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

Sophie Laurent^{1*}, Pierre Dubois¹, Marc Lefevre², Claire Moreau¹

Abstract

Amid worsening worldwide environmental degradation and escalating carbon outputs from the construction sector, school campuses—serving as the main settings for young people's education and daily life—hold significant importance in promoting designs that prioritize low-carbon approaches, enhanced energy conservation, and eco-friendly surroundings. This study examines the renovation of Yezhai Middle School in Qianshan, Anhui Province, as a specific example, investigating methods to improve airflow patterns and to implement facade-based energy conservation measures for hilly-terrain school facilities during upgrades to pre-existing structures. Within the broader push toward intelligent urban systems, embedding cutting-edge tools and eco-conscious methods into communal facilities has emerged as a central priority. By conducting airflow modeling and upgrading building exteriors for greater efficiency, the analysis demonstrates nonlinear increases in airflow velocity with increasing elevation, alongside notable influences of surface texture on fluctuations in wind conditions. Incorporating expanded polystyrene (EPS) boards, along with added thermal barriers, during exterior upgrades reduces heating demand in colder months and air conditioning demand in warmer months. The updated exteriors successfully block chilly drafts while minimizing unwanted solar heat absorption, resulting in energy savings of roughly 24%. These findings offer valuable technical guidance and real-world insights for implementing low-carbon, efficiency-focused upgrades across additional educational and civic structures, supporting the building sector's shift toward sustainable, lower-emission practices within intelligent urban frameworks.

Keywords Energy efficiency, Smart city development, Green campus design, Wind environment simulation, Insulation layers, Energy retrofitting

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Introduction

Growing issues with air quality degradation, water contamination, and climate change have underscored the urgent need for environments that promote well-being and comfort. Civic structures, integral to everyday activities and primary indoor gathering spaces, represent a vital focus area for progress within China's building sector. As part of intelligent city development, incorporating modern innovations and environmentally responsible approaches into shared infrastructure is

a core aim. Intelligent cities seek to elevate residents' living standards by harnessing digital tools and analytics to streamline asset use, upgrade public offerings, and lessen ecological footprints [1, 2].

Intelligent structures, forming part of broader smart settings, depend heavily on robust digital foundations that manage data flows. Various advanced construction methods, including Building Information Modeling (BIM), Internet of Things (IoT) integration, and blockchain applications, serve as essential enablers in intelligent urban contexts [3].

Reduced-carbon outcomes rank among the primary targets for smart structures. A range of rating systems has emerged to regulate architectural energy use, establishing benchmarks and accreditation frameworks like the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), and the German Sustainable Building Council standards [4]. In South Korea, for instance, Building Energy Efficiency Certificates (BEECs) have been rolled out, certifying 1648 school facilities via the HIPB simulation approach [5].

Recent investigations highlight a surge in proposals for efficiency-enhancing innovations across insulation products, outer shells, and heating, ventilation, and air conditioning (HVAC) systems. Examples include assessments of varying thicknesses of sisal-based fibers as an eco-friendly insulating option, identifying 7 cm as the most effective depth [6]. Additionally, Phase Change Materials (PCMs) enhance performance through latent heat storage. Techniques such as genetic algorithms (GA) and model predictive control (MPC) play key roles in refining design outcomes by optimizing goals under defined limits [7]. Passive low-energy cooling methods deliver strong thermal comfort with minimal power input, meeting standards requiring at least 84% of hourly temperature readings to fall within acceptable boundaries and tolerances. Simulations have aligned various comfort frameworks to regional climates for school applications. Ground-coupled water systems provide efficient cooling across climates by tapping stable subsurface temperatures, particularly during hot seasons. Thermally Active Building Systems (TABSS) supply substantial thermal mass to handle load peaks. Employing adaptive comfort standards permits indoor temperature swings within tolerable limits, cutting reliance on high-energy cooling. Hybrid setups (radiant elements for sensible heat and fan coils for moisture control) better address diverse requirements, yielding substantial savings [8]. Together, these innovations support the creation of more sustainable, lower-energy structures, contributing to international eco-targets while improving habitability and utility in built spaces.

Statistical reviews of civic building categories show that educational facilities (schools and preschools) account for roughly 40% of the total, signaling strong future demand in this area. Educational institutions, particularly those at the primary and secondary levels, serve as long-term environments for youth development. The quality of architectural features and campus settings not only reflects values but also influences educator productivity, student performance, and the fostering of sustainable, low-emission habits among learners. Thus, amid widespread upgrades to existing stock, selecting proven, widely adopted efficiency solutions—particularly for secondary school exteriors—carries substantial value [9, 10].

Recent scholarship on reduced-carbon approaches for educational campuses has emphasized efficiency improvements and upgrades, incorporation of clean energy sources, sustainable campus layouts, and efforts to promote low-emission awareness and actions. In efficiency and upgrade domains, Olsen *et al.* [11] outlined approaches for establishing low-carbon energy hubs on campuses; Chung and Rhee [12] assessed retrofit opportunities in South Korean campuses via on-site examinations; Soares *et al.* [13] reviewed real-world enhancements in higher education facilities; Liu and Ren [9] suggested efficiency-oriented strategies for Chinese universities based on green metrics. Di Stefano [14] examined the benefits of modernizing lighting at Melbourne University to achieve efficiency gains and reduce emissions; Ashrafian [15] analyzed the energy, financial, and comfort aspects of school upgrades amid shifting climates.

Regarding clean energy adoption, Shea *et al.* [16] detailed the University of Dayton's path to carbon neutrality via electrification and renewables; Hurwitz *et al.* [17] evaluated multi-source energy setups' economics and emissions; Bhavsar *et al.* [18] highlighted Mohawk College's zero-energy, zero-carbon achievements through advanced and renewable means.

In sustainable campus planning, Gui *et al.* [19] investigated the effects of academic scheduling on university energy use; Zheng *et al.* [20] combined ecological footprint tools with machine learning for low-carbon campus development in China; and Fonseca *et al.* [21] explored pathways to near-zero-energy campuses. Luo *et al.* [22] developed assessment frameworks and optimized technology selection for carbon mitigation in campus structures in the Yangtze River Delta.

On education and behavioral shifts for lower emissions, Roy *et al.* [23] contrasted the ecological effects of campus-based versus remote learning, noting major reductions from remote formats; Guerrieri *et al.* [24] quantified universities' role as micro-urban models in emission transitions.

Although notable strides have been made in implementing low-carbon campuses, persistent obstacles remain. Yoshida *et al.* [25] outlined Osaka University's sustainability roadmap and challenges; Mytafides *et al.* [26] addressed difficulties with zero-energy buildings in certain climates; Mustaffa *et al.* [27] examined motivators, barriers, and tactics for achieving low-carbon goals at the University of Technology Malaysia.

Further, various studies detail examples of low-carbon campus efforts in higher education worldwide. Sesana *et al.* [28] presented Italian university retrofit cases; Kourgiouzou *et al.* [29] reviewed UK higher education's net-zero carbon practices; Del Borghi *et al.* [30] highlighted European and American carbon-neutral campus designs and upgrades.

While international case studies abound, domestic research on eco-oriented school facilities remains limited, with most efforts centered on new constructions. As focus shifts to upgrading legacy structures, greater emphasis is needed on retrofit-oriented green, low-carbon strategies for campuses. This analysis centers on a secondary school upgrade initiative in Anhui Province, distilling suitable facade-efficiency upgrade approaches for mountainous Chinese campuses in hot-summer/cold-winter zones, derived from airflow simulations and exterior efficiency enhancements of the upgraded complex. The work aims to contribute references and insights for similar eco-focused retrofit efforts in educational settings.

Materials and Methods

Yezhai middle school

Overview of yezhai middle school

The campus expansion and enhancement initiative at Qianshan Yezhai Middle School is situated in Tianzhushan Town, Qianshan City, Anhui Province. The project covers the core campus along with the adjacent western and northern areas. It incorporates the former location of Tianzhushan Central Primary School, provided by local authorities, and the disused Yezhai mining supply depot, totaling 23.27 mu (roughly 1.56 hectares). Furthermore, it entails acquiring 78 mu (about 5.23 hectares) of community-owned mountain ponds, stepped fields, and ornamental plant areas in Fengjing Village (Figure 1). Upon project completion, the overall campus footprint for Yezhai Middle School is projected to expand by approximately 100 mu (6.7 hectares).



Figure 1. Location map of Yezhai Middle School.

The project benefits from comprehensive surrounding amenities and public service facilities. Infrastructure such as roadways, electricity, water supply, sewage systems, landscaping, and street lighting is already well developed and reliable. The location enjoys strong connectivity to various towns and rural areas within Qianshan City's jurisdiction, thanks to National Highway 318 along with provincial and local roads. Downtown Qianshan lies just 8 km away, making the delivery of construction materials and supplies straightforward and efficient.

The project's terrain slopes gently downward from north to south. It is backed by Tianzhushan Mountain to the north and bordered by the Qianshui River to the south, creating a highly favorable natural and ecological setting. To the south, the site borders Jingzhong Road, while its eastern edge links directly to the existing school campus. The neighboring areas are predominantly residential and commercial zones, which highlights the site's strong locational benefits and access to available resources.

An assessment of the existing structures at Yezhai Middle School determined that several outdated buildings no longer satisfy current functional standards and are slated for demolition. These areas will be modernized through renovation work and new additions. The overall development is organized into two main stages: the West Campus and the Main Campus. New construction efforts are concentrated primarily on the West Campus ([Figure 2](#)).

