



# Research on the Implementation Path of Wall Insulation Suitability Technology for Urban Renewal under the Low-Carbon Concept: A Case Study of a Nearly Zero Energy Consumption Residential Building in Hefei City

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**Abstract.** This article focuses on Nearly Zero Energy Consumption Residential Building. Using software such as Green Building SWIER, a model was established, and the simulation results under different operating conditions were compared and analyzed. The results show that when increasing the thickness of the insulation layer generally reduces energy consumption by improving thermal performance. Vacuum insulation panels (VIPs) reduce energy consumption for external wall insulation from 44.6 kWh/m<sup>2</sup> to 43.14 kWh/m<sup>2</sup> when the thickness increases from 20mm to 30mm. Similarly, rock wool boards show a reduction from 55.8 kWh/m<sup>2</sup> to 53.58 kWh/m<sup>2</sup> at the same thickness increase. VIPs are more energy-efficient at the same thickness compared to rock wool boards. Additionally, for VIPs, internal insulation consumes slightly less energy (42.11 kWh/m<sup>2</sup>) than external insulation (43.14 kWh/m<sup>2</sup>) at 30mm thickness. For rock wool, internal insulation is also more efficient than external insulation at both 20mm and 30mm thicknesses.

**Keywords:** Nearly Zero Energy, Consumption, Insulation Materials, Energy Efficiency.

## 1 Introduction

In the context of global warming and the urgent depletion of global energy reserves, the high energy consumption development model of the construction industry is becoming increasingly unsustainable<sup>[1]</sup>. "Carbon neutrality" and "carbon peak" have become major constraints for future development in China. Building energy conservation is no longer just a catchy slogan. To reduce carbon emissions and lower building energy consumption, the promotion of building energy-saving technologies is imperative. Among these technologies, wall insulation has attracted significant attention from

researchers worldwide due to its unique and excellent characteristics in building energy conservation. Bojic<sup>[2]</sup> studied the impact of different insulation methods on the annual cooling load of high-rise buildings in Hong Kong. As the thickness of the insulation layer increased, the annual cooling load decreased, with internal insulation proving more energy-efficient than sandwich insulation, and sandwich insulation more effective than external insulation. Masson<sup>[3]</sup> and others conducted a software analysis on office buildings in Botswana, Africa, investigating the annual cooling and heating loads of buildings under six different air conditioning set temperatures. The results showed the existence of a critical air conditioning set temperature: when the set temperature exceeded this value, increasing external wall insulation reduced the annual heating load. Kossecka<sup>[4]</sup> and colleagues calculated the annual heating and cooling loads of buildings in six typical climatic regions of the United States, finding that buildings with internal insulation consumed more energy annually than those with external insulation.

Since the early 1990s, with strong government support, the development of Zero Energy Buildings (ZEB) has been rapidly growing in China and is seen as an important trend for the future of the construction industry.

Wang Houhua<sup>[5]</sup> and others used energy consumption simulation software to analyze the impact of the thermal performance of various components of the external wall enclosure structure on building energy consumption. Wei Yannan<sup>[6]</sup> and others proposed using a comprehensive thermal stability coefficient method to calculate the thermal resistance index and thermal stability insulation index when evaluating the surface temperature under summer heat conditions. These can serve as indicators for assessing the insulation performance of external enclosure structures in hot summer and cold winter areas. Yu Jinghua<sup>[7]</sup> and others proposed a comprehensive evaluation system for the thermal energy performance of building enclosures, including the thermal conductivity coefficients and solar heat gain coefficients, to assess the overall thermal performance of residential building enclosures in regions with hot summers and cold winters.

In the past decade, Hefei has made great progress, with its urban landscape undergoing significant changes, economic output continuously growing, and population surging. The energy consumption of residential buildings has naturally become one of the key issues under observation<sup>[8]</sup>. This paper takes a residential building in Hefei, located in a hot summer and cold winter region, as an example to explore the design of near-zero energy buildings suitable for such climates.

## 2 Theoretical Analysis

### 2.1 Calculation of Building Thermal Parameters

#### 2.1.1 Thermal Transmittance Coefficient of Exterior Wall

The thermal transmittance coefficient of exterior walls plays a critical role in determining a building's energy consumption and the stability of its indoor thermal environment. This coefficient quantifies the amount of heat transferred through a unit area of the wall per unit time when there is a temperature difference of 1K (or 1°C) between the indoor and outdoor environments under steady-state conditions. It is influenced by several factors, including the thermal conductivity of the building materials, the overall

thickness of the wall structure, the arrangement and combination of different material layers within the wall, and the presence of thermal bridges. A lower thermal transmittance coefficient indicates superior insulation performance, meaning less heat is lost through the wall, which directly contributes to reduced energy consumption and more stable indoor temperatures. In the design of energy-efficient buildings, minimizing the thermal transmittance coefficient of exterior walls is a key strategy for improving overall energy performance and achieving sustainability goals.

