurately simulate changes in wind speed and pressure around the building, local mesh refinement was applied to the windward, leeward, and junction between the building and the ground, where the cell size was further reduced to 0.02 m. A higher-density mesh was also used to accurately capture fluid shear stress and temperature gradients in the boundary layer regions near the building surface.

Regarding mesh quality, strict quality control measures were implemented to ensure that the mesh orthogonality and aspect ratio remained within a reasonable range, thereby reducing computational errors and enhancing the stability of the numerical simulations. Finally, a mesh independence analysis was conducted to verify the suitability of the selected mesh scheme, ensuring that the simulation results were not affected by mesh size. These detailed meshing strategies provided a reliable data foundation for this study and ensured high-precision simulation results.

As shown in Table 1, the inlet wind speed and outlet pressure settings ensure that the airflow conditions in the simulation are consistent with actual conditions. A wind speed of 5 m/s was chosen based on the actual wind environment of the Yezhai Middle School campus. At the same time, an outlet pressure of 0 Pa ensures that air can leave the simulation area without obstruction, making the simulation results closer to real-world scenarios.

The no-slip boundary condition reflects the actual physical behavior of air when it comes into contact with the building surface, ensuring that the air velocity at the building surface is zero, thereby accurately reproducing the friction effect. It is crucial for accurately assessing the wind pressure on the building and the airflow patterns.

The ambient temperature is set to 30 °C, representing high-temperature conditions in summer. The aim is to consider energy consumption under high-temperature conditions in the heat conduction simulation, optimizing the building's energy-saving design.

Air density and air viscosity are the simulation's fundamental fluid dynamics and thermodynamics parameters. An air density of 1.2 kg/m^3 is used to calculate forces related to aerodynamics. In contrast, an air viscosity of 1.8×10^{-5} Pa·s determines the flow characteristics of air over the building surface and the accuracy of the heat transfer process simulation.

Boundary layer mesh refinement, achieved by setting a minimum mesh cell size of 0.02 m, allows for capturing acceptable variations in airflow in critical boundary layer regions, especially near the building surface. Applying such high-density meshing ensures high resolution and accuracy of the simulation, supporting precise analysis of the building's wind environment.

Table 1. Boundary conditions and input parameters for wind environment simulation.

Parameter Type	Specific Settings	Description
Inlet Wind Speed	5 m/s	Set to 5 m per second to simulate the typical wind speed around the Yezhai Middle School campus. This speed is used to describe the velocity of air entering the simulation area from the inlet.
Outlet Pressure	0 Pa	Set to zero pressure, representing free airflow out and assuming equilibrium with atmospheric pressure.
Wall Boundary Condition	No-slip	Adopting a no-slip condition means there is no relative motion between the fluid and the solid surface.
Ambient Temperature	30 °C	Represents the ambient temperature under typical high-temperature summer conditions.
Air Density	1.2 kg/m^3	Set according to standard atmospheric conditions.
Air Viscosity	1.8×10^{-5} Pa·s	Used to describe the magnitude of shear stress in the air during flow, affecting the flow characteristics of the boundary layer.
Boundary Layer Mesh Refinement	Minimum Cell Size 0.02 m	Mesh refinement is applied in the boundary layer regions near the building surface to capture fine variations in fluid flow in these areas, particularly the gradients of wind speed and temperature.

2.2.2. Heat Transfer Simulation

Heat transfer simulation is based on Fourier's law of heat conduction and the steady-state heat conduction equation, using numerical methods to compute heat transfer within building walls (Appendix B).

Based on the thermal properties of building materials, the parameters of each material layer were first determined, and a thermal resistance model was established. The thermal resistance of each layer was then calculated to derive the total thermal resistance. With indoor and outdoor boundary conditions set, numerical methods were employed to solve the steady-state heat conduction equation, facilitating the calculation of temperature distribution and heat flux. Heat flux was determined using Fourier's law of heat conduction, taking into account the temperature difference across the wall. This methodology allowed for an evaluation of the impact of different materials and structures on thermal performance, providing insights into optimizing building design and enhancing energy efficiency (Figure 5).

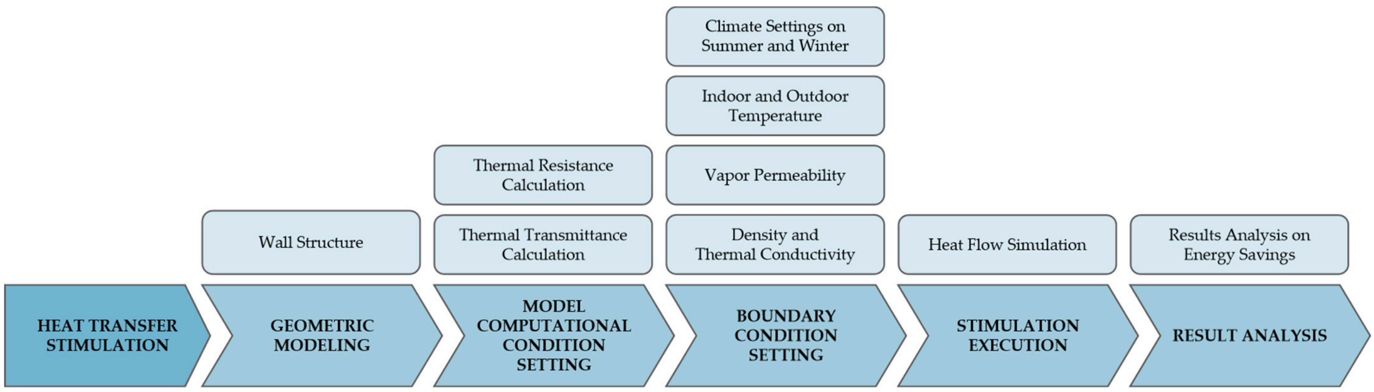


Figure 5. The flowchart of heat transfer simulation.

In the heat transfer simulation, the indoor–outdoor temperature difference (ΔT) was initially set to 20 °C to reflect the thermal resistance of the exterior wall under extreme weather conditions in winter or summer. High-density expanded polystyrene (EPS) was selected as the primary insulation material due to its low thermal conductivity and moderate thickness, effectively blocking heat transfer. The thermal boundary conditions were set as a fixed temperature difference and steady-state heat flow to ensure the heat conduction simulation could reflect the energy consumption under actual building operating conditions. The final calculated heat transfer coefficient (U-value) was 0.253 W/m^2·K, which was directly used to assess the energy-saving effect of the exterior wall renovation (Table 2).

Table 2. Boundary conditions and input parameters for heat transfer simulation.