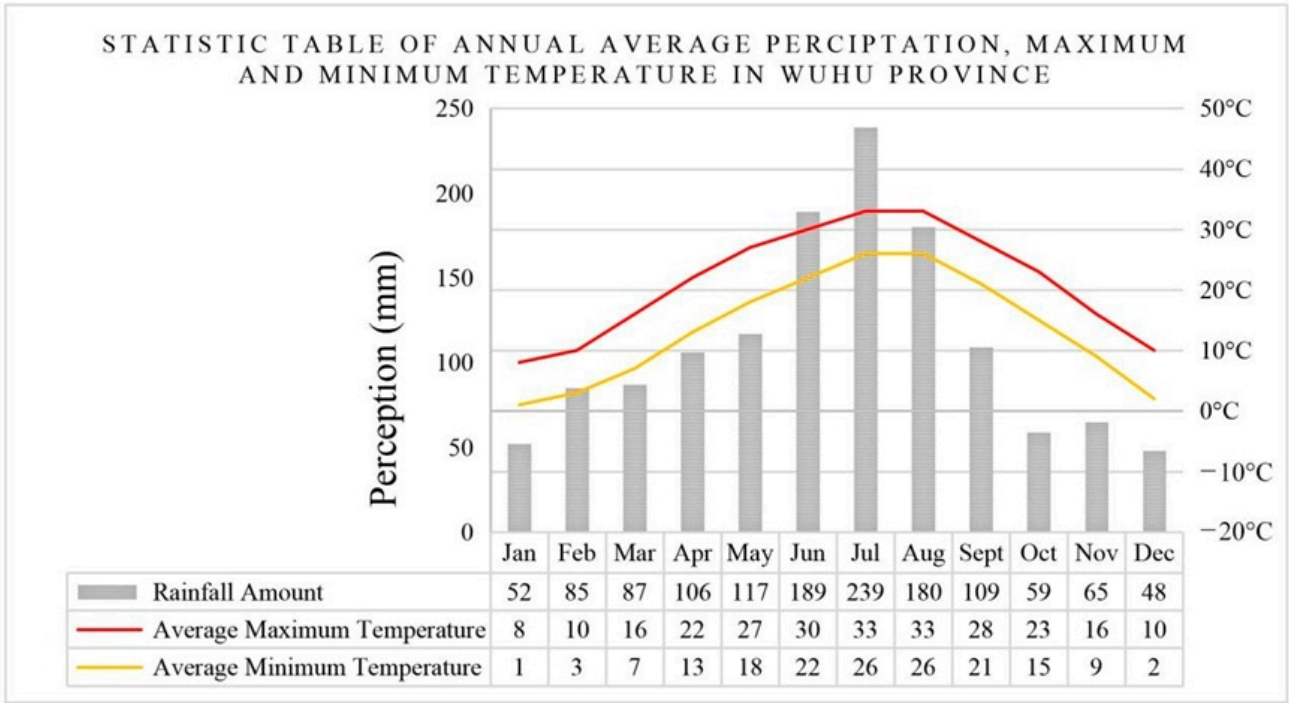


Figure 2. Annual average temperature and precipitation in Qianshan City.

Environmental analysis

Tianzhushan Town lies within the subtropical monsoon climate region. The long-term annual mean temperature stands at roughly 9.5 °C, while the yearly sunshine hours typically do not exceed 2000 h. The locality records foggy conditions on approximately 250–300 days annually, with a lower limit of around 200 days. Mean annual rainfall totals about 1900 mm, and the number of rainy days per year can climb to as many as roughly 150. The climate is marked by clearly defined seasons: spring and autumn are temperate, summer is warm to hot, and winter is cold and relatively dry. Thanks to generous sunlight and plentiful precipitation, the frost-free season extends for a considerable duration. Over multiple years, the average temperature registers 16.2 °C (Figures 2 and 3) [31, 32].

In Tianzhushan Town, the annual solar radiation averages around 154 MJ/m² per day. This radiation follows a distinct seasonal cycle, peaking during the summer months and dropping noticeably in winter. The highest daily values occur in July, reaching approximately 17 MJ/m²·d, whereas the lowest levels are observed in January, at roughly 8 MJ/m²·d.

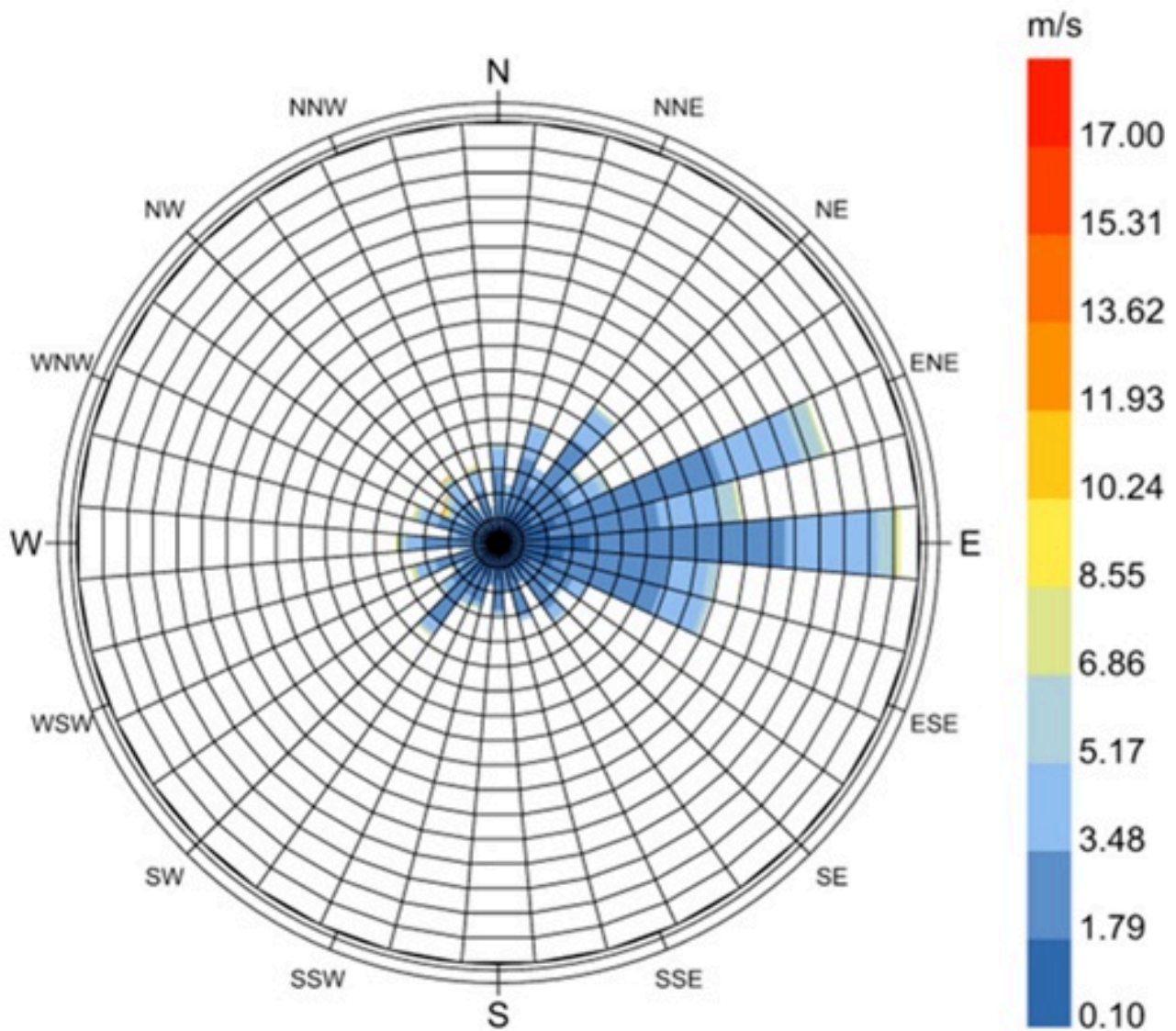


Figure 3. Wind rose diagram showing wind direction and wind speed.

Methodology

The present research centers on two primary aspects—the surrounding wind conditions and exterior wall thermal insulation—due to their substantial influence on enhancing the overall energy performance of school campus structures. Local wind patterns govern air movement and heat transfer near building surfaces, which, in turn, affect indoor thermal conditions and total energy use. Meanwhile, effective wall insulation ranks among the most important strategies for reducing building energy demand, markedly lowering the need for heating during cold months and cooling in warm periods. Consequently, improvements in both the wind field and wall thermal performance hold considerable theoretical and practical value for advancing low-carbon, energy-efficient objectives in educational facilities.

Wind environment simulation

Wind environment modeling relies on Computational Fluid Dynamics (CFD) techniques that use numerical methods to solve the governing equations of fluid flow around structures, thereby predicting wind velocity fields, pressure distributions, and airflow patterns. The fundamental physical relationships employed include the continuity, momentum, and energy conservation equations.

For this investigation, Ecotect software was selected to assess the wind environment at the Yezhai Middle School campus buildings. Ecotect stands out for its straightforward, user-friendly interface, making it especially well-suited for preliminary architectural studies and simulations. The software excels at producing highly visual outputs—such as clear diagrams, color-coded maps, and graphical representations—that allow design professionals and non-specialists alike to grasp the implications of the results quickly. This visual clarity supports fast concept testing and iterative refinement during the conceptual design phase.

Moreover, Ecotect demands relatively modest computing power, enabling it to perform effectively on standard or even lower-specification computers. This characteristic is especially valuable for modest-scale projects or teams working with constrained budgets and equipment, as it delivers reliable simulation outcomes without requiring high-end hardware investments.

While more sophisticated and precise building performance simulation platforms—such as EnergyPlus 8.4, OpenStudio, and IES VE—are now available and offer greater accuracy and broader analytical capabilities, Ecotect continues to offer distinct benefits in accessibility, speed, and flexibility, particularly in the initial stages of design exploration. In the context of this project, Ecotect facilitated rapid design iterations and multi-criteria performance assessments, proving instrumental in refining early proposals and informing key decisions.

Although official development and updates for Ecotect have ceased, its essential simulation capabilities remain dependable and continue to be applied in various early-stage research efforts. Its selection here was driven primarily by its ability to generate meaningful insights quickly during the project's formative phase, thereby establishing a solid basis for subsequent, more detailed investigations. In upcoming studies, more contemporary and advanced simulation tools will be employed to cross-verify and further enhance these findings.

In practice, the workflow begins with creating a detailed geometric model of the buildings in SketchUp. This model is then imported into the CFD environment and discretized into a suitable computational mesh. Boundary conditions are defined next, including wind inlet velocities, outlet pressure settings, and surface treatments for walls and other elements. An appropriate turbulence model and solver settings are chosen, after which the governing equations are solved iteratively until convergence. The resulting data fields—encompassing wind speeds, pressures, and temperatures—are processed and visualized to examine airflow characteristics at various heights and locations, ultimately evaluating how the architectural configuration influences the local wind environment (Figure 4).