The basic calculation formula for the thermal transmittance coefficient of exterior walls is:

$$K = \frac{1}{R_0} = \frac{1}{R_i + R + R_e} = \frac{1}{R_i + \frac{\delta}{\lambda} + R_e} \quad (1)$$

$K$  is the Exterior Wall Thermal Transmittance Coefficient,  $W/(m^2 \cdot K)$ .

$R_i, R_e$  is the Thermal Resistance of Inner and Outer Surfaces,  $m^2 \cdot K/W$ .

$R$  is the Thermal Resistance of Insulation Layer,  $m^2 \cdot K/W$ .

$\delta$  is the Thickness of the Insulation Layer,  $m$ .

$\lambda$  is the Thermal Conductivity of Insulation Material,  $W/(m \cdot K)$ .

Taking the second derivative of equation (1), we obtain the relationship between the increase in the heat transfer coefficient through the wall and the change in the insulation layer thickness.

Whether through building energy consumption simulation analysis or the derivation of the heat transfer coefficient principle for exterior walls, it is evident that increasing the thickness of the insulation layer is an effective energy-saving measure. However, after adding insulation, as the thickness increases, the energy-saving contribution per unit thickness becomes smaller. Therefore, it is important to determine the appropriate insulation thickness while also considering factors such as material, construction, maintenance, and economic feasibility.

### 2.1.2 Exterior Window (Curtain Wall)

The exterior windows (or curtain walls) of a building are the parts of the envelope structure most susceptible to external environmental influences. This is mainly because their thermal conductivity is usually higher, and their insulation capacity is not as strong as that of the roof or exterior walls. The operability of exterior windows requires them to have a certain level of air tightness, while changes in external wind pressure can quickly affect the indoor environment through the windows, potentially increasing the demand for cooling or heating.

### 2.1.3 Thermal Transmittance Coefficient of Exterior Windows

The heat transfer coefficient (also known as the U-value) of exterior windows has a significant impact on a building's energy consumption. The insulation performance of a window can be assessed by its heat transfer coefficient, which indicates the amount of heat transferred through the window per unit area over a given time (measured in

$\text{W}/\text{m}^2\cdot\text{K}$ ). The lower the U-value, the better the insulation performance of the window; conversely, a higher U-value means poorer insulation.

When the U-value of exterior windows is high, the window will more rapidly transfer indoor heat to the outside during winter, increasing the load on the heating system and raising energy consumption. Similarly, in summer, the window will allow more heat from the outside to enter the building, increasing the cooling system's workload and also raising energy consumption. Therefore, reducing the heat transfer coefficient of exterior windows is a key strategy for improving building energy efficiency and reducing energy consumption.

#### 2.1.4 Solar Heat Gain Coefficient

According to the definition in the "Thermal design code for civil building" (GB 50176)[9], the Solar Heat Gain Coefficient (SHGC) is defined as the ratio of the amount of solar heat entering a building through a transparent building envelope (such as windows) under solar radiation, to the total amount of solar radiation received by the outer surface of the envelope. This coefficient is used to measure the thermal performance of windows under solar radiation and is an important indicator for evaluating building energy efficiency. The corresponding calculation formula is as follows:

$$SHHC = \frac{Q_s \cdot (1 - R_f)}{Q_I} \quad (2)$$

In the formula:

$Q_s$  is The solar radiation energy entering the interior through the window,  $\text{W}/\text{m}^2$ .

$R_f$  is the reflectance of the window, which is the ratio of the solar radiation energy reflected back to the outside by the window to the incident solar radiation energy.

$Q_I$  is the solar radiation energy incident on the outer surface of the window,  $\text{W}/\text{m}^2$ .

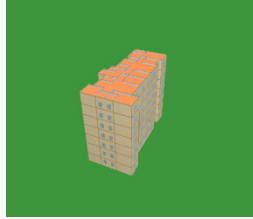
In practical applications, the Solar Heat Gain Coefficient (SHGC) is typically determined by the manufacturer through testing based on the window's construction, materials, glass type, and coatings, among other factors. It may vary depending on the specific configuration and conditions of the window. In building design and energy analysis, the SHGC value is commonly used to predict and calculate the overall energy consumption and thermal comfort of a building.

