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# Evaluating Energy Efficiency Potential in Residential Buildings in China's Hot Summer and Cold Winter Zones

Tianqing Shen[1*], Long Sun[2]

[1] School of Urban Construction and Transportation, Hefei University, Hefei 230601, China
[2] Anhui Provincial Key Laboratory of Urban Rail Transit Safety and Emergency Management, Hefei University, Hefei 230601, China

Corresponding Author Email: shtq@hfuu.edu.cn



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**ABSTRACT**

In the realm of building energy efficiency, the unique climatic conditions of China's hot summer and cold winter regions present distinct challenges and opportunities for residential energy saving. This study, centered on a residential case in Anhui Province, leverages the capabilities of the SVILLE energy-saving calculation software to simulate various configurations of building envelopes, focusing on energy-saving and insulation strategies. The investigation scrutinizes the correlation between the thermal performance of residential building envelopes and the enhancement of energy-saving potential, thereby offering empirical insights into the engineering aspects of energy-efficient design. The research aims to contribute to the development of energy-saving architectural strategies that are both economically viable and environmentally sustainable, specifically tailored to the climatic nuances of hot summer and cold winter areas. The study's outcomes are intended to provide a comprehensive reference for optimizing energy-saving designs in residential buildings, advocating a holistic approach that balances economic considerations with environmental sustainability. By presenting a robust theoretical framework, this research aspires to inform and refine energy-efficient residential investment strategies, thereby mitigating risks associated with investment decisions made without the benefit of informed analysis.

## 1. INTRODUCTION

Projected forecasts indicate that by 2040, global primary energy consumption will witness an increase of 32% in comparison to levels recorded in 2017 [1]. Reflecting on the past four decades, a steady growth in energy demand at an annual rate of approximately 1.8% has been observed, anticipated to constitute nearly 58% of total energy consumption by 2050 [2]. In this context, the construction industry emerges as a significant consumer, accounting for 32% of global energy use [3]. With the ongoing depletion of non-renewable resources worldwide, the momentum towards energy conservation and emission reduction is gaining paramount importance. Studies estimate that about 40% of a building's heat loss can be attributed to external walls, followed by 30% from windows, approximately 7% from roofs, 6% from basements, and the remaining 17% through air infiltration [4]. These insights underscore the necessity for buildings to either strengthen or adopt building envelope structures more resistant to heat loss. Moreover, the implementation of external wall insulation, transcending its role in energy conservation, emerges as an indispensable strategy to reduce energy loss, lower energy expenses, and thereby optimize energy efficiency [5].

The building envelope, interfacing directly with the external environment, significantly influences the indoor-outdoor heat transfer, thereby impacting the energy-saving potential of buildings. It has been recognized that mitigating the thermal conductivity of the building envelope to reduce energy consumption stands as a cost-effective approach to achieve architectural energy conservation [6, 7]. The climatic uniqueness of China's hot summer and cold winter zone, with its hottest months experiencing average temperatures between 25-30℃, about 2 degrees higher than similar latitudes, and coldest months averaging 2-7℃, approximately 8-10 degrees cooler than similar latitudes [8], necessitates both summer insulation and winter thermal retention. Historical factors [9] have led to the absence of centralized heating systems in this zone, resulting in a heavy reliance on mechanical heating and cooling systems for maintaining indoor thermal comfort, thereby culminating in significant energy usage [10]. It is evident that the energy consumed by space heating and cooling systems in residential settings accounts for a substantial proportion, ranging from 0-60% of the annual energy consumption [11]. This scenario highlights a considerable scope for energy saving in the region [12], emphasizing the critical role of enhancing the energy efficiency of building envelopes in reducing primary energy usage and curtailing greenhouse gas emissions.

In response to escalating demands for building energy conservation, a series of technical standards and regulations specifically targeting the hot summer and cold winter zones have been progressively established and implemented. The energy-saving rate for buildings in these zones has seen a gradual increase, moving from an initial requirement of 30% to a current standard of 65%. Correspondingly, the technology associated with external wall thermal insulation in buildings has experienced a significant evolution. This period has been marked by rapid advancements in insulation materials, with a continuous emergence and updating of novel thermal insulation products. Such dynamic development reflects the growing emphasis on energy-efficient building practices. Research conducted within this domain has been extensive. Liu et al. [13] undertook a study involving simulation calculations on typical residences in four distinct cities within the climate zone, namely Wuhan, Changsha, Hangzhou, and Chengdu. Their research, taking into account economic, energy, and greenhouse gas emission factors, proposed an innovative approach for determining the optimal thickness of insulation for residential exterior walls. Liu et al. [14] selected Changsha, Chengdu, and Shaoguan as representative cities of the zone, employing a heat and moisture transfer model to assess the influence of internal moisture transfer in exterior wall insulation materials on the zone's energy consumption. Similarly, Amani and Kiaee [15] conducted an investigation on a typical multi-storey apartment building located in this climate region. Their study identified several optimal solutions for significantly reducing building energy consumption and provided an analysis of the substantial variations in their environmental impacts.

The research question addressed in this study is twofold: Firstly, to what extent does enhancing the energy-saving system standards of the building envelope in hot summer and cold winter regions affect energy consumption? Secondly, what is the potential for energy-saving through an optimized combination design of the building envelope? This paper utilizes the SVILLE building energy-saving calculation software as an analytical tool, focusing on a residential case study in the Anhui region. Various combination schemes were simulated to mirror real-life conditions, facilitating a comprehensive comparison and analysis. The study examines the impact of the thermal performance of building envelopes on energy consumption from three key aspects: energy-saving rate, economic feasibility, and ecological sustainability. An analysis of energy consumption trends under varying thermal parameters is presented, aiming to encapsulate the energy-saving potential in the hot summer and cold winter region.