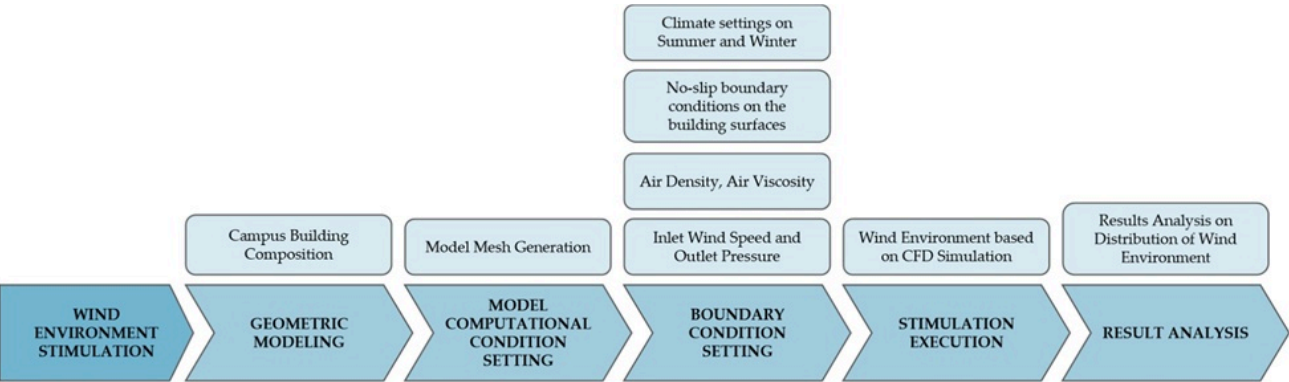


Figure 4. The flowchart of wind environment simulation.

In this research, careful attention was paid to the construction of the CFD model's computational grid to ensure the precision and reliability of the simulation results. An unstructured meshing approach was selected, which offers excellent adaptability to the intricate shapes and contours of the buildings. This method is particularly effective for accurately resolving flow patterns near sharp edges, corners, and other complex geometric features.

The grid cell dimensions were carefully varied: a minimum size of 0.05 m was applied in zones requiring high resolution, while larger cells up to 0.5 m were used in areas where flow variations are less abrupt, thereby optimizing overall computing time without sacrificing essential detail.

To better capture variations in wind velocity and surface pressure distribution around the structures, targeted grid refinement was applied at several key locations. These included the windward face, the leeward side, and the interface between the building base and the surrounding terrain, where cell sizes were further reduced to as small as 0.02 m. Additionally, a particularly dense mesh was implemented within the near-wall boundary-layer zones to precisely model shear stresses and thermal gradients near the building surfaces.

Mesh quality was rigorously controlled throughout the process. Parameters such as orthogonality and aspect ratio were kept within acceptable limits to minimize numerical inaccuracies and promote stable convergence of the solution.

A thorough mesh independence study was also carried out to confirm that the chosen grid resolution produced results that were effectively independent of further refinement. This step ensured that the outcomes were robust and trustworthy.

These comprehensive meshing techniques established a solid and dependable basis for the analysis, delivering simulation results of high accuracy and credibility.

As detailed in Table 1, specific boundary conditions were applied at the domain inlet and outlet to replicate realistic airflow behavior. An inlet wind velocity of 5 m/s was adopted, reflecting the prevailing wind conditions observed at the Yezhai Middle School site. Meanwhile, a static pressure of 0 Pa was prescribed at the outlet boundary. This setting allows unrestricted outflow of air from the computational domain, helping the modeled flow patterns closely match those encountered in the actual environment.

Table 1. Simulation parameters and boundary conditions for wind environment analysis.

Parameter	Specific value	Description
Wind speed at the inlet	5 m/s	Set to 5 meters per second to model the typical wind speed encountered around the Yezhai Middle School campus, representing air entering the simulation.
Pressure at the outlet	0 Pa	Zero pressure is applied to simulate free airflow exiting the simulation area, assuming it reaches equilibrium with atmospheric pressure.
Wall boundary behavior	No-slip	A no-slip condition is enforced, meaning the fluid has no relative motion with respect to the solid boundary.
Ambient temperature	30 °C	Models typical high-temperature conditions in summer, with an ambient temperature of 30°C.
Density of air	1.2 kg/m ³	The air density is set based on standard atmospheric conditions.
Air viscosity	1.8 × 10 ⁻⁵ Pa·s	Represents the air's viscosity, which affects shear stress and the behavior of air flow, especially in boundary layers.
Mesh refinement at the boundary layer	Minimum cell size: 0.02 m	Mesh refinement is applied near the building surfaces to capture small-scale variations in airflow, particularly for wind speed and temperature gradients.

The no-slip wall condition faithfully represents the real-world interaction between airflow and solid surfaces. This condition enforces zero air-molecule velocity directly at the building facade, accurately accounting for the viscous drag and frictional

resistance that occur in practice. It plays an essential role in reliably predicting surface wind pressures and the overall patterns of air movement around the structure.

For the thermal boundary, an ambient air temperature of 30 °C was specified to simulate typical hot summer conditions. This choice enables the evaluation of heat conduction and associated energy demands under elevated external temperatures, thereby supporting the development of more effective energy-efficient building envelopes and designs.

Key fluid properties were defined as follows: air density was set to 1.2 kg/m³ for the computation of aerodynamic forces and momentum transfer. Dynamic viscosity was set to 1.8 × 10⁻⁵ Pa·s, governing the flow near surfaces and ensuring realistic modeling of both momentum and thermal boundary layers, which directly influences the precision of heat transfer predictions.

To resolve the steep gradients near the walls, the boundary-layer mesh was refined by reducing the smallest cell dimension to 0.02 m in these near-surface zones. This localized high-resolution gridding captures fine-scale velocity and temperature variations with sufficient detail, significantly improving the overall fidelity and trustworthiness of the wind-flow and thermal simulation results.

Heat transfer simulation

The heat transfer analysis relies on Fourier’s law of heat conduction and the steady-state heat conduction equation. Numerical techniques are applied to determine temperature fields and heat fluxes through the building envelope layers.

Material-specific thermal properties were first collected for each component of the wall assembly. A layered thermal resistance network was then constructed, allowing calculation of the individual layer resistances and the composite wall’s overall effective thermal resistance (R-value). Indoor and outdoor temperature boundary conditions were imposed, and the steady-state heat conduction equation was solved numerically to obtain the temperature profile across the wall thickness and the resulting heat flux. Heat flux values were computed directly from Fourier’s law based on the local temperature gradient. This systematic approach enables quantitative assessment of how variations in material selection, layer thickness, or structural configuration affect thermal performance, offering valuable guidance for improving insulation strategies and reducing overall building energy consumption (Figure 5).

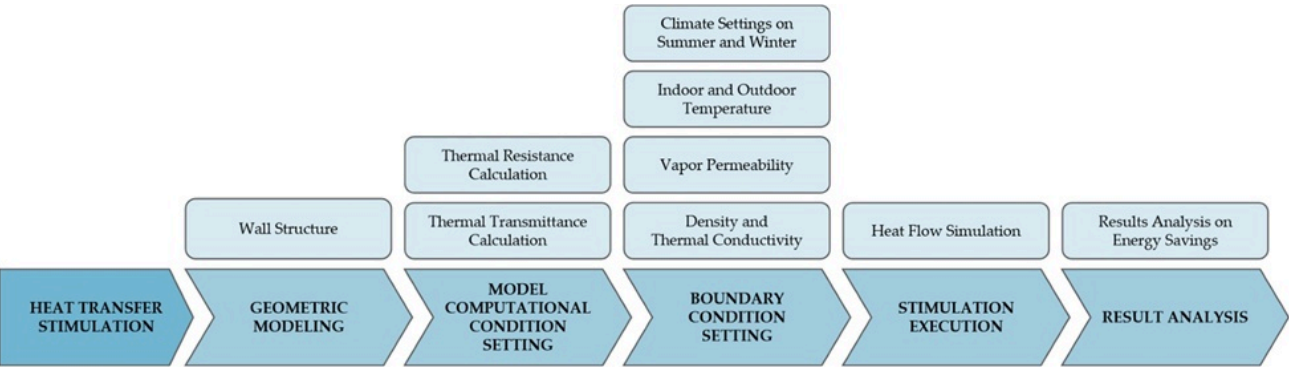


Figure 5. The flowchart of the heat transfer simulation.

In conducting the heat transfer modeling, an initial indoor-to-outdoor temperature differential (ΔT) of 20 °C was applied. This value was chosen to represent realistic extreme seasonal conditions—either severe winter cold or intense summer heat—allowing evaluation of the exterior wall’s thermal resistance performance under demanding circumstances.

High-density expanded polystyrene (EPS) was adopted as the main insulating layer, selected for its notably low thermal conductivity combined with a practical thickness that effectively interrupts conductive heat flow between the interior and exterior environments.

Boundary conditions for the simulation were established using a constant temperature difference across the wall assembly and steady-state heat-flux assumptions. These settings ensure that the computed results closely mirror the actual energy performance and heat-loss/gain behavior observed during real-world building operation.

The resulting overall heat transfer coefficient (U-value) for the insulated wall configuration was determined to be 0.253 W/m²·K. This value served as the key metric for quantifying the energy-saving benefits achieved through the proposed exterior wall upgrade and renovation measures (Table 2).

Table 2. Heat transfer simulation parameters and boundary conditions.

Parameter	Specific value	Description
Indoor–outdoor temperature difference (ΔT)	20 °C	The 20 °C temperature difference between indoors and outdoors is set to simulate the effects of the temperature gradient on heat conduction, a commonly used method for assessing wall insulation performance.
Wall insulation material	High-density expanded polystyrene (EPS)	The chosen material for wall insulation is high-density expanded polystyrene (EPS), with a thermal conductivity of 0.038 W/m·K and a thickness of 0.15 m, thereby enhancing thermal resistance and minimizing heat loss.
Thermal boundary conditions	Fixed temperature difference and steady-state heat flow	The simulation assumes a constant temperature difference between indoor and outdoor and steady-state heat conduction to assess heat flow and the wall's insulation performance in both summer and winter conditions.
Heat transfer coefficient (U-value)	0.253 W/m ² ·K	The U-value, calculated from the wall's multilayer composition, represents its overall thermal conductivity and is crucial for evaluating the wall's energy-saving efficiency.