Parameter Type	Specific Settings	Description
Indoor–Outdoor Temperature Difference (ΔT)	20 °C	Set the indoor–outdoor temperature difference to 20 °C to simulate the impact of the temperature gradient on heat flow during heat conduction. This temperature difference is commonly used to evaluate the thermal insulation performance of building exterior walls.
Wall Material Properties	High-Density Expanded Polystyrene (EPS)	The wall insulation material used is high-density expanded polystyrene (EPS) with a thermal conductivity of 0.038 W/m·K and a thickness of 0.15 m. This material was chosen to enhance the thermal insulation performance of the walls and reduce heat loss.
Thermal Boundary Conditions	Fixed Temperature Difference and Steady-State Heat Flow	Set up a steady-state heat conduction simulation, assuming a constant indoor–outdoor temperature difference, to calculate the heat flow under these conditions and evaluate the insulation performance of the wall in winter and summer.
Heat Transfer Coefficient (U-value)	0.253 W/m^2·K	The heat transfer coefficient calculated based on the wall's multilayer structure represents the wall's overall thermal conductivity. This value is crucial when evaluating the energy-saving performance of the wall.

3. West Campus Planning Scheme and Wind Environment Simulation

3.1. West Campus Planning Scheme

Figure 6 depicts the master plan and aerial view, respectively, of the newly constructed West Campus. In this design, the main entrance of the campus is located at the center, leading through the sports field area of the playground, then ascending via a grand staircase to reach the scenic pond area. The central axis of the campus is aligned with the comprehensive building and the teaching building, connected by a west-side corridor linking the comprehensive building with the cafeteria.

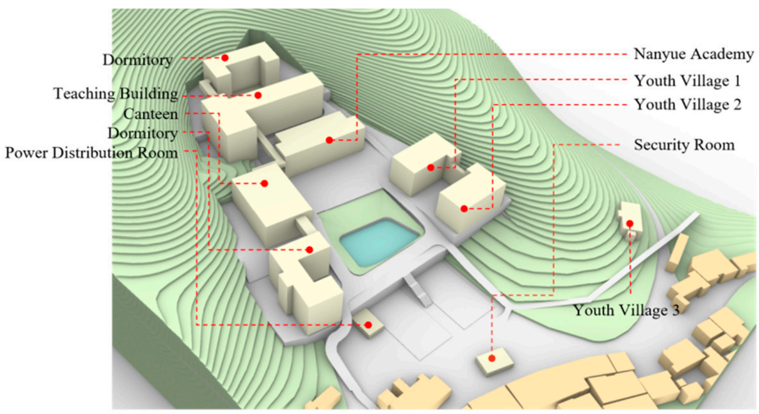


Figure 6. Overall aerial view of the West Campus.

On the northeast side of the campus, 2–3 buildings of teacher apartments are constructed, named “Youth Village”. The Youth Village complex includes teacher apartments and staff dormitories. On the southwest and northwest sides of the site, one building of a student dormitory is newly built on each side. The existing classrooms are retained and converted into a comprehensive building and an academy, with a new teaching building constructed behind (north side), connected by a corridor to ensure all-weather use.

3.2. Wind Environment Simulation of the West Campus

This experiment primarily simulated the corresponding conditions of the area where Yezhai Middle School is located under certain wind environmental conditions. SketchUp was used to geometrically model the Yezhai Central Building Group. According to the principle of architectural similarity, the buildings were simplified into cuboid shapes and modeled according to actual dimensions, which is conducive to improving computational efficiency. Taking the layout of Yezhai Middle School as an example, Ecotect software was utilized to analyze the wind environment of the school buildings [33,34].

3.2.1. Model Simplification and Parameter Settings

Create or import the architectural model of Yezhai Middle School in Ecotect. Ensure the accuracy of the model’s dimensions, orientation, and position.

In Ecotect, environmental parameters were set, including geographical location and climate data: an air density of 1.2 kg/m^3, air viscosity of 1.8×10^{-5}, and classification as a hot-summer and cold-winter region. The hottest month in this region has an average temperature ranging from 25 to 30 °C, accompanied by relatively high humidity, while the coldest month has an average temperature from 0 to 10 °C. This region is characterized by hot and humid summers with reduced sunshine. The prevailing wind direction during the summer is southeast, with a simulated wind speed of 5 m/s [35].

The WinAIR plugin was installed and launched to facilitate wind flow analysis. WinAIR is a specialized tool designed to conduct wind environment simulations within Ecotect. Upon simulation execution, WinAIR analyzed the airflow surrounding the building model based on the set parameters.

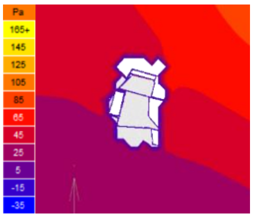
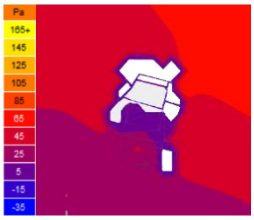
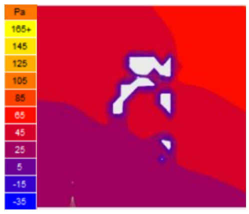
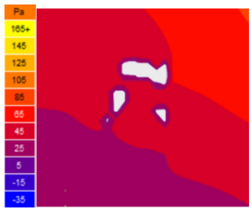
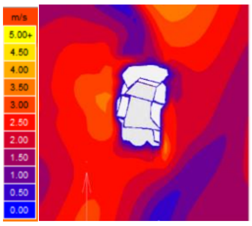
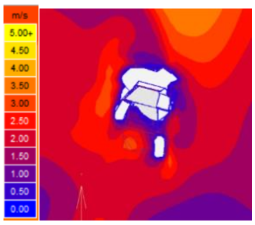
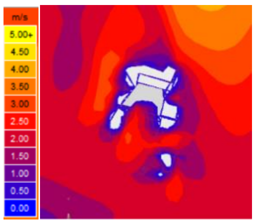
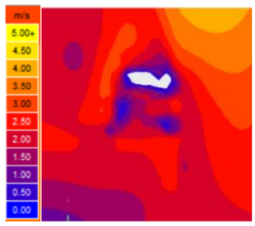
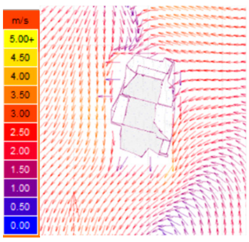
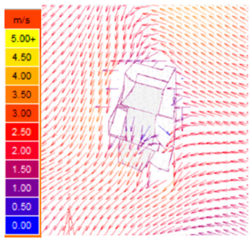
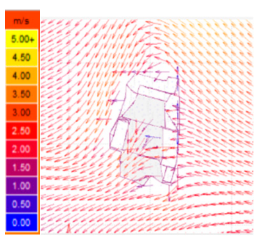
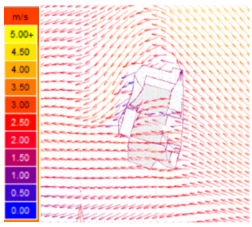
3.2.2. Analysis of Simulation Results

For both wind speed distribution and wind direction distribution, different sections at various heights correspond to different situations. This is primarily due to variations in building obstruction and the resulting wind resistance at different heights. To reflect the influence of architectural form on the wind environment, sections at heights of 0 m, 10 m, 20 m, and 30 m were selected for analysis [36].