## 2.2 Model Establishment

The reference building selected is a residential building in Hefei City. The building runs from east to west, with a north-facing orientation. The building has a total floor area of  $1968\text{m}^2$  above ground and  $0\text{m}^2$  below ground, with a total of 7 floors. The total building height is  $20.7\text{m}$ , and the building volume is  $5821.74\text{m}^3$ . The external surface area of the building is  $2105.2\text{m}^2$ . The model of the building is shown in Fig 1.

A typical seven-story residential building model was constructed, and the detailed information and parameters of the reference building were input according to the "Standard for Energy Efficiency Design of Residential Buildings" DB34/1466-2019<sup>[10]</sup>.

The main parameters of the building envelope are shown in Table 1, which include the thermal transmittance coefficients of the exterior walls, partition walls, interior walls, and other components, as well as the overall thermal transmittance coefficient and the overall shading coefficient of the exterior windows.



**Fig. 1.** BECS Model Diagram of Residential Buildings.

**Table 1.** Main Parameters of Building Envelope.

Component Name	Heat Transfer Coefficient
Roof $K/W \cdot (m^2 \cdot K)^{-1}$	$\leq 0.6$
Exterior Wall $K/W \cdot (m^2 \cdot K)^{-1}$	$\leq 0.9$
Partition Wall $K/W \cdot (m^2 \cdot K)^{-1}$	$\leq 1.8$
Floor Slab $K/W \cdot (m^2 \cdot K)^{-1}$	$\leq 1.1$
Partition Wall $K/W \cdot (m^2 \cdot K)^{-1}$	$\leq 1.8$
Overall Heat Transfer Coefficient of Windows $K/W \cdot (m^2 \cdot K)^{-1}$	$\leq 2.5$
Overall Solar Heat Gain Coefficient of Windows $S_w$	$\leq 0.4$

### 3 Software Comparison

#### 3.1 Introduction to BECS Software

BECS is a computational analysis tool designed to assist in building energy efficiency design<sup>[11]</sup>. It is built on the AutoCAD platform and utilizes 3D modeling technology. The software has the ability to directly read and import graphic data generated by popular architectural design software, eliminating the need for re-entering data and significantly reducing the workload required to create an energy-efficient thermal model. This feature reflects the integration of architectural design with energy efficiency design principles. BECS adheres to national and local energy efficiency standards and specific implementation guidelines, making it suitable for energy efficiency design, review, and energy consumption evaluation tasks for residential and public buildings across the country.

The data analysis in this paper is conducted using the energy consumption calculation software BES12024, which is based on the CAD platform and integrates the DOE2 core. BES12024 is a software tool that supports building energy efficiency design, highly integrated with building energy models, and capable of accurately and rapidly calculating dynamic ideal loads. The software fully complies with the requirements for energy efficiency rate calculation and overall building energy consumption evaluation as outlined in the "Building Energy Efficiency Labeling Technical Standard" and the "Green Building Evaluation Standard."

### 3.2 BES1 Calculation Principles

The calculation principles of BES12024 are based on detailed building energy simulations<sup>[12]</sup>, which comprehensively consider the thermodynamic processes of the building, external climate conditions, solar radiation, the heat transfer characteristics of building envelopes (such as walls, roofs, windows, etc.), and the operational modes of internal HVAC (Heating, Ventilation, and Air Conditioning) systems to predict and analyze the building's overall energy consumption performance. The software uses precise heat transfer equations, radiation and lighting calculation models, as well as air flow and temperature-humidity change models to simulate the energy demand of the building across different seasons and time periods. It is capable of evaluating the building's energy usage efficiency and providing energy optimization recommendations based on various design options and system configurations. Additionally, BES12024 supports dynamic analysis of both internal and external factors affecting the building, such as usage patterns, equipment loads, and climate variations.

## 4 Software Simulation and Analysis

### 4.1 Simulation Conditions

The following analysis examines the variations in building energy consumption under different operating conditions, with the same key parameter values selected for the external walls, roof, and windows of the residential building. The aim is to identify which wall insulation technology and material combination is the most energy-efficient. Regarding the external wall envelope structure, the following components of the building model are considered: external wall (filled wall) structure 1, thermal bridge structure 1, thermal bridge column structure 1, and thermal lift structure 1, along with the material usage for each. Building energy consumption is calculated using the Swerve energy consumption software.

(1) Same insulation technology, same insulation material, but different thicknesses. The specific operating conditions are shown in Table 2.