West Campus Planning Scheme and Wind Environment Simulation

West campus planning scheme

Figure 6 presents the overall site layout and an aerial perspective of the newly developed West Campus.

In this proposed design, the primary campus entrance is positioned centrally. From there, the main pathway proceeds directly through the sports field and playground zone before rising via a prominent grand staircase to an attractive, scenic pond feature.

The campus's central axis is deliberately aligned to connect the comprehensive building and the teaching building in a straight, coherent sequence. On the western side, a dedicated corridor provides a sheltered linkage between the comprehensive building and the cafeteria, enhancing both functional circulation and spatial continuity.

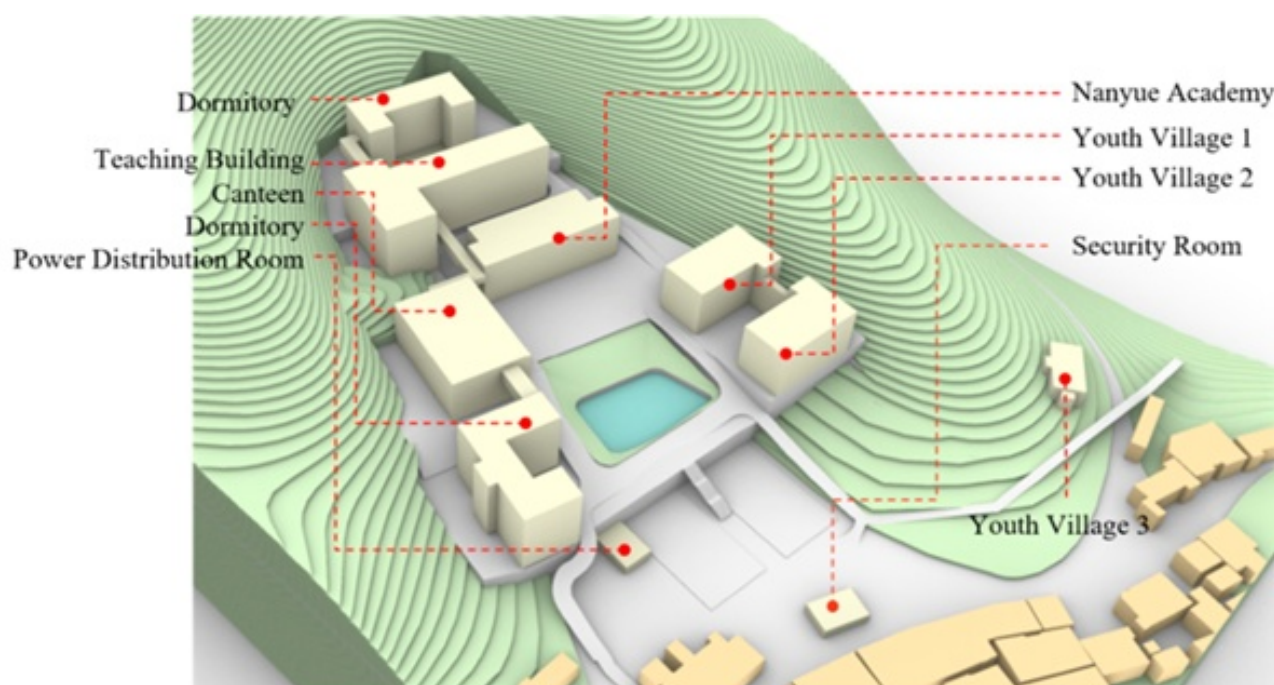


Figure 6. A comprehensive aerial perspective of the West Campus area.

In the northeastern portion of the campus, a cluster of 2–3 structures serving as teacher residences has been developed, collectively referred to as “Youth Village.” This complex accommodates both faculty apartments and staff housing. On the southwestern and northwestern edges of the site, one new student dormitory building has been added on each side. The pre-existing classroom structures have been preserved and repurposed—one transformed into a multipurpose, comprehensive building and the other into an academy—while a new teaching facility has been erected to the north (rear) and linked via a covered corridor to provide continuous, weather-independent access.

Wind environment assessment for the west campus

This study focused on modeling wind conditions at Yezhai Middle School under defined environmental scenarios. The central building group of Yezhai was represented geometrically using SketchUp. To enhance simulation efficiency while maintaining essential accuracy, the structures were approximated as simple rectangular prisms based on their real-world measurements, following the principle of architectural simplification.

Using the layout of Yezhai Middle School as the reference case, wind environment evaluation was performed with Ecotect software [33, 34].

Model simplification and input configuration

The architectural model of Yezhai Middle School was either built directly or imported into Ecotect, with careful verification of its scale, orientation, and geographic placement to ensure precision.

Key environmental inputs were configured in the software, including site-specific location and climate information: air density was set to 1.2 kg/m^3 , dynamic viscosity to 1.8×10^{-5} , and the region was classified as one with hot summers and cold winters. In this climate zone, the warmest month averages $25\text{--}30^\circ\text{C}$ and has elevated humidity, whereas the coldest month ranges from $0\text{--}10^\circ\text{C}$. Summers are typically hot and humid, with limited sunlight. The dominant summer wind direction is from the southeast, and simulations adopted a reference wind velocity of 5 m/s [35].

The WinAIR extension was activated in Ecotect to enable detailed wind-flow modeling. WinAIR serves as a dedicated module for simulating airflow patterns around structures in the Ecotect environment. Once the simulation was run, WinAIR computed the wind behavior around the simplified building geometry under the specified conditions.

Interpretation of simulation outcomes

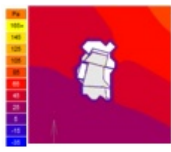
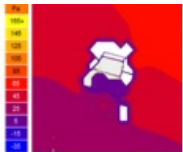
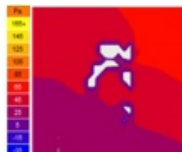
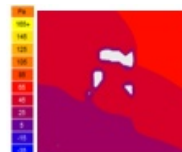
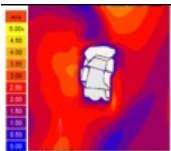
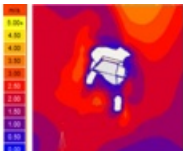
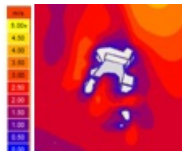
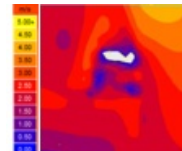
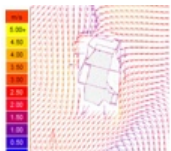
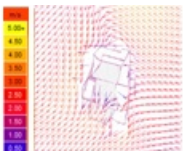
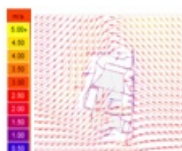
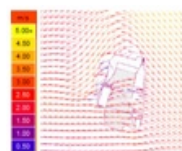
Wind speed and direction patterns vary considerably across horizontal sections at different elevations, mainly due to varying degrees of blockage and drag imposed by buildings at different levels. To capture how building geometry affects the local wind field, horizontal slices at 0 m, 10 m, 20 m, and 30 m above ground were examined [36].

Data presented in Table 3 indicate that wind velocity rises with increasing altitude, though the relationship is nonlinear. Near the surface, velocity increases more sharply, which can be attributed to stronger ground-level frictional drag. At higher altitudes, the rate of increase tapers off as airflow encounters fewer surface obstacles and encounters reduced resistance.

Wind pressure, which depends on the square of velocity, follows a comparable nonlinear trend but continues to show substantial growth even where velocity increments become smaller.

Evaluation of wind speed and pressure across various approach directions revealed distinct characteristics for each orientation. Westerly flows exhibit the greatest velocities and pressures, necessitating particular attention to wind loading in the design of tall structures and external spaces in that direction. In contrast, easterly and southerly winds tend to be gentler, which may support the incorporation of enhanced natural ventilation strategies in open areas facing those directions. Northerly winds demonstrate the lowest speeds and pressures, possibly due to greater obstruction or natural shielding from that side, offering potential benefits for creating sheltered or enclosed zones that require protection from strong airflow [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)	(d 1)
Wind speed				
	(a2)	(b2)	(c2)	(d 2)
Wind vector				
	(a3)	(b3)	(c3)	(d 3)

As depicted in **Figure 7**, the graph shows that wind speeds decrease near the buildings (negative distance values), likely because the buildings obstruct airflow. On the downwind side (positive distance values), wind speeds rise quickly but do not match those observed on the upwind side (the front of the buildings).