## 2. ASSESSMENT OF THE IMPACT OF EXTERNAL WALL INSULATION MATERIALS AND THICKNESS ON RESIDENTIAL ENERGY SAVING RATES

In the realm of building energy consumption analysis, two predominant methodologies are utilized: the steady-state heat transfer method and the dynamic heat transfer method. The former maintains a constant temperature field over time, whereas the latter, acknowledged for its enhanced accuracy, considers temporal fluctuations in the temperature field. For more precise simulation outcomes, the dynamic thermal simulation transfer approach necessitates the use of specialized energy-saving calculation software [16]. This investigation employs the SVILLE building energy-saving calculation software to simulate energy consumption. The focus of this study is the No. 20 residential project in a district in Lu'an City. A comprehensive overview of the project is provided in Table 1, and the floor plan is depicted in Figure 1. This analysis involves an optimized combination and techno-economic assessment of the project's energy-saving insulation system.

### 2.1 Project overview

Table 1 presents a detailed overview of the No. 20 Residential Project, encompassing various aspects such as the building area, location, shape coefficient, and other architectural details. Figure 1 illustrates the floor plan of the No. 20 residential building, providing visual insight into the project's layout.

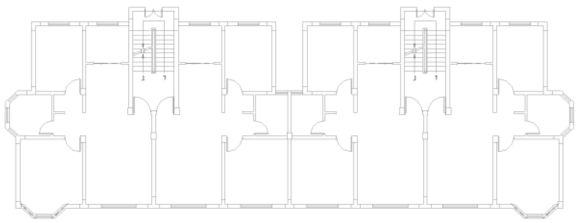

**Figure 1.** Floor plan of the No. 20 residential building

The calculation parameters for the SVILLE software are meticulously set, adhering to the standards for calculating comprehensive energy-saving indicators:

- Indoor temperatures for air-conditioned rooms during different seasons: 18℃ throughout the winter; 26℃ throughout the summer.
- Outdoor meteorological parameters are based on a typical meteorological year.
- Defined ventilation rate of 1.0 times/h during heating and air conditioning.
- The heating and air conditioning equipment specifications, such as domestic gas-source heat pump air conditioners, rated energy efficiency ratios of 2.3 and 1.9 for air conditioning and heating, are also incorporated.
- Calculations account for indoor lighting heat gain of 0.0141 kWh/m$^2$ per day and the average intensity of other indoor heat gains of 4.3 W/m$^2$.

**Table 1.** Overview of the No. 20 residential project

| **Project Name** | **No. 20 Residential Building in a District in Lu'an City** | **Building Area** | **Above Ground 2072.62 m$^2$, Underground–m$^2$** |
|---|---|---|---|
| Project Location | Lu'an City, Anhui Province | Shape coefficient | 0.34 |
| Northward Angle | 90 degrees | Building volume | 6010.59 m$^3$ |
| Building Shape | Strip-type building | Building surface area | 2026.16 m$^2$ |
| Number of Floors | 6 | Building height | 18.15 m |

**Table 2.** Energy-saving insulation system of the project envelope structure

| External Wall Type | Alkali-Resistant Shattered Mesh Fabric, Anti-Crack Mortar (5mm) - Polystyrene Board (30mm) - Porous Clay Brick (200mm) - Mixed Mortar (20mm) |
|---|---|
| Flat roof | Cement mortar (20mm) - extruded polystyrene board (30mm) - polyurethane waterproof coating (2mm) - cement mortar (20mm) - lightweight aggregate concrete (80mm) - reinforced concrete (110mm) - mixed mortar (20mm) |
| Floor type | Cement mortar flooring |
| Door type | Energy-saving external door |
| Window type | Plastic single-frame ordinary hollow glass window, thermal transmittance coefficient 3.00 W/($m^2$·K) |
| Thermal bridge column and beam type | Alkali-resistant shattered mesh fabric, anti-crack mortar (5mm) - extruded polystyrene board (30mm) - reinforced concrete (240mm) - mixed mortar (20mm) |