Table 3 demonstrates that wind speed increases with height, and this growth is non-linear. At lower heights, wind speed increases more rapidly, likely due to greater frictional effects closer to the ground. As height increases, the rate of wind speed growth gradually decreases, possibly because airflow at higher elevations is more free-flowing and less affected by friction. Wind pressure, as a function of wind speed, also exhibits a similar non-linear growth pattern. However, because it is proportional to the square of wind speed, wind pressure can still increase significantly even in regions where wind speed growth slows down.

Through an examination of wind speed and wind pressure distributions in different directions, it is evident that each direction exhibits unique wind environment characteristics. Westward wind environments may require special consideration for wind load effects, particularly in high-rise building design and outdoor architectural arrangements, as they have the highest wind speed and wind pressure. Wind environments from the east and south are relatively mild, suggesting that external space design in these directions may incorporate more natural ventilation measures. The low wind speed and pressure from the north may indicate more barriers or natural protection in that direction, which could be advantageous for designing enclosed spaces or areas requiring wind protection [37,38].

Table 3. Yezhai Middle School 0 m, 10 m, 20 m, 30 m wind environment simulation.

	0 m	10 m	20 m	30 m
Wind pressure	 (a1)	 (b1)	 (c1)	 (d1)
Wind speed	 (a2)	 (b2)	 (c2)	 (d2)
Wind vector	 (a3)	 (b3)	 (c3)	 (d3)

As shown in Figure 7, the line graph illustrates that wind speeds are lower in proximity to the buildings (negative distance values), likely due to the obstruction and blockage of airflow by the buildings. Wind speeds rapidly increase on the leeward side of the buildings (positive distance values) but do not reach the same heights as those on the windward side (i.e., the front of the buildings).

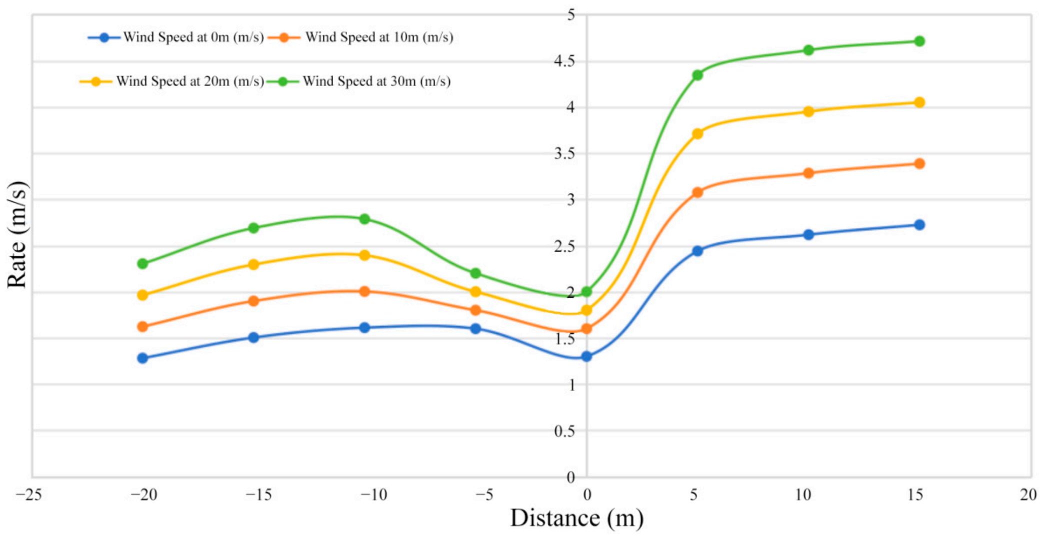


Figure 7. Line graph showing the variation in wind speed with distance.

Although the software cannot provide precise values between simulation points using Ecotect for wind environment simulation, we can still plot graphs based on the range of wind speeds obtained from the simulation to reflect the trend of wind speed changes with distance. The specific process is as follows:

Ecotect software simulated wind speeds at different heights, presenting the results as discrete points. These points represent the wind speed values at different heights and distances. Due to the limitations of Ecotect itself, the wind speed values between these points are not directly provided. However, based on the range of wind speeds at the simulation points, we can use interpolation methods to plot curves showing wind speed variation with distance.

The curves in the graph demonstrate the nonlinear relationship between wind speed and distance at different heights (0 m, 10 m, 20 m, and 30 m). Although Ecotect does not provide continuous precise values, combining the range of wind speeds in the simulation results can approximate the trend of wind speed changes. The curves show that the wind speed is lower on the windward side of the building while it gradually recovers on the leeward side, though this recovery is nonlinear. This nonlinear increase is likely due to the obstruction of airflow by the building and the subsequent vortex effects.

Through the above method, we utilized the simulation results of Ecotect and, despite some limitations, effectively demonstrated the characteristics of wind speed variation with distance, providing reference data for architectural design.

Effect of height on wind speed: The graph also demonstrates an overall upward trend in wind speed with increasing height. Wind speed growth is relatively gradual at lower heights (0 m and 10 m), while it increases rapidly at higher heights (20 m and 30 m).

Observing the data from the wind environment simulation of Yezhai Middle School, significant spatial variability of wind speed around the buildings is noted. Specifically, there is a pronounced decrease in wind speed in the vicinity of the buildings, suggesting the significant obstructive and blocking effects of the buildings on local airflow patterns. This decrease in wind speed is particularly noticeable on the windward side of the buildings. Additionally, the recovery of wind speed on the leeward side does not return to the level of open areas, reflecting the non-linear characteristics of the eddies induced by the building complex and wind speed recovery. Changes in height also reveal complex dynamics, with wind speed increasing more rapidly as height increases, consistent with the reduced physical obstruction at higher elevations and possible atmospheric boundary layer effects [39,40].

As shown in Figure 8, the graph depicts an increase in wind speed with height, which is consistent with the typical distribution of wind speeds within the boundary layer. At lower heights, wind speeds are relatively low, likely due to the obstructive effects of surface roughness, with wind speeds increasing with height above the ground as frictional resistance decreases.

The growth of wind speed exhibits non-linear characteristics, with rapid initial growth followed by a gradual slowing of the growth rate with further height increase. It may be related to the wind speed profile within the atmospheric boundary layer, where changes in wind speed with height are more pronounced in the lower layers closer to the ground, but the rate of change gradually decreases at certain heights.