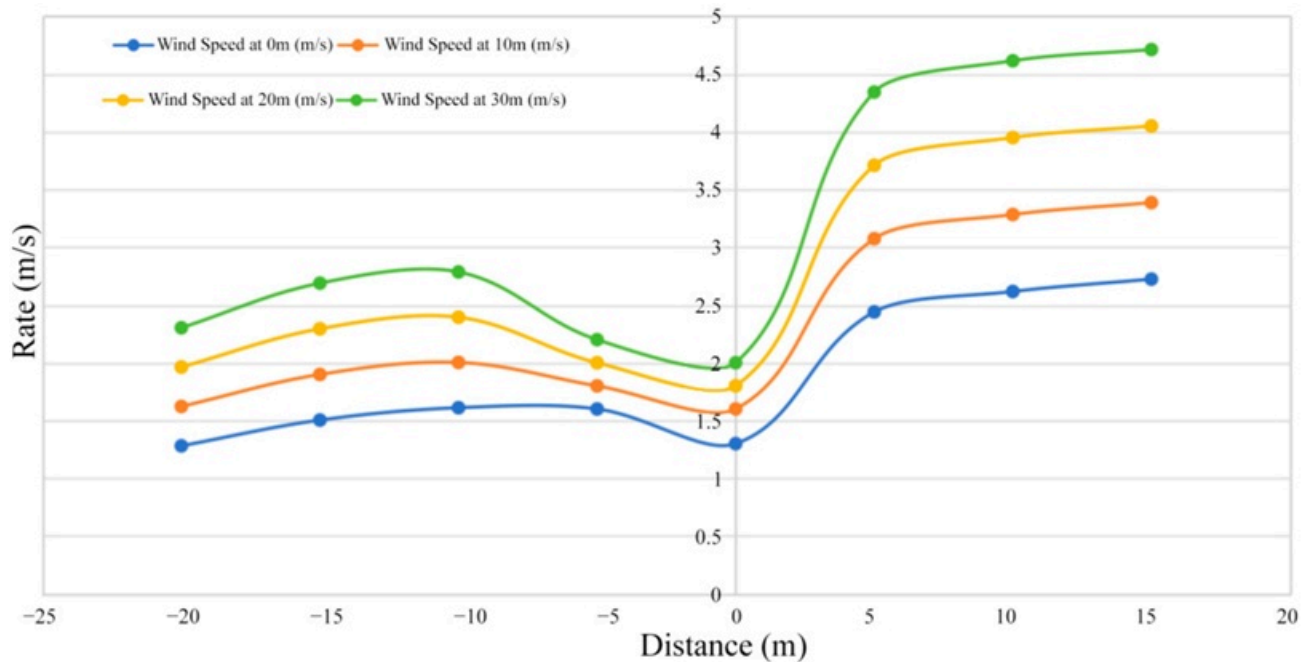


Figure 7. Line graph showing the variation in wind speed with distance.

While Ecotect cannot generate exact intermediate values between its computed simulation points for wind flow analysis, graphs can still be constructed using the simulated wind speed ranges to illustrate overall patterns of change relative to distance.

Ecotect's simulations yield discrete data points representing wind velocities at various heights and positions. The tool's inherent constraints prevent direct calculation of values in the gaps between these points. Nevertheless, by leveraging the observed ranges from those discrete points and applying interpolation techniques, approximate continuous curves can be generated to capture the general behavior of wind speed across distance.

These curves reveal a nonlinear correlation between wind velocity and distance at multiple elevations (0 m, 10 m, 20 m, and 30 m). Even without fully continuous precision from Ecotect, the approximated trends derived from the simulation data effectively highlight key patterns: wind speeds tend to be reduced on the upstream (windward) side of the structures due to blockage. At the same time, they exhibit a gradual, non-uniform recovery on the downstream (leeward) side. This uneven recovery pattern likely stems from the buildings' interference with airflow, creating wake zones and vortex formations that disrupt smooth acceleration.

By employing this approach, the Ecotect outputs—despite their discrete nature and associated constraints—were successfully used to visualize essential features of wind speed fluctuations with distance, offering valuable insights for building design considerations.

Regarding the influence of elevation, the graph shows a general increase in wind velocity with increasing height. The rate of this increase remains moderate at lower altitudes (0 m and 10 m), but becomes markedly steeper at higher altitudes (20 m and 30 m).

Analysis of the wind simulation results for Yezhai Middle School highlights substantial spatial differences in wind velocities near the structures. Wind speeds show a clear reduction in the immediate vicinity of the buildings, underscoring the strong blocking and sheltering effects of the built forms on surrounding air movement. This damping effect is especially evident on the windward faces. On the leeward side, wind speeds recover only partially, failing to regain levels typical of unobstructed open areas—a reflection of the complex, nonlinear vortex dynamics and wake recovery processes induced by the building cluster. Elevation-dependent variations further illustrate intricate flow behaviors, with velocities rising more sharply at higher levels, aligning with diminished ground-level friction and influences from the atmospheric boundary layer [39, 40].

As illustrated in **Figure 8**, the plot shows wind velocity rising with altitude, in line with standard profiles observed in the atmospheric boundary layer. Near the surface, velocities stay comparatively low, primarily owing to frictional drag from terrain and surface irregularities; as height grows, this resistance diminishes, allowing speeds to climb.

The velocity increase displays nonlinear behavior, with an initially steep rise that tapers off at higher altitudes. This pattern corresponds to the characteristic wind profile in the boundary layer, where velocity gradients are strongest in the lower regions and progressively weaken with increasing height.

Since wind pressure scales with the square of velocity, even a slowing rate of increase in velocity can produce substantial pressure growth with height. This underscores the need, in tall building design, to account for both velocity changes and the amplified pressure forces that affect structural integrity [41, 42].

In **Figure 9**, the data indicate that westward winds exhibit the highest velocities, approaching 4 m/s, and generate peak pressures of around 60 Pa among the four cardinal directions. This suggests the western orientation benefits from a larger open fetch or reduced frictional and obstructive influences from terrain and structures. Consequently, structural elements may require enhanced reinforcement to cope with these elevated westward wind loads.

Average wind speed and wind pressure at different heights

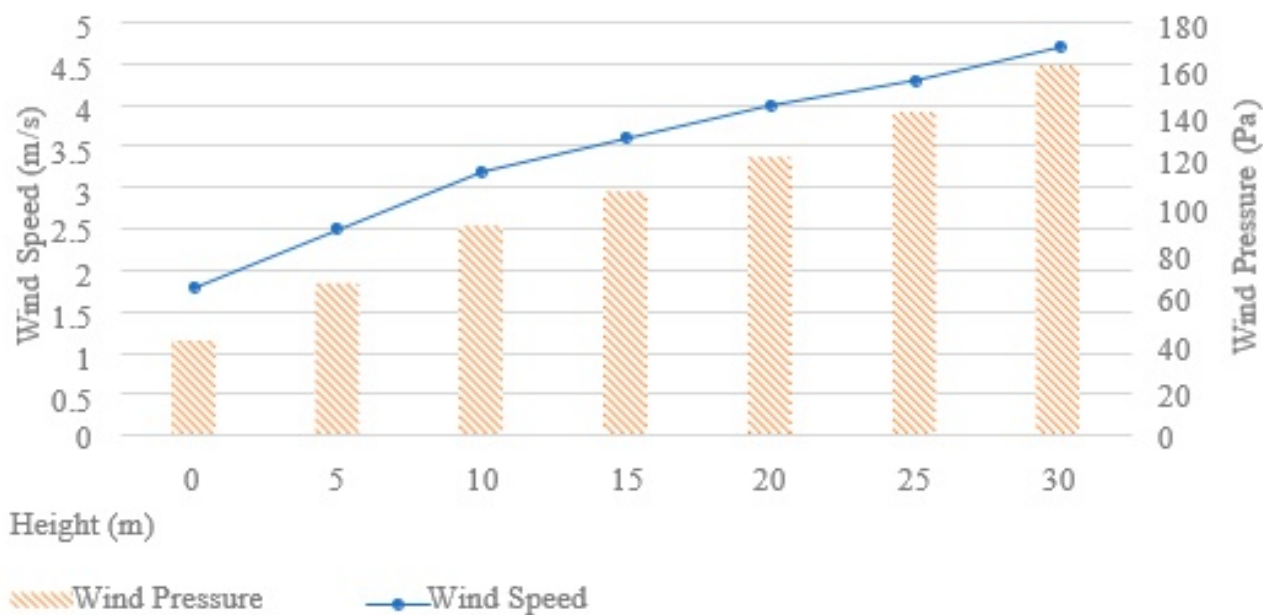


Figure 8. Trend of wind speed variation with height.

Average wind speed and wind pressure at different

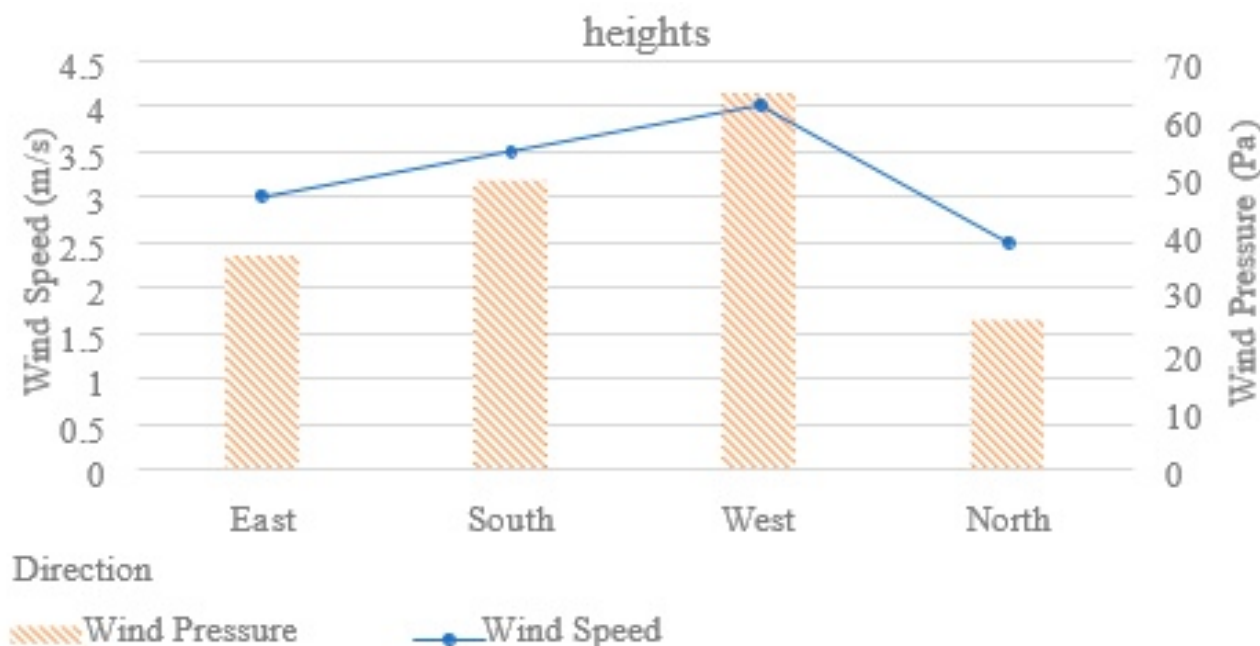


Figure 9. Distribution of wind pressure and wind speed in different directions at the reference height (10 m).