**Table 3.** Comparative analysis of insulation material thickness variations and residential energy saving rates

| Serial Number | Variable Parameters of Each Component | Variation Value | Thermal Transmittance Coefficient W/($m^2$·K) | Residential Energy Saving Rate | Decrease Rate of Energy Saving | Insulation Price of the Envelope (Yuan/$m^2$) | Increased Cost of Residential Energy Saving | Note |
|---|---|---|---|---|---|---|---|---|
| 1 | Powdered polystyrene granule external wall insulation thickness | 20mm | 1.31 | 52.46% | | 66 | 41.9 | External windows are thermal break aluminum alloy hollow glass windows (2.50$m^2$·K), roof is 30mm extruded polystyrene board (0.77$m^2$·K), thermal bridge columns and beams are 30mm powdered polystyrene granules |
| | | 25mm | 1.2 | 52.89% | 0.82% | 73 | 46.3 | |
| | | 30mm | 1.1 | 53.31% | 0.79% | 80 | 50.7 | |
| | | 35mm | 1.02 | 55.46% | 4.03% | 87 | 55.2 | |
| | | 40mm | 0.96 | 55.94% | 0.87% | 94 | 59.6 | |
| | | 45mm | 0.94 | 56.14% | 0.36% | 101 | 64.1 | |
| | | 50mm | 0.89 | 56.42% | 0.50% | 108 | 68.5 | |
| 2 | Polystyrene board external wall insulation thickness | 20mm | 1.09 | 53.08% | | 86 | 54.55 | External windows are thermal break aluminum alloy hollow glass windows (2.50$m^2$·K), roof is 30mm extruded polystyrene board (0.77$m^2$·K), thermal bridge columns and beams are 30mm powdered polystyrene granules |
| | | 25mm | 0.99 | 55.47% | 4.50% | 90 | 57.08 | |
| | | 30mm | 0.90 | 55.85% | 0.69% | 94 | 59.62 | |
| | | 35mm | 0.83 | 56.34% | 0.88% | 99 | 62.79 | |
| | | 40mm | 0.77 | 56.70% | 0.64% | 104 | 65.96 | |
| | | 45mm | 0.72 | 56.85% | 0.26% | 109 | 69.13 | |
| | | 50mm | 0.67 | 57.11% | 0.46% | 114 | 72.31 | |
| 3 | Rigid polyurethane foam insulation thickness | 20mm | 0.91 | 56.55% | | 108 | 68.50 | External windows are thermal break aluminum alloy hollow glass windows (2.50$m^2$·K), roof is 30mm extruded polystyrene board (0.77$m^2$·K), thermal bridge columns and beams are 30mm powdered polystyrene granules |
| | | 25mm | 0.79 | 57.03% | 0.85% | 119 | 75.48 | |
| | | 30mm | 0.69 | 57.72% | 0.42% | 130 | 82.45 | |
| | | 35mm | 0.62 | 57.73% | 0.80% | 141 | 89.43 | |
| | | 40mm | 0.56 | 57.96% | 0.40% | 152 | 96.41 | |
| | | 45mm | 0.51 | 58.12% | 0.28% | 163 | 103.38 | |
| | | 50mm | 0.47 | 58.37% | 0.43% | 174 | 110.36 | |
| 4 | Autoclaved aerated concrete external wall insulation thickness | 200mm | 1.02 | 56.03% | | 85.2 | 54.3 | External windows are thermal break aluminum alloy hollow glass windows (2.50$m^2$·K), roof is 30mm extruded polystyrene board (0.77$m^2$·K), thermal bridge columns and beams are 30mm powdered polystyrene granules |
| | | 210mm | 1.00 | 56.24% | 0.37% | 89.5 | 56.8 | |
| | | 220mm | 0.98 | 56.41% | 0.30% | 93.7 | 59.4 | |
| | | 230mm | 0.96 | 56.52% | 0.20% | 97.6 | 62.1 | |
| | | 240mm | 0.94 | 56.74% | 0.39% | 102.2 | 64.8 | |

Note: The cost assessment for external wall insulation incorporates expenses related to waterproofing, anti-crack layers, and labor. The insulation pricing for the building's envelope is calculated based on the total area of the project. The specifications for window materials include aluminum hollow glass (4+6A+4) and polyvinyl chloride (PVC) steel hollow glass (4+6A+4). The surface area covered by the external walls of the project is distributed as follows: 1285 $m^2$, 368.5 $m^2$, and 372.6 $m^2$, respectively.

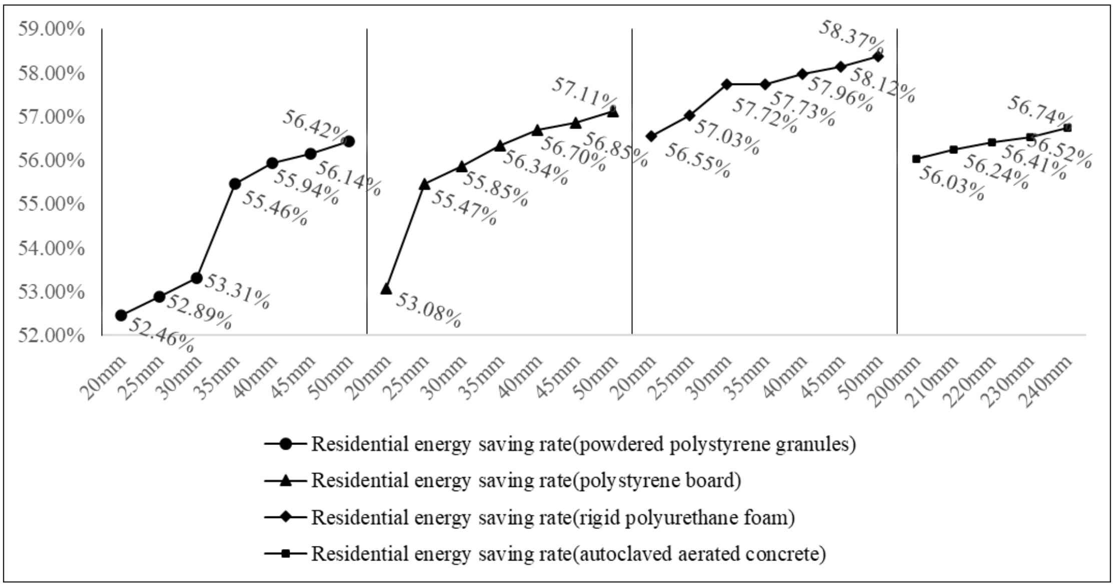


**Figure 2.** Graphical representation of the relationship between insulation material thickness variations and residential energy saving rates

### 2.2 Envelope structure of the actual project

The envelope structure of the project under study has been designed with an energy-saving system, the details of which are comprehensively outlined in Table 2. This table enumerates the components of the envelope structure, including the types of external walls, roof, floor, doors, windows, and thermal bridge columns and beams, along with their respective materials and dimensions.

Utilizing the SVILLE building energy-saving calculation software, this segment of the study focuses on analyzing how variations in different external wall insulation materials influence the building's energy-saving rate. The relationship between these material variations and the resultant changes in energy efficiency is methodically examined. Table 3 and Figure 2 present the findings of this analysis, offering a visual and quantitative representation of the impact of insulation material choices on the energy-saving performance of the building.

In this segment of the study, variations in the thickness of different insulation materials and their corresponding impacts on residential energy-saving rates are quantitatively assessed. Table 3 presents a detailed comparison, focusing on the thermal transmittance coefficients and the resulting energy saving rates achieved with different insulation materials and thicknesses.

This study further investigates the relationship between the thickness of various insulation materials and the corresponding changes in residential energy-saving rates, as illustrated in Figure 2. The analysis includes powdered polystyrene granules, polystyrene board, rigid polyurethane foam, and autoclaved aerated concrete, each assessed for its impact on energy efficiency.