**Table 2.** Table of working conditions for different thicknesses.

Operating conditions	Thermal insulation technology	thermal insulation material	Thick insulation (mm)
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1	Exterior wall insulation	Vacuum insulation panels for construction	20/30
2	Insulation of the exterior walls	Vacuum insulation panels for construction	20/30
3	Exterior wall insulation	Rock wool board	20/30
4	Insulation of the exterior walls	Rock wool board	20/30

(2) The same insulation material, the same thickness of the insulation material, different external wall insulation technology.

The specific working conditions are shown in Table 3.

**Table 3.** Table of working conditions for different insulation technologies.

Operating conditions	thermal insulation material	Thick insulation (mm)	Thermal insulation technology
5	Vacuum insulation panels for construction	20	Exterior wall external insulation/internal insulation
6	Vacuum insulation panels for construction	30	Exterior wall external insulation/internal insulation
7	Rock wool board	20	Exterior wall external insulation/internal insulation
8	Rock wool board	30	Exterior wall external insulation/internal insulation

(3) The same external wall insulation technology, the same thickness, different insulation materials. The specific working conditions are shown in Table 4.

**Table 4.** Table of working conditions of different insulation materials.

Operating conditions	Thermal insulation technology	Thick insulation (mm)	thermal insulation materia
9	Exterior wall insulation	20	Vacuum insulation panels/rock wool panels for construction
10	Exterior wall insulation	30	Vacuum insulation panels/rock wool panels for construction
11	Insulation of the exterior walls	20	Vacuum insulation panels/rock wool panels for construction
12	Insulation of the exterior walls	30	Vacuum insulation panels/rock wool panels for construction

On the basis of the above working conditions, the energy consumption corresponding to each situation is calculated separately by setting it in the engineering structure.

### 4.2 Simulated Operating Condition Analysis

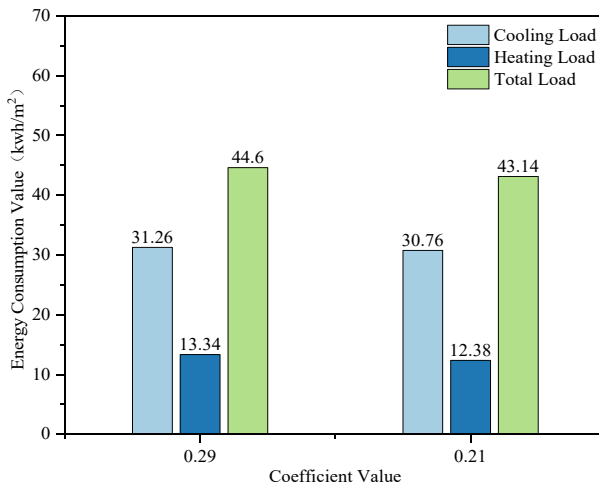
(1) Firstly, the energy consumption values of the first four working conditions are summarized, as shown in Table 5. The external wall insulation method is adopted, the wall insulation material is used 20 thick and 30 thick building vacuum insulation board materials respectively, and the vacuum insulation board insulation materials used for buildings are replaced with 20 thick and 30 thick rock wool board insulation materials, and the energy consumption value is compared.

**Table 5.** Energy meters of different thicknesses.

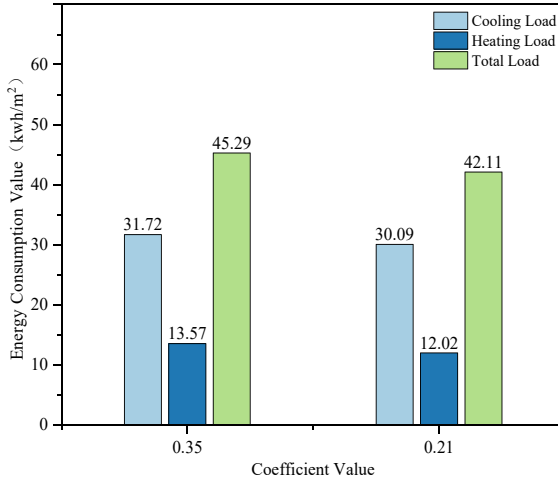
Operating conditions	Energy consumption		
	Cooling consumption (kwh/m <sup>2</sup> )	Heat consumption (kwh/m <sup>2</sup> )	Total (kwh/m <sup>2</sup> )
1	31.26/30.76	13.34/12.38	44.6/43.14
2	31.72/30.09	13.57/12.02	45.29/42.11
3	36.01/35.24	19.79/18.34	55.8/53.58
4	33.81/33.15	18.2/16.94	52.01/50.09