Wind pressure increases with height, as wind pressure is proportional to the square of wind speed. Therefore, even if the growth of wind speed slows down, wind pressure can still increase significantly. This phenomenon highlights the importance of considering not only the effects of wind speed but also the impact of increased wind pressure on the structural design of buildings when designing tall structures [41,42].

As shown in Figure 9, the westward wind speed is the highest among the four directions, reaching close to 4 m per second, corresponding to the highest wind pressure of approximately 60 pascals. It indicates that the westward direction may have the largest open space or be less affected by ground friction and building obstruction. Therefore, reinforcement of the building structure may be necessary to withstand the higher wind loads from the westward direction.

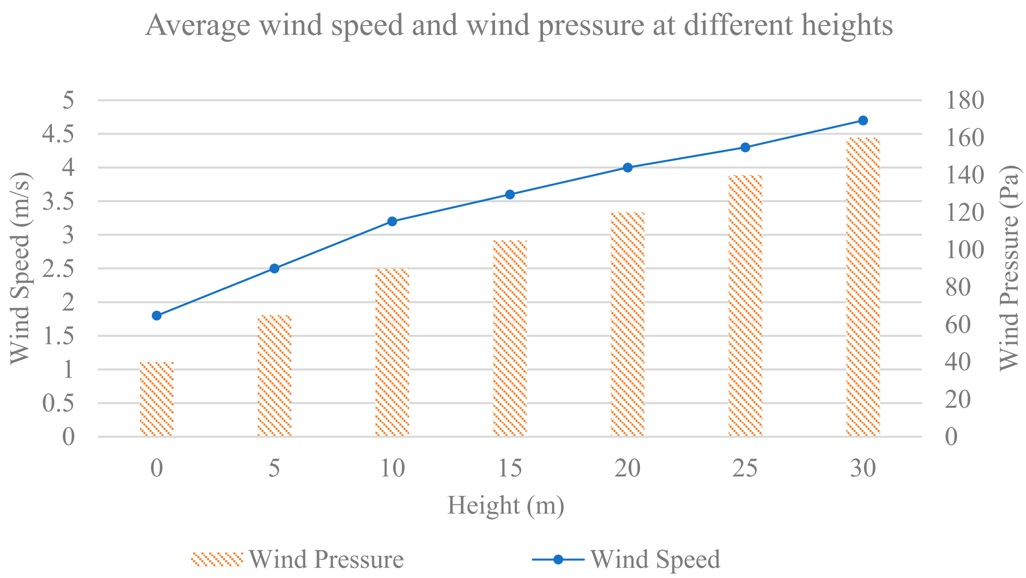


Figure 8. Trend of wind speed variation with height.

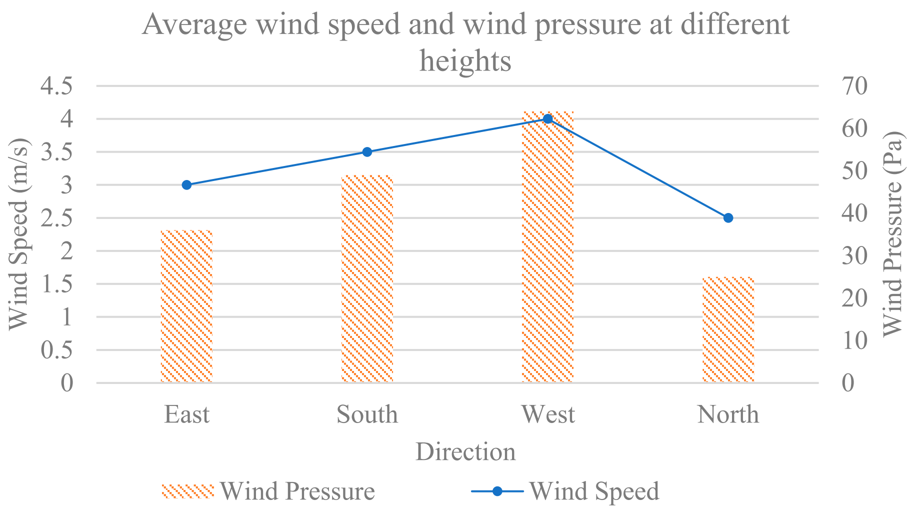


Figure 9. Distribution of wind pressure and wind speed in different directions at the reference height (10 m).

The wind speeds and wind pressures from the eastward and southward directions are relatively close, suggesting similar influences on the wind environment from these two directions, exhibiting a degree of consistency. The eastward wind speed is 3 m per second, with a wind pressure of approximately 36 pascals, while the southward direction is slightly higher, with a wind speed of 3.5 m per second and a wind pressure of approximately 50 pascals.

The wind speed and wind pressure from the northward direction are the lowest, at 2.5 m per second and below 20 pascals, respectively, indicating that this direction may have more natural or artificial obstructions, such as buildings or trees, which have a more significant obstructive effect on the wind [43].

In the analysis of the simulation results, there are significant differences in wind speed and wind pressure at different heights. This result reflects the impact of building design on the wind environment and highlights key factors that need to be considered in architectural planning. Firstly, the increased wind speed in high-rise building areas may raise the wind load on the structure, requiring reinforcement of these areas' load-bearing capacity in structural design. Secondly, areas with low wind speed can serve as ideal locations for natural ventilation, helping to reduce the use of air conditioning systems and thereby further lower energy consumption. Lastly, the distribution characteristics of wind speed and wind pressure provide data support for optimizing building layout and external space design, such as implementing windbreak measures in high wind speed areas to protect pedestrian safety.

In terms of wind mitigation measures, this study implemented several key strategies to minimize the adverse effects of wind on buildings while enhancing the overall energy efficiency of the structures.

Firstly, during the design phase, the orientation and shape of the buildings were carefully considered to minimize the windward surface area as much as possible. The primary orientation of the buildings was designed to avoid alignment parallel to the prevailing wind direction, thereby reducing the direct impact of wind on the building surfaces. This layout effectively reduces wind pressure and decreases the likelihood of cold winds directly entering the building, improving indoor environmental comfort. Additionally, streamlined or polygonal designs were adopted for the building shape design. Such designs allow wind to flow more smoothly around the buildings, avoiding the formation of large pressure concentration areas and thus reducing the impact of wind on the exterior walls and potential structural damage.

Secondly, this study utilized a high-performance multilayer structural design to enhance the wind resistance and thermal insulation performance of the exterior walls. This structure not only enhances the mechanical strength of the walls, allowing them to withstand the pressure from wind forces better, but also improves the thermal insulation effect through air layers between the multiple materials, reducing the likelihood of external heat transferring into the building.