The examination of diverse external wall insulation scenarios, as delineated in Table 3, reveals that augmenting the insulation of external walls in a residential energy-saving system can significantly elevate the rate of energy savings. Incrementing the thickness of the insulation layer by 5mm correlates with an increase in the energy-saving rate by 1%-2%. A pronounced decrease in the thermal transmittance coefficient of external walls is observed within the 20-30mm thickness range, accompanied by a substantial enhancement in the energy-saving rate. However, it is noted that beyond a 50mm thickness, despite a continual decline in the thermal transmittance coefficient, the rate of change in energy savings is markedly less pronounced. This observation suggests that beyond a certain threshold, additional increments in the thickness of external wall insulation materials do not significantly amplify the overall energy-saving efficiency of the building. The economic advantages derived from the external wall insulation layer are intricately linked with the initial investment. The application of insulation technology to residential external walls necessitates an initial increase in technological investment costs. Nonetheless, this investment results in reduced energy consumption over the insulation layer's lifespan, thereby lowering the residence's annual operational costs compared to buildings lacking external wall insulation energy-saving technology. The degree of energy conservation achieved through insulation energy-saving technology is proportionate to the sophistication of the technology employed, with more advanced technologies contributing to greater operational cost savings.

With an increase in the thickness of external wall insulation layers, an enhancement in energy efficiency is observed, along with a corresponding decrease in overall costs. However, it is noted that after surpassing a certain threshold, further augmentation in insulation thickness leads to a substantial increase in overall expenses. Gonzalo and Bovea [17] introduced a methodology to ascertain the economically optimal thickness of external wall insulation, aimed at diminishing energy demand during a building's operational phase. This pivotal thickness, termed 'critical thickness', denotes the point beyond which additional insulation material yields decreasing returns [18]. Figure 3 delineates the correlation between the insulation layer's thickness and cost. It elucidates that the lifecycle cost of the insulation layer exhibits a parabolic trajectory with respect to its thickness, identifying a minimum cost point.

In assessing the economic implications of external wall insulation in energy-saving technologies, it is crucial to consider the critical thickness point, as depicted in Figure 3. This analysis highlights that insulation thicknesses substantially deviating from the critical point *M* can lead to increased total costs. This figure demonstrates the relationship between insulation layer thickness and various cost components, including total cost, insulation layer investment cost, and operational cost. It indicates that when insulation thickness significantly exceeds or falls short of the critical point *M*, it adversely affects the overall economic viability. A thickness far beyond point *M* incurs unnecessary investment costs, whereas a thickness below this point necessitates an increase due to the dynamics of one-time production costs and the escalation of operational costs over time. Below the critical point *M*, the economic benefits of a thicker insulation layer become increasingly evident [19, 20].

The role of insulation materials in near-zero energy consumption buildings is also examined, particularly their potential to diminish building energy requirements and carbon emissions. However, indiscriminately increasing the thickness of insulation materials in the building envelope may adversely affect the energy environment. Therefore, the study emphasizes the need to optimize insulation thickness, balancing considerations of energy efficiency, economic feasibility, and environmental impact [17].

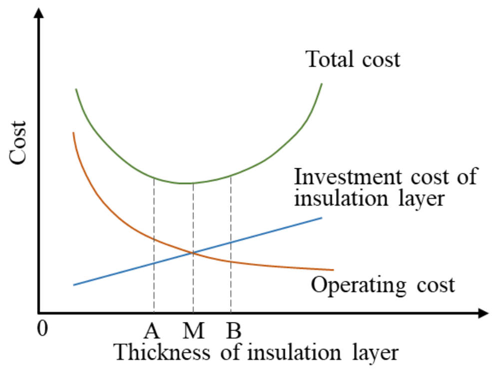


**Figure 3.** Graphical illustration of the optimal and economic thickness of the insulation layer

## 3. ASSESSMENT OF ENERGY-SAVING BUILDING ENVELOPE COMBINATIONS FOR ACHIEVING 65% STANDARD IN HOT SUMMER AND COLD WINTER ZONES

In the context of the energy-saving system of residential building envelopes, it has been observed that, despite energy consumption being influenced by factors such as architectural design, building usage, and climatic zone, the external wall, as the predominant portion of the building envelope's surface area, plays a pivotal role in energy saving. It is found that the thermal transmittance coefficient and thermal inertia index of the external wall have direct implications for the building's energy consumption and the comfort of the indoor environment.

For a comprehensive assessment, only those design schemes of residential building envelopes that consider the entire lifecycle exhibit significant objectivity and reliability. These schemes serve as a guide for optimizing energy-saving and insulation systems, consequently elevating the standard of energy-efficient design. The selection of innovative external wall insulation materials and technologies that reduce the external wall's thermal transmittance coefficient has been identified as a key factor in achieving elevated energy-saving rates. Additionally, the performance of external windows emerges as a crucial component in energy conservation. Enhancement of external window performance has been shown to effectively boost energy-saving rates, although the scope for substantial improvements beyond existing benchmarks appears limited. It is revealed that achieving a thermal transmittance coefficient below 2.0 using high-grade thermal break aluminum or PVC steel with hollow glass is challenging and generally feasible only with the incorporation of LOW-E glass, which entails significant cost implications. Moreover, considering the roof's relatively minor proportion in the building envelope, the potential for augmenting energy-saving rates through enhanced roofing insulation is relatively constrained, despite its considerable influence on energy consumption and the comfort level of residents on the top floor, underscoring the necessity for efficient roofing insulation [21].

**Scheme 1**

The insulation characteristics and corresponding parameters for the external walls in the specified scheme are comprehensively detailed in Table 5.

Presently, Anhui Province mandates a 65% energy-saving standard for residential buildings. To fulfill this requirement, this study explores a variety of energy-saving design optimization combination schemes for building envelopes. The No. 17 residential building in a district in Lu'an City is chosen as a case study, with the project specifications detailed in Table 4 and the residential layout depicted in Figure 4.