For the above working conditions, Case 1 as shown in Figure 2:

- a: 20 thick Exterior wall heat transfer coefficient: 0.29;
  - b: 30 thick Exterior wall heat transfer coefficient: 0.21;
- Case 2 is shown in Figure 3:
- a: 20 thick Exterior wall heat transfer coefficient: 0.35;
  - b: 30 thick Exterior wall heat transfer coefficient: 0.21;



**Fig. 2.** Energy consumption diagram of external wall insulation vacuum insulation panel



**Fig. 3.** Energy consumption table of vacuum insulation panel for external wall insulation.

Case 3 is shown in Figure 4:

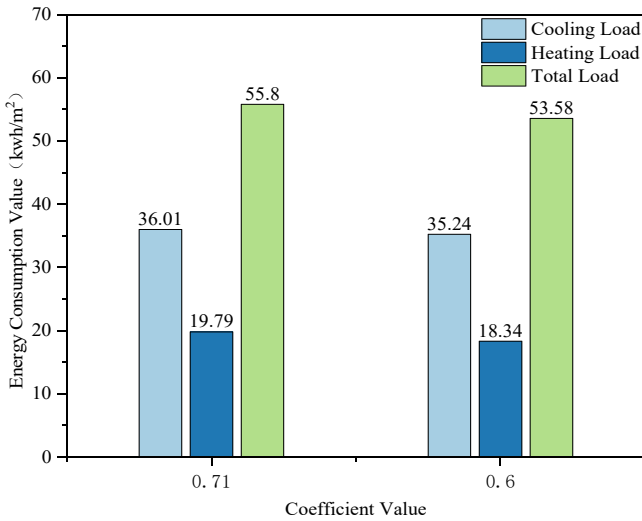
a: 20 thick Exterior wall heat transfer coefficient: 0.71;

b: 30 thick Exterior wall heat transfer coefficient: 0.6;

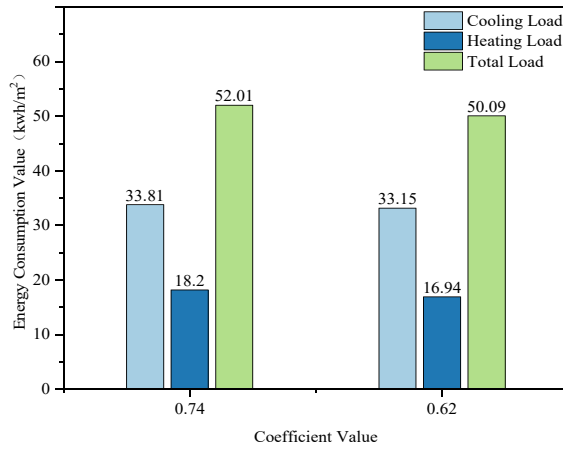
Case 4 is shown in Figure 5:

a: 20 thick Exterior wall heat transfer coefficient: 0.74;

b: 30 thick Exterior wall heat transfer coefficient: 0.62;



**Fig. 4.** Energy consumption table of external wall insulation rock wool board.



**Fig. 5.** Energy consumption diagram of thermal insulation rock wool board in external wall.

Combined with the above analysis, for the same insulation technology, whether it is the external wall insulation technology or the external wall internal insulation technology, when the same insulation material is used, the layer thickness of the insulation material is increased, and the heat transfer coefficient of the external wall becomes correspondingly smaller, and the energy consumption value will be reduced at this time.

(2) Summarize the energy consumption values of the four working conditions, as shown in Table 6.

**Table 6.** Energy consumption table of thermal insulation rock wool board in external wall.

Operating conditions	Energy consumption		
	Cooling consumption (kwh/m <sup>2</sup> )	Heat consumption (kwh/m <sup>2</sup> )	Total (kwh/m <sup>2</sup> )
5	31.26/31.72	13.34/13.57	44.6/45.29
6	30.76/30.09	12.38/12.02	43.14/42.11
7	36.01/33.81	19.79/18.2	55.8/52.01
8	35.24/33.15	18.34/16.94	53.58/50.09

For case 5 above (2), as shown in and Figure 6:

- a: Exterior wall insulation;
  - b: Insulation of the exterior walls;
- Case 6 is shown in and Figure 7:
- a: Exterior wall insulation;
  - b: Insulation of the exterior walls;