Lastly, strategically placing green belts and windbreak barriers around the buildings beautifies the environment. It effectively reduces wind speed, minimizing the direct impact of wind on the exterior walls of the buildings. The arrangement of trees and shrubs can disperse and weaken the wind force, lowering the wind speed in the local environment surrounding the buildings and thus reducing the wind pressure on the exterior walls. Additionally, windbreak barriers, such as walls or permeable panels, can further diminish wind forces, protecting the buildings from strong winds.

Through the integrated application of optimized building layout, improved exterior wall design, and environmental design, this study effectively reduced the negative impact of wind on the buildings.

3.3. Validation

To ensure the reliability of the CFD simulation results, we conducted experimental validation. We set up multiple measurement points in the actual building environment of Yezhai Middle School. These measurement points covered key wind environment areas around the building, including measurement locations at different heights and distances. Specifically, the arrangement of the measurement points is as follows:

Measurement Point 1: Located at the bottom of the building's windward side, at a height of 2 m above the ground, to measure the wind speed after the windward side of the building blocks it.

Measurement Point 2: Located on the side of the building at mid-height, at a height of 10 m above the ground and 5 m horizontally from the building surface, to measure the recovery of wind speed on the building's side.

Measurement Point 3: Located on the leeward side of the building, at 20 m above the ground and 10 m horizontally from the building surface, to measure the wind speed changes after it passes around the building.

Measurement Point 4: Located above the building, at a height of 30 m above the ground, to measure the wind speed at high altitude and the wind speed changes at the top of the building.

At these measurement points, precise anemometers were used for continuous measurements, and the results were compared with the CFD simulation data.

Table 4 compares the experimental and simulation data for the primary measurement points. From the comparison data, the CFD simulation can accurately reflect the actual wind environment. Although the Ecotect software may have specific limitations in accuracy in complex environments, this validation with experimental data enhances the credibility of the results. Therefore, the simulation results in this study can serve as a reliable basis for guiding building design and improvements.

Table 4. The comparison of the experimental and simulation data for the primary measurement points.

Measurement Point	Measured Wind Speed	Simulated Wind Speed	Relative Error (%)
1	4.8	4.6	4.17
2	3.2	3.1	3.13
3	2.7	2.8	3.70
4	1.5	1.6	6.67

4. Facade Regeneration and Energy-Efficient Exterior Wall Design

4.1. Campus Building Facade Energy-Saving Renovation Design

Facade renovation refers to the replacement of the architectural skin to enhance the building's aesthetics while keeping the overall structure, function, and spatial layout unchanged. The most commonly used methods for facade renovation include replacing wall cladding materials, external cladding, and complete facade replacement [44].

Principles for school building facade renovation include the following: firstly, unifying the architectural style to give the school buildings a distinctive campus character, while appropriately incorporating modifications within the context of preserving the school's historical heritage, reflecting both its rich cultural legacy and modern functionalities. Secondly, adherence to energy-saving and environmentally friendly design principles by utilizing eco-friendly materials for facade renovation. Considering the increasingly severe energy situation in China from a sustainable development perspective, reducing the energy consumption of existing buildings is urgent, making energy-saving renovations for school buildings imperative [45,46].

Facade renovation typically involves three main approaches: external cladding, replacement of wall cladding materials, and complete facade replacement. Yezhai Middle School adopts the second method for facade renovation, emphasizing the enhancement of the facade based on the school's century-old historical and cultural heritage. It involves corresponding facade modifications to teaching buildings, libraries, cafeterias, and science and technology museums, following a unified architectural style [47].

4.2. Facade Renovation of Yezhai Middle School

Table 5 outlines the main contents of the facade landscape renovation at Yezhai Middle School. During the facade renovation, the project re-integrated the landscape resources of the East Campus to make it "orderly, scenic, and distinctive". A landscaped plaza was designed in front of the main teaching building to create a sense of a campus gateway. At the same time, the facade style of the existing buildings in the East Campus was unified, using gray and white as the main theme colors, showcasing the unique charm of Hui-style architecture, especially the facade renovation of the main buildings next to the Martyrs Shrine, including the Science and Technology Museum, and the exterior renovation and interior decoration of the Museum, as well as the exhibition arrangement.

Addressing the issue of aging facades in many buildings on the main campus, the design was guided by scene renewal, with multiple schemes designed for each scene based on different needs. The design primarily focused on improving the composition of building facades, creative combinations of building materials, and unified color schemes to inject fresh vitality into public spaces on the main campus.

Table 5. Analysis of facade renovation before and after at Yezhai Middle School. (Source: TJ2021290171).

	Elevation		**Orientation**	**Cladding**
	Before Transformation	**After Transformation**		
Comprehensive Building (Nanyue Academy)			Facing south with a slight tilt towards the west.	- Partially add ventilated and transparent aluminum-plastic panels to the outer layer. - Adjust the color and style of the building to maintain visual harmony with surrounding structures.
Teaching Building 1			Facing south with a slight tilt towards the west.	- Optimize the building lobby, utilizing the central axis as a guiding route. - Extend the central axis to the middle part of the building, while adopting a more unified design language to enhance the overall consistency and coherence of the architecture, thereby strengthening the solemn visual effect of the building as the main approach to the main entrance.
Teaching Building 2			Facing south with a slight tilt towards the west.	- Partially add vertical decorations to the facade of some windows, which helps control ventilation and lighting. - Replace the iron-framed fence with solid concrete to protect the internal structure and avoid prolonged exposure to the external environment. - Canopy extended along the path leading to the teaching building.
Specialist Building ("Renlu")			Facing west.	- The newly constructed building's entrance section will be set back and a canopy will be added to provide better outdoor conditions for building users. - Larger floor-to-ceiling windows will be utilized to improve the building's lighting and ventilation. - The color and style of the building will be adjusted to maintain visual consistency with surrounding structures.

Table 5. *Cont.*

	Elevation		Orientation	Cladding
	Before Transformation	After Transformation		
Dormitory			 Facing east with a slight tilt towards the south.	- By fine-tuning the building facade, enhance the building's recognizability and readability. - Utilize horizontal decorative elements to shield the air conditioning system, improving the overall appearance of the building facade while providing better protection for the air conditioning system. - Optimize the building lobby area by adding spaces for lingering, enhancing the surrounding landscape, and providing students with a better dormitory environment.
"Juehou" Pavilion			 Facing west with a slight tilt towards the north.	- Optimize the surrounding landscape of the building to increase its utilization rate.

4.3. Analysis of Facade Renovation for the Senior High Teaching Building

Figure 10 depicts the schematic diagram of the renovation optimization for the Senior High Teaching Building at the main entrance of Yezhai Middle School. The renovation of the Senior High Teaching Building is divided into three phases. In each phase of renovation, apart from optimizing functionality and form, energy efficiency is achieved through the selection of facade materials and the application of insulation layers to reduce heat transfer.