The cost analysis for the external wall insulation utilizing powdered polystyrene granules is meticulously detailed. The pricing of this insulation type is 157 Yuan/m$^2$ translating to 99.6 Yuan/m$^2$ of the building. For the PVC steel low-radiation glass, the cost is 510 Yuan/m$^2$, amounting to 92.8 Yuan/m$^2$. The roof insulation, employing extruded polystyrene, is priced at 121 Yuan/m$^2$, leading to an expense of 22.3 Yuan/m$^2$. Consequently, the total cost for the insulation project per unit area of the building is calculated to be 214.7 Yuan/m$^2$. The results derived from these calculations suggest that achieving the targeted 65% energy-saving standard is not attainable solely through this specific combination of energy-saving insulation systems. Utilizing powdered polystyrene granules with a thickness of 120mm results in an energy-saving rate of merely 63.6%. Furthermore, this thickness introduces potential construction challenges and safety hazards, particularly concerning the risk of detachment.

**Table 4.** Project overview

| **Project Name** | **No. 17 Building in a District in Lu'an City** | **Building Area** | **Above Ground 2533.22 m$^2$, Underground – m$^2$** |
|---|---|---|---|
| Project location | Lu'an City, Anhui Province | Shape coefficient | 0.31 |
| Northward angle | 90 degrees | Building volume | 7619.04 m$^3$ |
| Building shape | Strip-type building, two units, one elevator | Building surface area | 2394.21 m$^2$ |
| Number of floors | 6 | Building height | 18.80m |

**Table 5.** Energy-saving insulation system scheme 1

| External Wall Insulation type | Powdered Polystyrene Granules 120mm, Average Thermal Transmittance Coefficient 0.47 W/(m²·K) |
|---|---|
| Door and window type | Energy-saving door, PVC steel hollow low-radiation glass window, thermal transmittance coefficient 1.8 W/(m²·K) |
| Roof insulation type | Extruded polystyrene insulation 100mm, thermal transmittance coefficient 0.29 |
| Annual electricity | Designed building 37.72KWh/m², reference building 51.31 KWh/m² |
| Energy-saving rate | 63.6% |

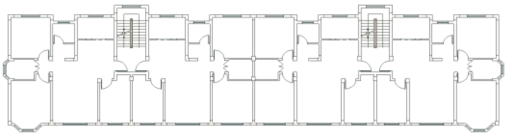

**Figure 4.** Layout of the No. 17 Building in a district in Lu'an City

**Scheme 2**

The insulation characteristics and corresponding parameters for the external walls in the specified scheme are comprehensively detailed in Table 6.

**Table 6.** Energy-saving insulation system scheme 2

| External Wall Insulation Type | Polystyrene Board 80mm, Average Thermal Transmittance Coefficient 0.37 W/(m²·K) |
|---|---|
| Door and window type | Energy-saving door, PVC steel hollow low-radiation glass window, thermal transmittance coefficient 1.8 W/(m²·K) |
| Roof insulation type | Extruded polystyrene insulation 80mm, thermal transmittance coefficient 0.29 |
| Annual electricity | Designed building 36.12KWh/m², reference building 51.31 KWh/m² |
| Energy-saving rate | 64.8% |

Analysis of the cost-effectiveness reveals that the polystyrene board external wall insulation incurs a cost of 129 Yuan/m², equating to an average cost of 81.8 Yuan/m² for the building area. The PVC steel low-radiation glass is priced at 510 Yuan/m², translating to 92.8 Yuan/m² per building area. Roof insulation with extruded polystyrene is valued at 121 Yuan/m², amounting to 22.3 Yuan/m² per building area. The overall insulation project cost per unit building area is calculated at 196.9 Yuan/m². The energy-saving rate of 64.8% closely approaches the 65% target. Adjustments to the shape coefficient, window-to-wall ratio, or the incorporation of external shading on east and west walls could feasibly achieve the 65% energy-saving standard. However, the construction demands associated with an 80mm thick polystyrene board are noteworthy.

**Scheme 3**

The insulation characteristics and corresponding parameters for the external walls in the specified scheme are comprehensively detailed in Table 7.

The analysis reveals that the cost of rigid polyurethane foam for external wall insulation is 207 Yuan/m², which equates to 131.3 Yuan/m² per unit of building area. The cost for PVC steel hollow glass is 510 Yuan/m², leading to 92.8 Yuan/m² per unit of building area. The cost for roof insulation with extruded polystyrene is 108 Yuan/m², amounting to 19.9 Yuan/m² per unit of building area. The total insulation project cost per unit of building area is calculated at 244 Yuan/m². The results demonstrate an energy-saving rate of 65.2%, surpassing the 65% standard and illustrating the practicality of this energy-saving approach.

**Table 7.** Energy-saving insulation system scheme 3

| External Wall Insulation Type | Rigid Polyurethane Foam 60mm, Average Thermal Transmittance Coefficient 0.36 W/(m²·K) |
|---|---|
| Door and window type | Energy-saving door, PVC steel hollow low-radiation glass window, thermal transmittance coefficient 1.8 W/(m²·K) |
| Roof insulation type | Extruded polystyrene insulation 80mm, thermal transmittance coefficient 0.29 |
| Annual electricity consumption | Designed building 35.71KWh/m², reference building 51.31 KWh/m² |
| Energy-saving rate | 65.2% |

**Scheme 4**

The insulation characteristics and corresponding parameters for the external walls in the specified scheme are comprehensively detailed in Table 8.