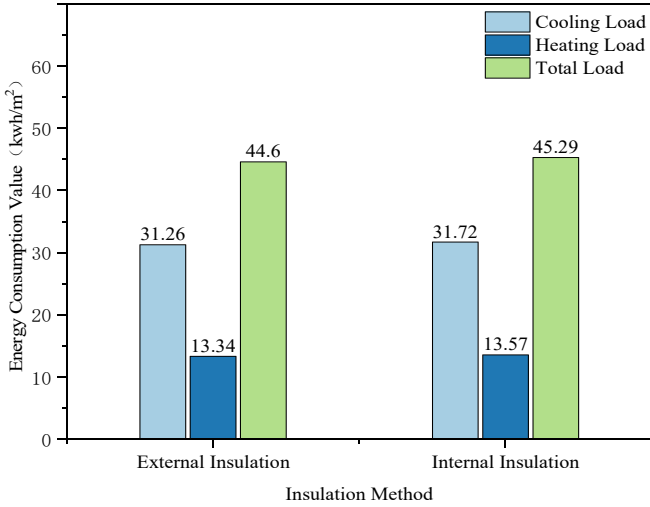


Fig. 6. Energy consumption diagram of 20 thickness vacuum insulation panel for

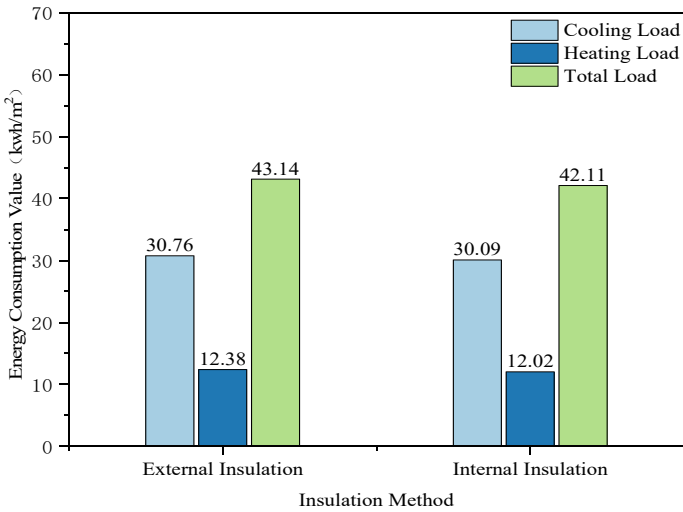


Fig. 7. Energy consumption diagram of 30 thick vacuum insulation panel for construction.

Case 7 is shown in and Figure 8:

- a: External wall insulation;
- b: Insulation of external walls;

Case 8 is shown in and Figure 9:

- a: External Wall Insulation;
- b: Internal Wall Insulation;

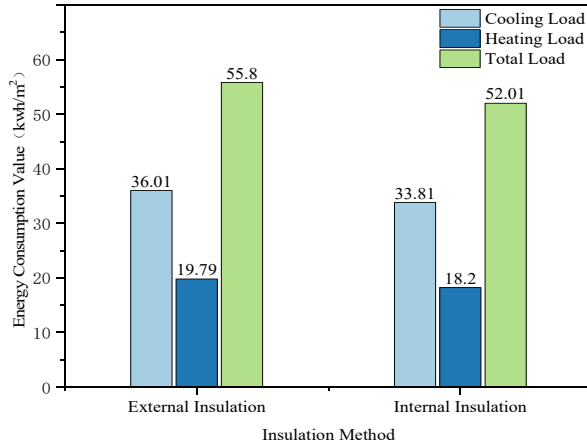


Fig. 8. Energy consumption diagram of 20 thickness of rock wool board.

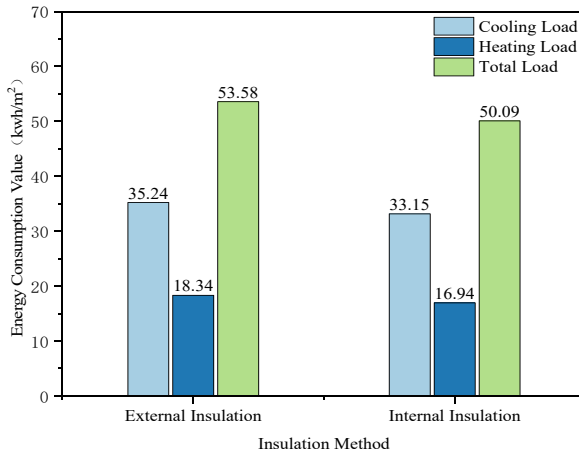


Fig. 9. Energy Consumption Diagram of 30mm Rock Wool Board.