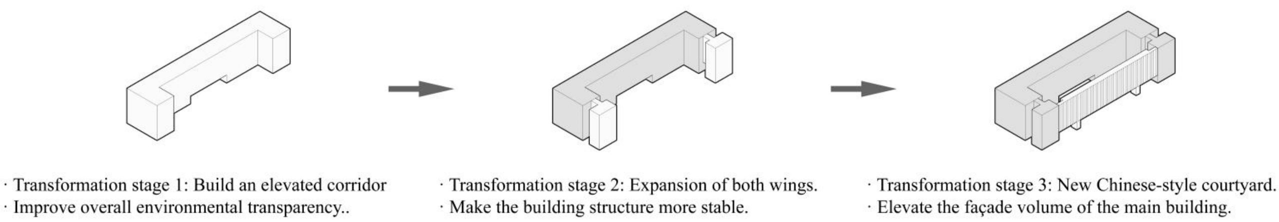


Figure 10. Schematic diagram of renovation phases for the Senior High Teaching Building.

4.3.1. Thermal Energy Efficiency Analysis of Facade Renovation

For the overall renovation, a thermal energy efficiency analysis was conducted. The facade renovation of the Senior High Teaching Building utilizes Expanded Polystyrene (EPS), a material known for its excellent insulation properties. The thickness of the EPS insulation layer after renovation is 0.15 m. The thermal conductivity of EPS is approximately 0.038 W/mK. The wall area is approximately 200 square meters. The temperature difference between the inside and outside during winter averages 20 Kelvin. It is assumed that the facade renovation will not alter the internal heat or cooling sources of the building, such as heating and air conditioning [48–50] (Appendices C and D).

4.3.2. Exterior Wall Heat Transfer Simulation

The exterior wall insulation material used by Yezhai Middle School is Expanded Polystyrene (EPS), with the following physical characteristics: Density: Approximately 15–30 kg/m^3; Specific Heat Capacity: Around 1.3 kJ/kg·K; Thermal Conductivity (k): 0.038 W/mK; Vapor Permeability: 0.12–0.26 mg/(Pa·h·m) (Figure 11).

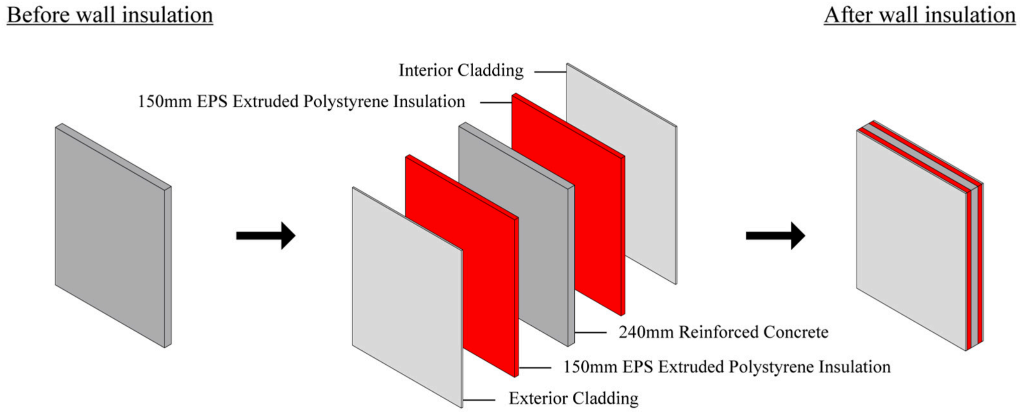


Figure 11. Wall insulation model.

In the thermal transfer simulation and analysis of the exterior walls of the Yezhai Middle School area in Anhui Province, this study relies on the Fourier heat conduction law and the principle of heat conduction of multilayer solid walls in a steady state. The Fourier law is the foundation of heat transfer research, explicitly stating that heat is propagated along temperature gradients, and the rate of transfer is directly proportional to the magnitude of the temperature gradient.

$$q = -k \cdot \frac{dT}{dx}$$

For a composite wall in a steady state, its thermal resistance is determined by the thickness and thermal conductivity of the materials, as well as the cross-sectional area perpendicular to the heat flow. The overall thermal resistance of the wall is the sum of the thermal resistances of its layers. Based on these parameters, the heat flux of the wall can be estimated through the relationship between total thermal resistance and the temperature difference across the wall.

$$q = \frac{\Delta T}{\sum R}$$

During the simulation process, the thickness and thermal conductivity of each material are initially assessed, followed by the calculation of thermal resistance for each layer. These values are then summed to obtain the total thermal resistance, ultimately used to calculate the heat flux across the entire wall by applying the Fourier law and the determined temperature gradient. This analysis aids in assessing the insulation performance of different materials and provides a scientific basis for designing more energy-efficient buildings [51].

In the simulation settings, the outdoor winter minimum temperature is set to the lowest value possible for the Wild Village Middle School, −10 °C, while the summer maximum temperature is set based on regional climate characteristics at 28 °C. Whether in winter or summer, the indoor temperature is set at a constant 24 °C to simulate actual living conditions. The grid size is set to 3 cm to balance calculation speed with simulation accuracy [52].

By observing the simulated results of the temperature distribution in the walls of the Wild Village Middle School, the influence of insulation layers on the internal temperature distribution of the walls is evident (Table 6). With insulation layers, whether in winter or summer, the temperature variation in the walls is more gradual, demonstrating that the insulation layers effectively mitigate the impact of external extreme temperatures on the internal walls. Winter simulations indicate that insulation layers significantly reduce the ability of cold air to penetrate the walls and enter indoors, helping to maintain indoor warmth. Summer simulations show that insulation layers effectively isolate external high temperatures, slowing down the rate of heat entering indoors [53,54].

Through comprehensive analysis of wall heat conduction in both summer and winter, it is evident that the walls and their insulation materials effectively mitigate the impact of high temperatures during summer and protect indoor spaces from cold invasion in winter, ensuring stable indoor temperatures. Empirical validation confirms a 24% reduction in energy consumption post-renovation compared to pre-renovation levels for the exterior walls. Therefore, whether in hot or cold seasons, the wall design at Yezhai Middle School meets energy-saving requirements, ensuring comfort indoors and efficient energy utilization [55].

Table 6. Facade heat transfer simulation.