**Table 8.** Energy-saving insulation system scheme 4

| External Wall Insulation Type | Autoclaved Aerated Concrete 200mm, Powdered Polystyrene Granules 60mm, Average Thermal Transmittance Coefficient 0.36 W/(m²·K) |
|---|---|
| Door and window type | Energy-saving door, PVC steel hollow low-radiation glass window, thermal transmittance coefficient 1.8 W/(m²·K) |
| Roof insulation type | Extruded polystyrene insulation 80mm, thermal transmittance coefficient 0.29 W/(m²·K) |
| Annual electricity consumption | Designed building 35.71KWh/m², reference building 51.31 KWh/m² |
| Energy-saving rate | 65.2% |

The cost analysis revealed that the combination of autoclaved aerated concrete and powdered polystyrene granule insulation for the external walls incurred a cost of 133.3 Yuan/m² per unit of building area. Additionally, PVC steel hollow glass accounted for 510 Yuan/m², equating to 92.8 Yuan/m² per unit of building area. The cost for roof insulation using extruded polystyrene was 108 Yuan/m², amounting to 19.9 Yuan/m² per unit of building area. The total insulation project cost per unit of building area was thus calculated at 246 Yuan/m². The results indicate an energy-saving rate exceeding the 65% standard, confirming the feasibility of the construction approach in this scheme.

A comprehensive comparative analysis was conducted for four distinct building envelope energy-saving combination schemes. The comparison, presented in Table 9, encapsulates the insulation types and their respective parameters for each scheme. The analysis focused on evaluating the energy-saving rate and cost-effectiveness of each scheme, considering the insulation types used in external walls, doors and windows, and roofing.

The economic implications of employing various insulation materials in external wall construction were rigorously analyzed. It was found that for polystyrene board insulation, each incremental increase of 0.1% in the energy-saving rate correlates with a rise in construction costs ranging from 0.2 to 0.65 Yuan/m$^2$. This cost increment is marginally higher than that for powdered polystyrene granules. In contrast, rigid polyurethane foam wall insulation incurs the highest cost increase for the same enhancement in the energy-saving rate, amounting to 1.8 Yuan/m$^2$. Autoclaved aerated concrete walls exhibit a cost increase of approximately 0.7 Yuan/m$^2$ for every 0.1% improvement in the energy-saving rate. Regarding energy-saving doors and windows, the cost escalates by 9.1 Yuan/m$^2$ for thermal break aluminum windows and 5.6 Yuan/m$^2$ for PVC steel windows, per 0.1% increment in energy-saving rate. Roof insulation improvements result in an additional expenditure of 4 Yuan/m$^2$ for each 0.1% increase in the energy-saving rate. This analysis reveals that external wall insulation systems offer the most cost-effective contribution to building envelope energy savings.

**Table 9.** Comparison of four building envelope energy-saving combination schemes

| **Insulation Types and Related Parameters of Each Scheme** | | | | | | |
|---|---|---|---|---|---|---|
| Scheme | External wall insulation type | Door and window type | Roof insulation type | Annual electricity consumption | Energy-saving rate | Cost per unit area |
| Scheme 1 | Powdered polystyrene granules 120mm, average thermal transmittance coefficient 0.47W/(m$^2$·K) | Energy-saving door, PVC steel hollow low-radiation glass window, thermal transmittance coefficient | Extruded polystyrene insulation 100mm, thermal transmittance coefficient | Designed building 37.72Wh/m$^2$, reference building 51.31Wh/m$^2$ | 63.6% | 214.7 Yuan/m$^2$ |
| Scheme 2 | Polystyrene board 80mm, average thermal transmittance coefficient 0.37W/(m$^2$·K) | Energy-saving door, PVC steel hollow low-radiation glass window, thermal transmittance coefficient 1.8W/(m$^2$·K) | Extruded polystyrene insulation 80mm, thermal transmittance coefficient 0.29W/(m$^2$·K) | Designed building 36.12Wh/m$^2$, reference building 51.31Wh/m$^2$ | 64.8% | 196.9 Yuan/m$^2$ |
| Scheme 3 | Rigid polyurethane foam 60mm, average thermal transmittance coefficient 0.36W/(m$^2$·K) | Energy-saving door, PVC steel hollow low-radiation glass window, thermal transmittance coefficient 1.8W/(m$^2$·K) | Extruded polystyrene insulation 80mm, thermal transmittance coefficient 0.29W/(m$^2$·K) | Designed building 35.71Wh/m$^2$, reference building 51.31Wh/m$^2$ | 65.2% | 244 Yuan/m$^2$ |
| Scheme 4 | Autoclaved aerated concrete 200mm, powdered polystyrene granules 60mm, average thermal transmittance | Energy-saving door, PVC steel hollow low-radiation glass window, thermal transmittance coefficient 1.8W/(m$^2$·K) | Extruded polystyrene insulation 80mm, thermal transmittance coefficient 0.29W/(m$^2$·K) | Designed building 35.71Wh/m$^2$, reference building 51.31Wh/m$^2$ | 65.2% | 246 Yuan/m$^2$ |

The study further examined the energy-saving rates associated with different insulation materials and thicknesses. The analysis, derived from Table 9, indicates that polystyrene board insulation of identical thickness provides a superior energy-saving rate compared to powdered polystyrene granules. Rigid polyurethane foam demonstrates an even higher energy-saving effect than polystyrene boards. Moreover, it was observed that increasing the thickness of the insulation layer by 5mm in external walls could enhance the energy-saving rate by 1%-2%. Autoclaved aerated concrete walls also exhibit notable energy-saving efficiency, where a 10mm increase in wall thickness can lead to a 0.3% rise in the energy-saving rate.

The study undertook a comprehensive evaluation of the ecological efficiency associated with various insulation materials. Ecological efficiency was analyzed as the ratio between the reduction of environmental impact and the enhancement of energy efficiency. It was imperative to include the environmental impact of materials during both production and operational phases of buildings. Additionally, the total cost encompassed the energy consumption during the operational phase of building energy use [22]. The analysis highlighted that decreasing the costs of insulation materials could potentially aggravate global warming. Building insulation materials are instrumental in significantly reducing heating and cooling energy demands. A lifecycle perspective was adopted for comparing different types of insulation materials, considering the environmental emissions and energy consumption during their manufacturing, production, transportation, use, and recycling stages [23].