The velocities and corresponding pressures from easterly and southerly winds exhibit close similarity, indicating comparable effects on the local wind field from these orientations and a notable level of uniformity.

For the eastward direction, the recorded wind velocity stands at 3 m/s, accompanied by a dynamic pressure of roughly 36 Pa. The southerly direction registers a modestly elevated velocity of 3.5 m/s, yielding an approximate pressure of 50 Pa.

In contrast, the northerly winds exhibit the lowest values, with a speed of 2.5 m/s and a pressure below 20 Pa. This pattern suggests the presence of greater natural or constructed barriers—potentially including nearby structures or vegetation—that exert a stronger damping influence on airflow from this quadrant [43].

Examination of the simulation outcomes reveals marked variations in both wind velocity and pressure across different elevations. These findings underscore the role of architectural form in shaping the surrounding wind regime and pinpoint critical considerations for planning and design. First, elevated wind speeds in areas with tall structures can impose greater loads on the building envelope and framework, requiring strengthened structural components to withstand increased forces. Second, zones with subdued wind movement offer favorable conditions for passive ventilation, which can reduce reliance on mechanical cooling systems and lower overall energy use. Finally, the observed patterns in velocity and pressure distribution supply empirical support for refining site layouts and outdoor spaces—for instance, by incorporating shielding elements in regions prone to high winds to safeguard pedestrian comfort and safety.

Regarding strategies for wind attenuation, the present investigation incorporated multiple targeted approaches to mitigate unfavorable wind impacts on structures while simultaneously improving energy performance.

In the initial design stage, careful attention was given to building orientation and geometry to limit the projected area exposed to incoming winds substantially. The main axes of the structures were aligned to avoid direct parallelism with dominant wind paths, thereby lessening the intensity of direct wind impingement on facades. This configuration effectively lowers surface pressures and curbs the infiltration of chilly drafts, enhancing internal thermal comfort. Furthermore, aerodynamic or multifaceted forms were selected for the building envelopes. These configurations facilitate smoother airflow deflection around the structures, preventing the development of pronounced high-pressure zones and, consequently, diminishing stresses on cladding and the risk of structural compromise.

Next, a robust multi-layered wall assembly was employed to bolster both wind resistance and thermal resistance of the building envelope. This system enhances the walls' capacity to resist mechanical loads from gusts and sustained pressures, while incorporating insulating interstitial spaces that prevent unwanted heat ingress from the exterior, thereby supporting thermal efficiency.

Finally, intentional placement of vegetative buffers and artificial windbreaks encircling the development not only enhances aesthetic appeal but also substantially attenuates local wind velocities. Strategic arrangements of trees, shrubs, and similar elements can fragment and diffuse incoming airflow, reducing speeds in the immediate vicinity and alleviating pressure on building exteriors. Supplementary barriers—such as solid walls or perforated screens—further dissipate wind energy, providing additional protection against severe conditions.

By synergistically combining refined site planning, enhanced envelope detailing, and landscape interventions, the study successfully curtailed detrimental wind influences on the built environment.

Validation

To confirm the reliability of the CFD-based results, field measurements were conducted for validation. Several monitoring stations were established within the real-world setting of Yezhai Middle School, strategically positioned to capture representative wind conditions in critical zones around the structures, encompassing diverse elevations and offsets.

The deployment of measurement locations was arranged as detailed below:

- Measurement point 1: Positioned at ground level on the upstream (windward) face of the building, 2 m above grade, intended to quantify velocity reduction caused by direct blockage.
- Measurement point 2: Situated laterally along the building at intermediate elevation, 10 m above ground and displaced 5 m horizontally from the facade, aimed at assessing lateral flow acceleration or recovery.
- Measurement point 3: Placed on the downstream (leeward) side, 20 m above ground and 10 m horizontally offset from the structure, to evaluate post-obstacle velocity adjustments.
- Measurement point 4: Located at roof level or above, 30 m above ground, to record upper-level velocities and vertical profile influences near the building crest.

High-precision anemometry equipment was deployed at each station for ongoing data collection, with recorded values subsequently compared against the corresponding CFD predictions.

Table 4 presents a side-by-side evaluation of field-measured and simulated figures at the principal monitoring sites. The alignment between experimental and computational results demonstrates that the CFD modeling reliably reproduces the prevailing wind conditions. While Ecotect imposes certain constraints on precision in intricate urban settings, on-site validation substantially reinforces confidence in the findings. Accordingly, the simulation outputs from this work provide a trustworthy foundation for informing architectural decision-making and subsequent enhancements.

Table 4. Comparison of experimental and simulated data at key measurement points.

Measurement point	Simulated wind speed	Observed wind speed	Percentage error
1	4.6	4.8	4.17
2	3.1	3.2	3.13
3	2.8	2.7	3.70

4	1.6	1.5	6.67
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Facade Renewal and Energy-Efficient Building Envelope Design

Energy-saving upgrades to school building exteriors

Facade renewal involves updating the outer envelope of a structure to improve its visual appeal without altering the core framework, intended use, or internal organization. Common techniques encompass installing new surface finishes, adding outer insulation layers with cladding, or undertaking full exterior overhauls [44].

Key guidelines for renovating educational facilities include establishing a cohesive design language that imparts a recognizable institutional identity to the campus, while sensitively integrating updates that respect and preserve any historical significance, thereby balancing cultural continuity with contemporary requirements. Additionally, priority is given to sustainable, low-impact practices, favoring environmentally responsible materials in the renewal process. Given China's escalating energy challenges and the push toward long-term viability, retrofitting older structures—particularly schools—to cut energy demand has become a pressing necessity [45, 46].

Renewal projects generally fall into three categories: application of supplementary outer layers, substitution of existing wall finishes, and comprehensive facade reconstruction. At Yezhai Middle School, the chosen strategy centers on replacing and upgrading wall surfaces, with careful attention to reinforcing the exterior in harmony with the institution's longstanding historical and cultural values. This approach extends to targeted enhancements for instructional blocks, the library, dining facilities, and specialized science centers, all aligned under a consistent aesthetic framework [47].

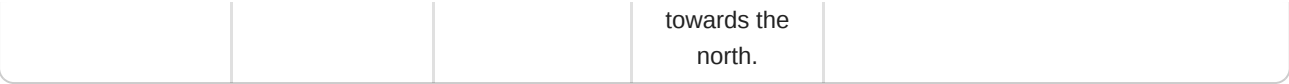
Exterior renewal initiative at yezhai middle school

Table 5 summarizes the principal elements of the landscape and facade enhancement program implemented at Yezhai Middle School. The renewal effort reorganized landscape features across the East Campus to achieve greater coherence, visual appeal, and distinctiveness. A prominent landscaped entry plaza was introduced in front of the central teaching structure, establishing a welcoming campus threshold. Concurrently, the exteriors of structures throughout the East Campus were standardized, adopting a predominant gray-and-white color scheme that evokes the distinctive elegance of Hui-style architecture. This is particularly evident in the upgrades to key edifices adjacent to the Martyrs Shrine—such as the Science and Technology Museum—along with comprehensive external refurbishments, internal enhancements, and interpretive displays for the associated museum.

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

	Evaluation before transformation	Evaluation after transformation	Orientation	Cladding
Comprehensive Building (Nanyue Academy)			 Facing south with a slight tilt towards the west.	-Integrate semi-ventilated and transparent aluminum-plastic panels into the outer facade. -Modify the building's color and design to ensure it blends aesthetically with the surrounding buildings.

Teaching Building 1			 Facing east with a slight tilt towards the south.	-Improve the building lobby by using the central axis as a guiding pathway. -Prolong the central axis to the building's core, incorporating a cohesive design language to increase the architectural consistency and coherence, enhancing the grand visual impact of the main entrance.
Teaching Building 2			 Facing south with a slight tilt towards the west.	-Introduce vertical decorative elements on some window facades to regulate ventilation and lighting. -Replace the iron-framed fence with solid concrete to safeguard the internal structure and prevent prolonged exposure to the external elements. -Extend a canopy along the pathway leading to the teaching building.
Specialist Building ("Renlu")			 Facing west.	-The entrance of the newly constructed building will be recessed, with the addition of a canopy to enhance outdoor conditions for users. -Larger floor-to-ceiling windows will be incorporated to enhance natural light and ventilation within the building. -The building's color and design will be modified to ensure visual harmony with the surrounding structures.
Dormitory			 Facing east with a slight tilt towards the south.	-Refine the building's facade to improve its visibility and clarity. -Incorporate horizontal decorative features to conceal the air conditioning system, enhancing the building's overall look and offering better protection for the system. -Improve the building lobby by creating areas for relaxation, enhancing the surrounding landscape, and offering students a more comfortable dormitory setting.
"Juehou" Pavilion			 Facing west with a slight tilt	- Enhance the surrounding landscape of the building to improve its functionality and overall usage.



To address the deterioration evident in numerous main-campus structures, the renewal was approached through thematic scene revitalization, with tailored proposals developed for various site contexts and functional demands. Emphasis was placed on refining facade proportions, innovative material pairings, and uniform coloration to infuse the campus's communal areas with renewed energy and vibrancy.

Evaluation of exterior upgrades for the senior high school teaching block

Figure 10 presents an illustrative overview of the proposed optimization and upgrade plan for the facade of the Senior High Teaching Building at the primary entrance to Yezhai Middle School. The upgrade process for this building has been structured into three distinct stages. During each stage, improvements focus not only on enhancing operational use and architectural appearance but also on improving energy performance. This is accomplished by carefully choosing appropriate facade materials and incorporating thermal insulation layers to minimize heat transmission.

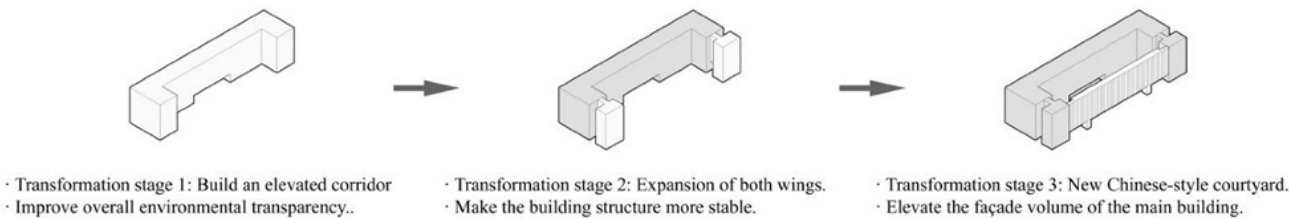


Figure 10. Schematic diagram of renovation phases for the Senior High Teaching Building.