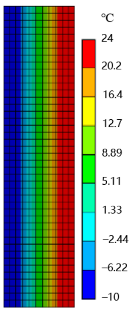
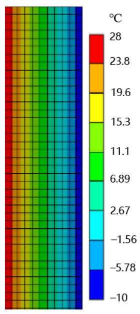
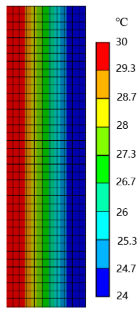
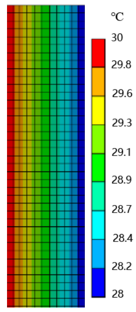
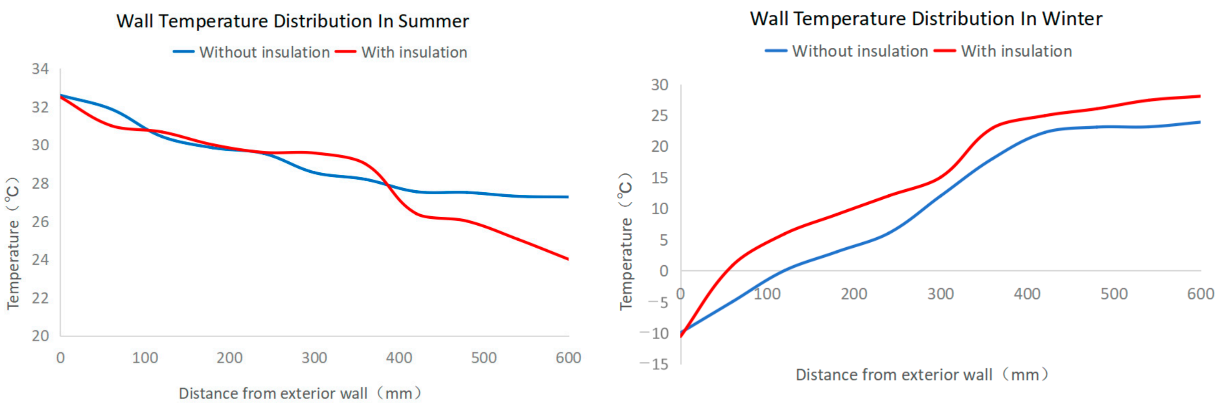
Without insulation	With insulation	Without insulation	With insulation
			
Winter		Summer	

Figure 12 shows the temperature variation in the wall. It can be observed that during the summer, when external temperatures are the same, the experimental group with insulation effectively prevents external heat from entering the interior, resulting in an indoor temperature reduction of approximately 2 °C compared to the non-insulated group. This is because the insulation material effectively inhibits heat transfer. In winter, when the external temperature is −10 °C, the group with insulation effectively prevents internal heat loss, maintaining an interior temperature approximately 1.8 °C higher than the group without insulation.



(**a**) (**b**)

Figure 12. Wall temperature distribution in summer (**a**) and winter (**b**).

The relationship between wind conditions and thermal efficiency analysis primarily includes two aspects: the influence of wind conditions on thermal convection and the analysis of thermal conduction about wind conditions:

- Influence of wind conditions on thermal convection:

Wind conditions affect the convective heat transfer coefficient on building surfaces. Strong winds increase the surface heat transfer coefficient, accelerating heat transfer and increasing heat loss or gain. Therefore, higher wind speeds produce more robust convective heat transfer on the exterior wall surface, leading to more heat loss or gain through convection.

- Analysis of thermal conduction about wind conditions:

Thermal conduction analysis focuses on heat transfer through wall materials (e.g., EPS insulation layer), calculated based on the material's thermal conductivity and thickness. While thermal conduction occurs within the wall material, heat exchange (including convection) between the wall surface and the external environment also affects the overall thermal efficiency of the building.

In summary, wind conditions affect heat transfer in thermal efficiency analysis by influencing thermal convection. Strong winds increase the convective heat transfer coefficient of the building surface, thereby accelerating heat loss or gain. Therefore, the impact of wind conditions on thermal convection must be considered in the overall thermal efficiency analysis. Although this paper primarily focuses on thermal conduction, the influence of wind conditions on thermal convection is equally essential, especially in environments with higher wind speeds.

The conclusions of this study are based on detailed simulation and calculation results. The wind environment simulation shows that wind speed exhibits a nonlinear increase with height, particularly in areas close to the ground, providing a basis for considering wind loads in building design. Through the renovation of the exterior walls, the use of EPS (expanded polystyrene) insulation effectively reduced the energy consumption for heating in winter and cooling in summer, achieving an energy-saving effect of 24%. These results indicate that reasonable building design and energy-saving renovations can significantly improve energy efficiency and provide valuable references for low-carbon renovations of other campuses and public buildings.

Calculation Process:

- Application of the Heat Conduction Formula:

Fourier's Law of Heat Conduction was used to calculate the heat loss through the walls before and after the renovation. The specific formula is provided in Appendix C.

- Selection of Material Parameters:

After renovation, the exterior walls used expanded polystyrene (EPS) as the primary insulation material, with a thickness of 0.15 m and a thermal conductivity coefficient k of 0.038 W/m·K. The wall area is approximately 200 square meters, and the temperature difference between the interior and exterior in winter is assumed to be 20 K.

- Calculation of Thermal Resistance and Heat Transfer Coefficient:

The thermal resistance R was calculated using the formula in Appendix D, yielding a value of 3.95 m^2·K/W. The heat transfer coefficient U is the reciprocal of the thermal resistance, resulting in a U value of 0.253 W/m^2·K.

- Estimation of Annual Heat Demand:

Based on the calculated heat transfer coefficient and temperature difference, the annual heat demand Q_{year} after renovation was estimated to be 2920 kWh.

By comparing the energy consumption data before and after the renovation, it was found that the annual energy consumption of the building was reduced by approximately 24% after the renovation.

5. Discussion

Existing research and practical implementations in the campus building energy efficiency field have provided actionable directions and suggestions for energy efficiency and retrofitting from various perspectives. These include improving lighting systems, managing integrated energy systems [11], adopting flexible energy system configurations, and combining ecological footprint assessments with machine learning technologies. Existing campus buildings have significant energy-saving potential that can be utilized and explored. This study focuses on facade retrofitting and, through actual retrofitting measures, significantly reduces the energy consumption of Yezhai Middle School, achieving energy saving and emission reduction goals.

This study proposes specific energy-saving retrofitting strategies tailored to the climatic conditions of mountainous campus buildings in China's hot summer and cold winter regions, which have a certain degree of regional applicability and reference significance. In the context of smart city development, integrating advanced technologies and sustainable practices into public infrastructure has become a key objective. In addition to energy-saving facade retrofitting, this study also considers wind environment optimization and the thermal insulation performance of building materials, providing a multi-dimensional energy-saving design scheme. Finally, through the practical retrofitting of a specific campus, the research results have high operability and practical reference value, providing detailed implementation paths and technical support for similar projects.