The ecological impact of polystyrene boards was scrutinized, given their petrochemical origins. The production of these materials is energy-intensive, leading to significant emissions of sulfur dioxide and nitrogen oxides, contributing to acid rain and ozone layer degradation. The release of photochemical oxidants such as hydrocarbons from these materials causes ecological damage of varying degrees. Additionally, the production process emits large molecular organic compounds and emissions that lead to environmental pollution. In the event of fire, these materials can release gases detrimental to human respiratory health. Conversely, autoclaved aerated concrete is derived from more sustainable sources, such as brick factory materials and industrial waste like fly ash and coal gangue. This reuse of urban waste concrete exemplifies the principle of recycling waste into valuable resources, thus minimizing the consumption of natural resources and reducing production energy requirements. Such practices alleviate the environmental burden and help maintain ecological balance. Moreover, these materials do not pose health hazards to humans, as their inorganic nature precludes the production of toxic substances, thereby exerting minimal environmental impact [24].

## 4. ANALYSIS OF ENERGY SAVING POTENTIAL IN HOT SUMMER AND COLD WINTER ZONES

The comparative analysis of four distinct building envelope combination schemes has demonstrated that in hot summer and cold winter regions, residences with a smaller shape coefficient can feasibly attain the 65% energy-saving standard. This achievement is possible through the implementation of advanced building envelope energy-saving insulation systems, coupled with high-performance energy-saving windows and sufficient roof insulation. Conversely, for buildings with a larger shape coefficient, reaching the 65% energy-saving standard is achievable through the strategic use of external window shading and a well-considered window-to-wall ratio design.

The analysis further revealed that solely enhancing the insulation performance of the building envelope is a misconception. Merely increasing the limit values of the building envelope to reach a 65% energy-saving rate leads to significant increases in construction costs and presents challenges in construction techniques. These challenges include safety concerns with current external wall insulation boards and longevity issues with insulation systems. To effectively enhance residential energy-saving rates, it is recommended to initially focus on reducing the building's shape coefficient during the architectural design phase. For external wall insulation, a dual-layer insulation approach should be considered, comprising both external wall composite insulation and intrinsic wall insulation. Additionally, for windows that have reached their limit values, the incorporation of movable external shading can contribute to improved overall energy efficiency.

In alignment with Anhui Province's latest 65% residential energy-saving design standard, a case study of a residence in Cuo Town, Anhui, was undertaken. Simulations were conducted using the SVILLE energy-saving calculation software. Figure 5 depicts the building calculation model established by the software for this specific residence.

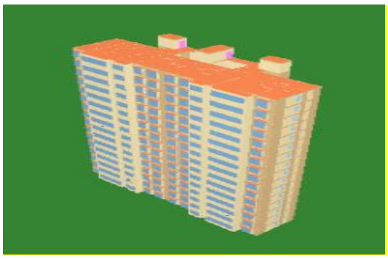

**Figure 5.** Residential building calculation model

A residential building located in Cuo Town, Anhui Province, served as the subject of this study. The building's above-ground area spans 6728m², comprising 17 floors with a total height of 50.2 meters. It possesses a building energy-saving calculation volume of 19848$m^3$ and an external surface area of 7575m². With a shape coefficient of 0.38, this building does not comply with the "Anhui Province Residential Building Energy Saving Design Standard" DB34/1466-2019, clause 4.2.1. The energy-saving design of its envelope incorporates the following components:

• Roof construction: It consists of a layering of polymer mortar (20mm), a low-strength mortar separation layer (10mm), B1 grade extruded polystyrene board (80mm), premixed mortar (20mm), lightweight aggregate concrete (30mm), and reinforced concrete (120mm).

• External wall: This includes flexible water-resistant putty (2mm), anti-crack mortar with mesh (8mm), homogeneous fireproof insulation board (50mm), special adhesive (6mm), polymer waterproof cement mortar (15mm), coal gangue hollow brick (200mm), and a 1:3 cement mortar (9mm).

• Energy-saving doors and windows: The building features metal thermal break profiles with a height of 26mm (K=2.8) consisting of 6 Low-E+12 air+6 layers (K=1.8), achieving a thermal transmittance coefficient of 2.400W/$m^2$.K and a solar heat gain coefficient of 0.400. The aluminum alloy casement windows are composed of 5+19Ar (blinds)+5 double silver high-transparency Low-E layers, resulting in a thermal transmittance coefficient of 2.000W/$m^2$.K and a solar heat gain coefficient of 0.522.

Upon implementing intermediate shading in the building's energy-saving design, dynamic balancing calculations yielded an energy-saving rate of 68%. This rate is tabulated in Table 10, which presents the annual electricity consumption and the corresponding energy-saving rate for both the designed and reference buildings.

**Table 10.** Energy-saving rate of designed building

| Calculation Results | Designed Building | Reference Building | Energy-Saving Rate |
|---|---|---|---|
| Annual electricity consumption (KWh/$m^2$) | 28.76 | 31.57 | 68.1% |

Upon setting parameters in accordance with established standards and employing the SVILLE building energy-saving software for simulation, insightful conclusions regarding the potential for energy savings in regions experiencing hot summers and cold winters were drawn:

• It has been observed that achieving a 65% energy-saving standard in residential buildings is heavily influenced by the energy-saving insulation system of the building envelope. To surpass a 65% energy-saving standard, enhancement of air conditioning and heating equipment efficiency is essential. For instance, achieving energy-saving rates like 75% or higher, such as zero-energy standards, necessitates the utilization of high-efficiency air conditioning or heating systems. This requirement, however, results in elevated investment costs.