Assessment of thermal performance in the building’s facade upgrade

A comprehensive evaluation of thermal energy performance was carried out for the entire upgrade project. The facade improvement for the Senior High Teaching Building incorporates Expanded Polystyrene (EPS), which is recognized for its superior thermal insulation capabilities. Following the upgrade, the EPS insulation layer measures 0.15 meters in thickness. EPS has a thermal conductivity of approximately 0.038 W/m·K. The relevant wall surface covers about 200 square meters. In winter, the average indoor-outdoor temperature differential is 20 Kelvin. The facade modifications are not expected to affect the building’s existing internal heating or cooling systems, including any HVAC equipment [48-50].

Modeling of heat transmission through the external wall

Yezhai Middle School employs Expanded Polystyrene (EPS) as the insulation material for the exterior walls, with the key physical attributes listed as follows: Density: Roughly 15–30 kg/m³; Specific Heat Capacity: Approximately 1.3 kJ/kg·K; Thermal Conductivity (k): 0.038 W/mK; Vapor Permeability: 0.12–0.26 mg/(Pa·h·m) (Figure 11).

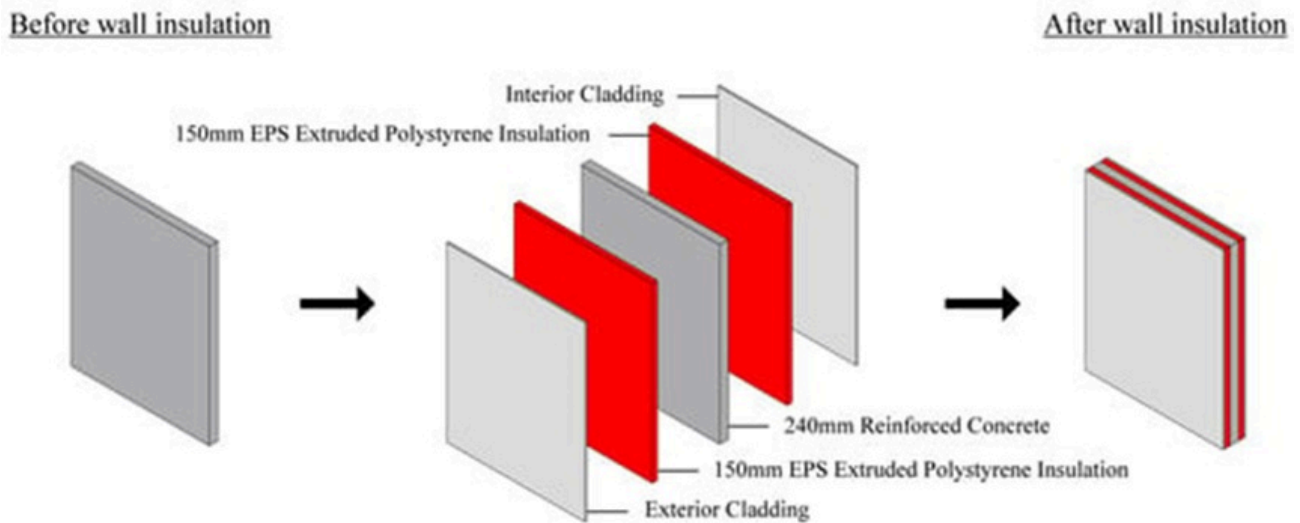


Figure 11. Wall insulation model.

In the heat transfer simulation and evaluation of the exterior walls of Yezhai Middle School in Anhui Province, the present research is based on Fourier's law of thermal conduction and the steady-state heat conduction theory for multilayer solid structures. Fourier's law serves as the fundamental principle of heat transfer analysis, clearly indicating that heat flows in the direction of the temperature gradient and that the magnitude of the heat flux is directly proportional to the size of that gradient.

$$q = -k \cdot \frac{dT}{dx} \quad (1)$$

In a composite wall under steady-state conditions, the total thermal resistance depends on the thickness and thermal conductivity of each material layer, as well as the cross-sectional area normal to the heat flow. The overall thermal resistance of the entire wall is obtained by adding the individual thermal resistances of all its layers. Using this total resistance along with the temperature difference across the wall, the heat flux can be determined.

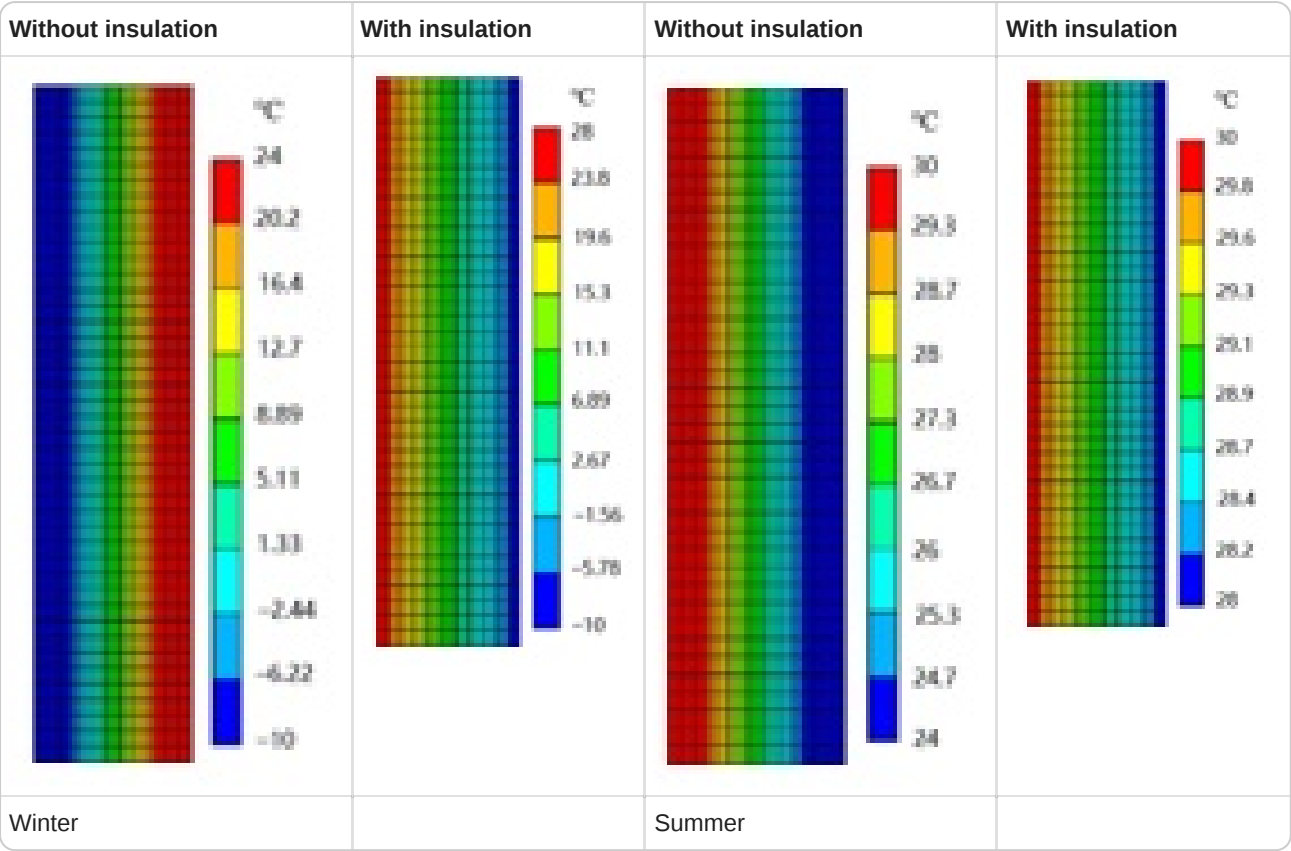
$$q = \frac{\Delta T}{\sum R} \quad (2)$$

Within the simulation workflow, the thickness and thermal conductivity of each material are first determined, allowing the calculation of the thermal resistance contributed by each layer. These layer resistances are combined to produce the wall system's total thermal resistance. Finally, the heat flux through the entire wall is computed by applying Fourier's law and the known temperature difference. This method enables a clear comparison of the insulating effectiveness of different materials and supplies a scientifically sound foundation for the design of buildings that achieve higher energy efficiency [51].

For the simulation boundary conditions, the lowest possible outdoor winter temperature for the area around Yezhai Middle School was adopted at $-10\text{ }^{\circ}\text{C}$. In comparison, the peak summer outdoor temperature was set to $28\text{ }^{\circ}\text{C}$ in accordance with local climate data. In both winter and summer scenarios, the indoor temperature was held constant at $24\text{ }^{\circ}\text{C}$ to represent typical occupied conditions. A mesh size of 3 cm was chosen to strike a reasonable balance between computational time and result accuracy [52].

Examination of the simulated temperature distribution patterns within the walls of Yezhai Middle School (Table 6) demonstrates the significant effect of the insulation layers on the internal thermal profile. Regardless of the season—winter or summer—the temperature change across the wall is noticeably more gradual when insulation is present, indicating that these layers effectively reduce the transmission of extreme external temperatures into the interior. The winter results reveal that the insulation greatly restricts the infiltration of cold outdoor air through the wall into the indoor space, thereby helping sustain comfortable indoor warmth. Conversely, the summer simulations indicate that the insulation effectively blocks external high temperatures, substantially slowing the rate of heat flow into the building [53, 54].

Table 6. Facade heat transfer simulation.



Through a detailed examination of heat conduction behavior in exterior walls under both summer and winter conditions, it is clear that the wall construction, along with its insulation components, effectively mitigates the effects of elevated outdoor temperatures in summer while shielding the indoor environment from cold penetration in winter. This helps maintain consistently stable indoor thermal conditions. Real-world measurements validate that, following the renovation, energy use associated with the exterior walls decreased by 24% relative to the pre-renovation state. Consequently, the wall configuration implemented at Yezhai Middle School meets energy conservation standards in both warm and cold periods, delivering comfortable indoor conditions while optimizing energy performance [55].