Despite the achievements in exploring low-carbon energy-saving designs for campus building facades, this study has some limitations. These include limitations in data sources and scope, the singularity of energy-saving measures, and insufficient evaluation of long-term effects. Future research can improve and advance from the following directions:

1. Future studies should be conducted in more regions and different types of campus buildings to validate and expand the conclusions of this study, enhancing the generalizability and reliability of the results.
2. Future research should combine building interior system optimization, intelligent control technologies, and renewable energy applications to conduct comprehensive energy-saving research, aiming for more efficient energy-saving effects.
3. Future efforts could establish long-term monitoring systems to continuously track and evaluate the energy-saving effects of retrofitted buildings under different seasons and weather conditions, providing data support for optimizing retrofitting measures.
4. Future studies could take a multidisciplinary collaborative research approach, integrating insights from architecture, environmental science, energy engineering, and other fields to explore best practices for campus building energy retrofitting, promoting the development of green campuses within the framework of smart city initiatives.

6. Conclusions

Through the low-carbon energy-saving renovation study of Yezhai Middle School in Qianshan City, Anhui Province, this research explores the wind environment optimization and energy-saving facade design strategies for mountainous campus buildings in the context of existing building stock updates.

1. Wind environment simulations show that with the increase in height, the variation in wind speed is nonlinear, particularly in lower height areas where ground roughness significantly affects wind speed changes. Through reasonable architectural design and planning, it is possible to effectively optimize wind speed and pressure distribution in different orientations within the campus, improving outdoor activity environments and ensuring the safety of building structures.
2. The facade energy retrofitting involved EPS panels and insulation layers for inner and outer walls, boasting excellent insulation properties. By employing 0.15 m EPS panels and a thermal conductivity of 0.038 W/mK, a substantial reduction in thermal energy demand was achieved. These measures significantly reduced energy demand for winter heating and summer cooling. Simulation results indicate that the insulation layers effectively prevent cold air intrusion during winter and reduce external heat gain in summer. The renovated facade achieved a 24% energy savings, demonstrating that facade energy retrofitting not only enhances indoor comfort but also achieves

substantial energy efficiency gains. Moreover, the calculated annual heat demand post-renovation, approximately 2920 kWh, highlights the significant improvement in energy efficiency, reinforcing the value of facade retrofitting in enhancing indoor comfort and achieving energy savings.

3. The wind environment simulations indicated that optimizing wind speed and pressure distribution through thoughtful architectural design could improve outdoor activity environments and ensure structural safety. The nonlinear variation in wind speed with height, particularly influenced by ground roughness, underscores the importance of integrating wind environment considerations into building design to enhance overall campus comfort and safety. By analyzing the wind environment simulation and thermal performance of energy-saving facade materials for the new west campus of Yezhai Middle School, this research provides scientific theoretical foundations and practical experience for the low-carbon energy-saving renovation of other campuses and public buildings. These results not only help improve the comfort and sustainability of campus environments but also provide effective technical pathways and design references for achieving green and low-carbon development goals in the construction industry.
4. In the context of smart city development, integrating advanced technologies and sustainable practices into public infrastructure has become a key objective. This study's findings offer valuable practical insights for the low-carbon energy-saving renovation of other campuses and public buildings. By providing a detailed analysis of both wind environment optimization and energy-saving facade materials, this research contributes to the development of more energy-efficient and sustainable building practices. The results offer a solid theoretical foundation and practical guidelines for achieving green and low-carbon development goals within the construction industry. Future research can further expand to campus buildings in different regions and climatic conditions, comprehensively considering more energy-saving technologies and renewable energy applications to achieve more comprehensive and efficient low-carbon energy-saving renovations. This approach will contribute significantly to the broader goals of smart city initiatives, enhancing urban living quality and environmental sustainability.

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Appendix A

Continuity equation (mass conservation equation):

$$\frac{\partial_\rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{A1}$$

here ρ represents air density, and u represents the velocity vector.

Momentum equation (Navier–Stokes equations):

$$\rho\left(\frac{\partial_u}{\partial t} + u \cdot \nabla u\right) = -\nabla p + \nabla \cdot \left(\mu\left(\nabla u + (\nabla u)^T\right)\right) + F \tag{A2}$$

here p represents pressure, μ represents the dynamic viscosity of air, and F represents external forces.

Appendix B

Fourier's law of heat conduction:

$$q = -k\nabla T \tag{A3}$$

here q represents heat flux density, k represents the material's thermal conductivity, and ∇T represents the temperature gradient.

For steady-state heat conduction, the conduction equation simplifies to the following:

$$\nabla\cdot(k\nabla T) = 0 \tag{A4}$$

Thermal resistance model of multilayer walls: For composite walls, the total thermal resistance can be represented as the sum of the thermal resistances of each layer of mate-rial.

$$R_{sum} = \sum_{i=1}^{n} \frac{d_i}{k_i} \tag{A5}$$

here di represents the thickness of the ith layer of material, and ki represents the thermal conductivity of the ith layer of material.

Heat flux calculation: The heat flux through a wall can be represented by the following equation:

$$Q = \frac{\Delta T}{R_{sum}} \tag{A6}$$

Appendix C

Thermal Conduction Calculation:

We will employ Fourier's law to calculate thermal conduction.

$$Q = \frac{\kappa\cdot A\cdot\Delta T}{d} \tag{A7}$$

Q represents the heat flow (Watt).
k stands for the thermal conductivity of the material (W/mK).
A denotes the wall area (m^2).
ΔT signifies the temperature difference between the interior and exterior (K).
d indicates the thickness of the material (m).

Appendix D

Thermal Resistance and Overall U-value Calculation:

Calculate the thermal resistance R and U-value (thermal transmittance) of the entire wall.

The formula for R is R = d/k, and the U-value is the reciprocal of the thermal resistance, i.e., U = Wall modelAnnual Heat Demand Estimation:

Estimate the annual heat demand and potential energy savings after renovation using the U-value and temperature difference.

$$Q_{year} = U\cdot A\cdot\Delta T\cdot t \tag{A8}$$

where t is the number of hours in a year requiring heating or cooling.

Thermal Resistance and U-value Calculation

Thermal Resistance (R):

$$R = \frac{d}{k} \tag{A9}$$

Calculation:

$$R = \frac{0.15\ \text{m}}{0.038\ \text{W/mK}} = 3.95\ \text{m}^2\text{K/W} \tag{A10}$$

value (Thermal Transmittance):

$$U = \frac{1}{R} \tag{A11}$$

$$U = \frac{1}{3.95\ \text{m}^2\text{K/W}} = 0.253\ \text{W/m}^2\text{K} \tag{A12}$$

The calculated value for Qyear is 2920 kWh, indicating that after the facade renovation, the total heat energy demand for the entire winter is approximately 2920 kWh.

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