• Analysis indicates that heat transfer through external walls decreases with an increase in wall thickness. The optimal scenario involves minimizing wall heat transfer to zero. Despite continuous developments in external wall energy-saving insulation materials and construction techniques, limitations exist in the possible increase of insulation thickness and the reduction of external walls' average thermal transmittance coefficient. Thus, architects are advised to consider including an air gap alongside the insulation layer in external walls to further decrease the thermal transmittance coefficient.

• Improvements in external window performance can effectively elevate the energy-saving rate. However, given the current technological capabilities and manufacturing processes in China, enhancing the energy-saving rate beyond 65% through improved window performance presents limited potential, particularly in hot summer and cold winter regions. The habitual opening of windows by residents in these areas significantly reduces the energy-saving effect of low-E glass. Consequently, achieving the optimal energy-saving rate becomes challenging, coupled with the high costs associated with extensive low-E glass installations. Design strategies incorporating middle-placed shading are suggested as viable alternatives.

• Thermal bridging in columns and beams is identified as a crucial element for boosting residential energy-saving rates [25]. Case study calculations revealed that replacing the insulation material in thermal bridge columns and beams from powdered polystyrene granule mortar (40mm thick) to rigid foam polyurethane board (60mm thick) could elevate the energy-saving rate by 1-2%. Hence, attaining a 65% energy-saving standard necessitates enhancing the thermal insulation of residential thermal bridge columns and beams.

- It has been identified that surpassing the 65% energy-saving threshold significantly depends on the architectural design. Key factors such as the shape coefficient and the window-to-wall ratio substantially influence energy consumption. Exceeding the standard shape coefficient prevents achieving above 65% energy-saving solely through enhancing the building envelope's thermal insulation. Design strategies should include increasing the building volume, length, and depth, with minimal variations in form and a focus on maintaining regularity. Additionally, careful planning of the number of floors and floor heights is essential.
- The size of windows in a building plays a dual role, ensuring adequate daylight and lighting, and facilitating natural ventilation. Insufficient window areas fail to meet daylighting and lighting requirements. The window-to-wall area ratio needs to balance insulation needs and solar heat gains, thus establishing the correct window size to meet indoor ventilation and lighting standards while maintaining environmental comfort. In hot summer and cold winter regions, controlling the east-west window-to-wall ratio is crucial. Design should minimize or reduce the size of east and west windows where lighting is not necessary. Natural ventilation, especially during transitional seasons and comfortable nighttime temperatures, is pivotal for energy efficiency in these regions, balancing air tightness with the need for natural ventilation.
- In the context of hot summer and cold winter regions, reaching a 75% energy-saving standard in residences significantly elevates costs and introduces technical challenges, including safety and durability concerns associated with external wall composite insulation boards. Since residences are often delivered bare-shell, controlling the energy efficiency of installed equipment becomes a challenge. Thus, achieving over 65% energy-saving in residences necessitates comprehensive finished decoration to manage equipment energy efficiency effectively.

Regarding heating and cooling systems, the utilization of natural energy sources, such as geothermal heating, presents a viable solution. Ground source heat pump technology, being approximately 40% more efficient than conventional air conditioning systems, offers substantial energy and cost savings. The stable temperatures of the ground contribute to the system's reliable and efficient operation, enhancing both effectiveness and economy. Emissions from ground source heat pumps are significantly lower than those from air source heat pumps and electric heating, aligning with national objectives for energy conservation and emission reduction.

## 5. CONCLUSIONS AND FUTURE PERSPECTIVES

This research establishes that a 65% energy-saving standard in hot summer and cold winter zones can significantly enhance comfort levels. However, there exists a disparity in the economic development of cities within these regions, necessitating a nuanced approach to implementing higher energy-saving standards in residential buildings. The adoption of near-zero energy consumption residences, with standards exceeding 75%, mandates a thorough analysis of regional climatic features and economic conditions, including the housing affordability for local populations. The evolving standards in building energy conservation highlight the potential for employing composite internal and external insulation technologies in residential buildings within these zones. Utilizing thermosetting polystyrene foam boards for external insulation, paired with inorganic insulation mortars for internal use, can be effective. External wall insulation and thermal technologies, pivotal in these regions, require relentless innovation and advancement to meet escalating energy-saving objectives.

There is a pressing need for continued research and innovation in key insulation material technologies, as well as comprehensive studies on thermal insulation techniques. The development of lightweight, energy-saving composite wall panels using nanotechnology is critical for enhancing ecological environments, safeguarding land resources, and promoting their rational utilization [26]. Exploring the integration of photovoltaic building technology with insulation and decorative systems, and the application of adjustable water curtain enclosures for external envelope cooling, represent promising directions for future research and development. These approaches can address the energy-saving demands of ultra-low energy consumption buildings in hot summer and cold winter regions, thereby fostering the efficient advancement of energy-saving technologies in the construction industry.

This study emphasizes that the advancement of near-zero energy consumption residences must prioritize energy conservation. It has been observed that numerous green residences, while achieving near-zero emission standards and receiving commendations, predominantly rely on extensive new energy capacities to offset the energy demands of the building itself. This approach, however, does not align with environmental sustainability principles. It is imperative that the development of near-zero energy consumption residences adhere to economic practicality, aligning with China's national context. Passive energy-saving technology should be the cornerstone of this development. Innovations in architectural design methods that reduce reliance on conventional energy sources and the integration of renewable energy systems are crucial for attaining the goal of near-zero energy consumption [15]. Furthermore, the existing residential building stock, being substantially larger than new developments, necessitates a strategic focus on energy retrofitting and optimization for the forthcoming two decades. These measures are projected to have a significant impact on reducing environmental pollution [27].

This research, centered on urban areas within the Anhui region, underscores that climatic variances between different cities within each climate zone necessitate tailored analyses. Each engineering project should be evaluated based on its unique environmental and climatic conditions to ensure the most effective and appropriate energy-saving solutions are implemented.

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