Based on the above analysis, it can be concluded that when using the same insulation material and thickness, but different external wall insulation technologies, the energy consumption values for indoor spaces using building-grade vacuum insulation panels are as follows: with 20 mm thick external and internal insulation, the energy consumption values are 44.6 kWh/m<sup>2</sup> and 45.29 kWh/m<sup>2</sup>, respectively; with 30 mm thick external and internal insulation, the energy consumption values are 43.14 kWh/m<sup>2</sup> and 42.11 kWh/m<sup>2</sup>, respectively. When using rock wool board insulation, the energy consumption values for indoor spaces with 20 mm thick external and internal insulation are 55.8 kWh/m<sup>2</sup> and 52.01 kWh/m<sup>2</sup>, respectively; with 30 mm thick external and internal insulation, the energy consumption values are 53.58 kWh/m<sup>2</sup> and 50.09 kWh/m<sup>2</sup>, respectively.

For the building-grade vacuum insulation panels, the energy consumption of the indoor space with 20 mm thick external insulation is lower than that with internal insulation, while with 30 mm thick external insulation, the energy consumption is higher than with internal insulation. When selecting the thickness for this type of insulation material, there is no absolute difference in energy consumption between external insulation technologies. There is no insulation technology that is definitively more energy-efficient than the other.

For rock wool board insulation, with the same thickness, the energy consumption of the indoor space with external wall insulation is always higher than that with internal wall insulation, indicating that the internal wall insulation method is more energy-efficient.

(3)A summary of the energy consumption values for the four conditions is shown in Table 7.

**Table 7.** Energy Consumption of Different Insulation Materials.

Operating Conditions	Energy consumption value		
	Cooling consumption /kwh·m <sup>2</sup>	Heat consumption /kwh·m <sup>2</sup>	
9	31.26/36.01	13.34/19.79	44.6/55.8
10	30.76/35.24	12.38/18.34	43.14/53.58
11	31.72/33.81	13.57/18.2	45.29/52.01
12	30.09/33.15	42.11/16.94	53.58/50.09

For the above (3), Case 9 as shown in Figure 10:

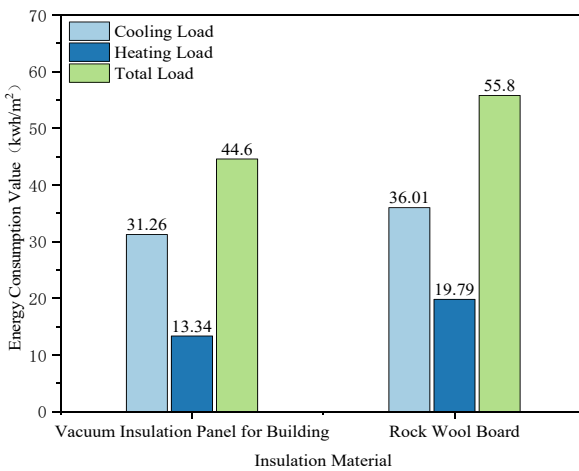
a: Vacuum Insulation Panel for Buildings;

b: Rock Wool Board;

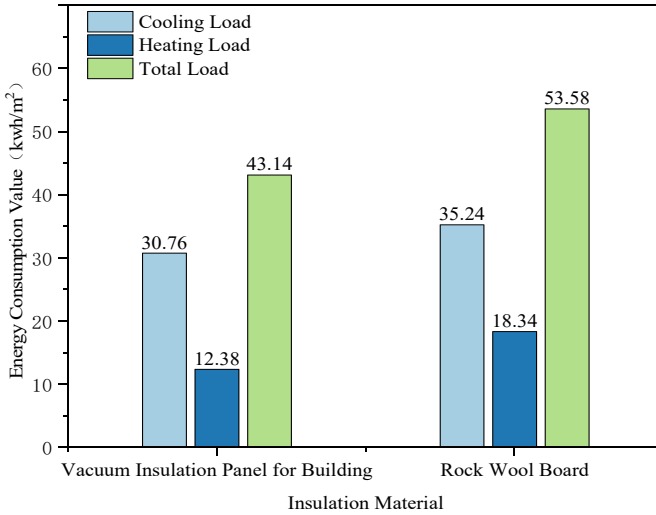
Case 10 as shown in Figure 11:

a: Vacuum Insulation Panel for Buildings

b: Rock Wool Board



**Fig. 10.** Energy Consumption Diagram of 20mm External Insulation Technology.



**Fig. 11.** Energy Consumption Diagram of 30mm External Insulation Technology.

Case 11 as shown in Figure 12:

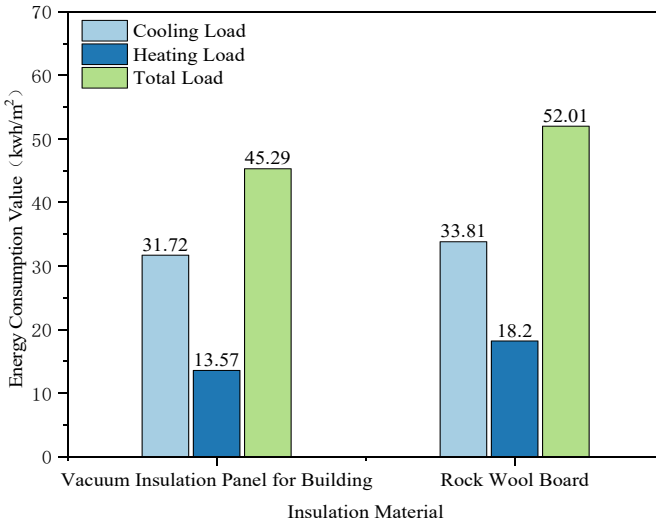
a: Vacuum Insulation Panel for Buildings;

b: Rock Wool Board;

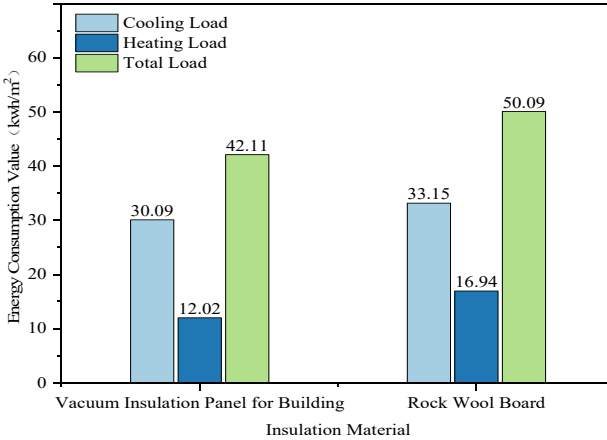
Case 12 as shown in and Figure 13:

a: Vacuum Insulation Panel for Buildings;

b: Rock Wool Board;



**Fig. 12.** Energy Consumption Diagram of 20mm Internal Insulation Technology.



**Fig. 13.** Energy Consumption Diagram of 30mm Internal Insulation Technology.

Based on the above analysis, the energy consumption differences are examined for the same external wall insulation technology using different materials and the same thickness. When using external wall insulation technology, the indoor energy consumption with 20 mm thick building-grade vacuum insulation panels is reduced by 11.2 kWh/m<sup>2</sup> compared to 20 mm thick rock wool board insulation. Similarly, with 30 mm thick external insulation, the indoor energy consumption using building-grade vacuum insulation panels is reduced by 10.44 kWh/m<sup>2</sup> compared to using 30 mm thick rock wool board insulation.

When using internal wall insulation technology, the indoor energy consumption with 20 mm thick building-grade vacuum insulation panels is reduced by 6.72 kWh/m<sup>2</sup> compared to 20 mm thick rock wool board insulation. With 30 mm thick internal insulation, the indoor energy consumption using building-grade vacuum insulation panels is reduced by 7.98 kWh/m<sup>2</sup> compared to using 30 mm thick rock wool board insulation.

In conclusion, for the same external wall insulation technology and thickness, the indoor energy consumption with building-grade vacuum insulation panels is lower than that with rock wool board insulation.

## 5 Conclusion

Based on the above analysis the conclusion is drawn that the same external wall insulation technology and the same insulation material, increasing the thickness of the insulation layer generally leads to a reduction in energy consumption. Increasing the thickness of the insulation material improves the thermal insulation capacity of the wall, thus reducing energy consumption. When different insulation technologies and materials are used, increasing the thickness of the insulation layer will reduce the thermal conductivity of the external wall, leading to a corresponding decrease in energy consumption. For vacuum insulation panels used in buildings, the energy consumption of external wall insulation technology depends on the thickness. The energy consumption

values of external wall insulation technologies vary with the thickness of the vacuum insulation panel material. Therefore, thickness selection is crucial when using vacuum insulation panels for external wall insulation. For rock wool board materials, when the same thickness is selected, the energy consumption value of internal wall insulation is generally lower than that of external wall insulation. This suggests that internal insulation may be a more suitable option when using rock wool board materials.

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