Figure 12 illustrates the patterns of temperature change within the wall structure. The data reveal that, under identical summer outdoor temperatures, the insulated configuration (experimental group) substantially blocks external heat from entering the indoor space, resulting in an approximate 2 °C lower indoor temperature than in the uninsulated reference group. This outcome stems from the insulation material's strong resistance to heat flow. In winter, with outdoor conditions at −10 °C, the insulated setup effectively limits indoor heat loss, resulting in an interior temperature roughly 1.8 °C higher than in the non-insulated case.

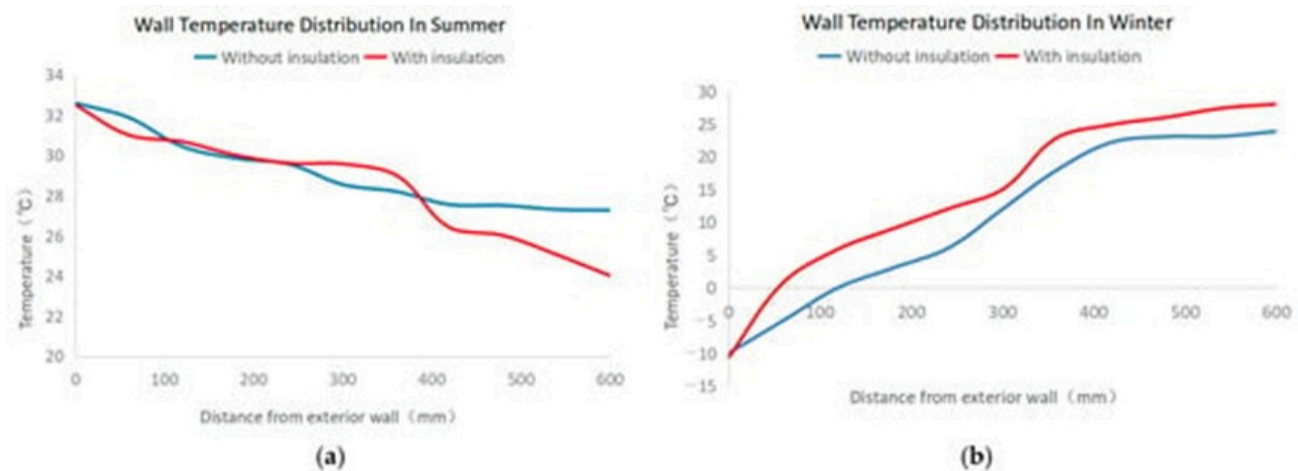


Figure 12. Wall temperature distribution in summer (a) and winter (b).

The interplay between wind patterns and thermal performance evaluation primarily comprises two key elements: how wind influences convective heat transfer and the examination of conductive heat transfer in relation to wind factors.

- Impact of wind patterns on convective heat exchange: Wind patterns significantly influence the convective heat transfer coefficient at building exteriors. Higher wind velocities increase this coefficient, thereby accelerating heat transfer and amplifying both heat losses (in cold conditions) and heat gains (in warm conditions). As a result, elevated wind speeds lead to stronger convective heat transfer at the outer wall surfaces, thereby increasing overall thermal exchange via convection.

- Examination of conductive heat transfer in relation to wind patterns: Conductive heat transfer analysis centers on the passage of heat through structural components, such as wall materials (e.g., EPS insulation), and is determined by the material's thermal conductivity and thickness. Although conduction primarily occurs within the wall assembly, surface-level interactions with the outdoor environment—including convective exchanges—also influence the building's overall thermal performance.

In essence, wind patterns primarily influence thermal performance assessments by affecting convection. Increased wind speed increases the surface convective heat transfer coefficient, thereby hastening heat losses or gains. Thus, accounting for wind impacts on convection is crucial in holistic thermal efficiency evaluations. While this analysis emphasizes conductive aspects, the role of wind in convective processes remains vital, particularly in regions experiencing stronger winds.

The findings of this investigation stem from thorough modeling and quantitative assessments. Simulations of the wind field reveal that wind velocity increases nonlinearly with elevation, especially noticeable near ground level, offering important insights for incorporating wind forces into structural planning. The exterior wall upgrades, featuring EPS (expanded polystyrene) insulation, substantially reduced winter heating needs and summer cooling demands, delivering an energy reduction of 24%. These outcomes demonstrate that thoughtful architectural planning and efficiency upgrades can markedly boost energy performance, serving as useful examples for low-carbon upgrades in other educational and public facilities.

Calculation methodology:

- The heat conduction equation (Fourier's Law) was applied to quantify heat losses through walls before and after the upgrade.

- Choice of material properties: Post-upgrade, the outer walls were insulated with expanded polystyrene (EPS) as the primary insulation, with a thickness of 0.15 m and a thermal conductivity of $k = 0.038 \text{ W/m}\cdot\text{K}$. The relevant wall surface area measures about 200 m^2 , with an assumed indoor-outdoor temperature differential of 20 K during winter.
- Determination of thermal resistance and U-value: Thermal resistance R was computed per, resulting in $3.95 \text{ m}^2\cdot\text{K/W}$. The overall heat transfer coefficient U , being the inverse of R , equals $0.253 \text{ W/m}^2\cdot\text{K}$.
- Projection of yearly heating requirement: Using the derived U-value and temperature differential, the post-upgrade annual heating load, Q_{year} , was projected at approximately 2920 kWh.

Comparisons of pre- and post-upgrade energy usage data revealed an approximate 24% decrease in the building's yearly energy consumption after the modifications.

Results and Discussion

Prior studies and real-world applications in campus energy conservation have offered practical guidance and recommendations across multiple angles, including upgrading lighting infrastructure, implementing integrated energy management [11], adopting adaptable energy systems, and integrating ecological assessments with machine learning approaches. Campus structures possess considerable untapped potential for energy conservation that warrants further investigation. This work concentrates on envelope improvements and, via concrete retrofit actions, achieved notable reductions in energy use at Yezhai Middle School, advancing objectives for energy conservation and emissions mitigation.

This investigation proposes targeted efficiency improvement strategies tailored to the context of mountainous educational facilities in China's hot-summer/cold-winter zones, thereby conferring regional relevance and value as a reference. Amid the push toward smart urban growth, embedding cutting-edge technologies and eco-friendly methods into public facilities has emerged as a central priority. Beyond envelope efficiency upgrades, this work also addresses wind-field enhancements and thermal insulation of materials, delivering a multifaceted approach to energy-efficient design. Ultimately, the on-site retrofit at a particular campus provides strong feasibility and practical applicability, offering concrete implementation pathways and technical support for comparable initiatives.

Although progress has been made in investigating low-carbon efficiency designs for campus envelopes, certain constraints remain, including limited data availability and coverage, a limited range of efficiency measures, and inadequate assessment of enduring outcomes. Subsequent investigations could refine and extend these efforts in the following ways:

- Conduct additional studies across broader geographic areas and varied campus facility types to confirm and broaden this work's findings, thereby strengthening applicability and dependability.
- Integrate indoor system optimization, smart automation controls, and renewable energy sources to conduct more holistic efficiency studies and achieve superior conservation outcomes.
- Develop ongoing monitoring frameworks to persistently observe and assess retrofit performance across seasons and meteorological variations, yielding empirical data to refine upgrade strategies.
- Adopt interdisciplinary collaboration, drawing on fields such as architecture, ecology, energy systems engineering, and beyond, to identify optimal methods for campus efficiency upgrades and to foster green campus advancement within smart city frameworks.

Conclusion

This examination of low-carbon efficiency upgrades at Yezhai Middle School in Qianshan City, Anhui Province, investigates strategies for wind-field improvement and envelope energy conservation during renovations of existing structures in mountainous campus settings.

· Wind field modeling shows nonlinear increases in wind velocity with altitude, with pronounced effects from surface roughness at lower elevations. Strategic building arrangement and layout can optimize wind velocities and pressure patterns across campus orientations, enhancing the usability of external spaces and safeguarding structural integrity.

· The envelope efficiency upgrade used EPS panels with insulation for both exterior and interior wall applications, providing superior thermal resistance. Implementation of 0.15 m EPS layers with a conductivity of 0.038 W/mK resulted in significant reductions in thermal energy requirements. These interventions markedly decreased demands for winter heating and summer cooling. Modeling outcomes confirm that insulation barriers effectively block winter cold penetration and limit summer heat ingress. The upgraded envelope delivered around 24% energy savings, demonstrating that envelope improvements not only improve indoor conditions but also yield significant efficiency benefits. Furthermore, the post-upgrade annual heating estimate of about 2920 kWh underscores the marked performance improvement, affirming the merits of envelope retrofits for comfort and conservation.

· Wind simulations highlighted that deliberate design can refine wind speed and pressure layouts, benefiting outdoor spaces and structural resilience. The nonlinear, height-dependent wind behavior, heavily shaped by terrain friction, underscores the need to incorporate wind considerations into planning to boost campus livability and security. By evaluating wind simulations alongside the thermal characteristics of efficiency envelope materials for Yezhai Middle School's new west campus, this work provides a rationale grounded in evidence and hands-on insights for low-carbon efficiency upgrades at other educational and civic structures. These insights help elevate environmental quality and sustainability on campuses while providing viable technical pathways and planning resources for pursuing eco-friendly, low-carbon construction objectives.

· Within the evolution of smart cities, integrating innovative tools and sustainable methods into civic infrastructure is a primary aim. This study's outcomes deliver useful applied knowledge for similar upgrades elsewhere. An in-depth review of wind optimization and efficiency envelope solutions supports progress toward more resource-efficient, eco-conscious building approaches. The discoveries provide robust conceptual grounding and actionable directives for realizing sustainable, low-carbon aims in the sector. Future efforts can extend to facilities in diverse locales and climates, fully incorporating additional conservation measures and renewables to achieve more integrated, high-impact, low-carbon retrofits. This direction will meaningfully support smart city ambitions, improving urban livability and ecological health.

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