Reduction in Carbon Dioxide Emission and Energy Saving Obtained by Renovation of Building Envelope of Existing Residential Buildings

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ABSTRACT

Reducing energy consumption and carbon dioxide (CO₂) emissions in the construction industry is integral to solving environmental issues, which affect the whole of society and have become increasingly prominent. We selected a residential dwelling from the many buildings in southern Jiangsu Province, China, which consume and emit extremely large amounts of energy and CO₂, respectively, and assessed various energy-saving renovation schemes for improving the thermal envelope. First, we used energy consumption simulation software (BESI) to individually analyze the energy performance of each scheme. Then, setting the static payback period as the evaluation index, we applied the orthogonal test method to determine the economic efficiency of different combinations of schemes. Finally, we identified the optimal combination for conserving energy and decreasing CO₂ emissions as 120-mm-thick expanded polystyrene insulating board for both the exterior wall and the roof, and 5-mm-thick triple-silver low-emissivity glass and 5-mm-thick normal glass separated by 12 mm of air for the exterior windows, which resulted in a cooling capacity, heating consumption, total building energy consumption, static payback period, and dynamic payback period of 28.37 kWh m⁻² a⁻¹, 4.22 kWh m⁻² a⁻¹, 32.59 kWh m⁻² a⁻¹, 13.76 years, and 22.84 years, respectively, as well as an annual reduction in CO₂, sulfur dioxide (SO₂), and nitrogen oxides (NO_x) emissions of 86.01 tons, 2.59 tons, and 1.29 tons, respectively.

Keywords: Building envelope, Energy-saving renovation, Carbon dioxide emission, Energy consumption simulation, Economical and environmental benefit

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1 INTRODUCTION

With the rapid development of social economy, the increasing scale of urbanization and the improvement of people's requirements for living comfort, there is an increasing demand for energy and favorable environment. Energy plays a crucial role in facilitating development in a country (Beidari *et al.*, 2017). One of the essential priorities for society's future is the sustainable development and provision of projects that actualize sustainable principles (Puko *et al.*, 2020). Compared with the chemical industry, transportation and other related fields, the construction industry has a great prospect in both reducing energy consumption and coping with climate change in present world. According to the International Energy Agency (IEA), buildings and building construction sectors together consume 36% of the total global energy consumption and are responsible for almost 40% of direct and indirect greenhouse gas (GHG) emissions (Hamburg and Kalamees, 2019; Mancini and Nastasi, 2019; Tokbolat *et al.*, 2019; Mahmoodzadeh *et al.*, 2020; Mejjaoui and Alzahrani, 2020). Currently, around 35% of buildings in Europe are over 50 years old. Meanwhile, they are responsible for 40% of energy consumption and 36% of GHG emissions in the European Union (Hamburg and Kalamees, 2019). Up to 2018, the energy used in construction and operation of buildings in China accounted for 37% of the total social energy consumption, of which the energy used in construction accounted for about 14% and operation of buildings accounted for about 23% (Yu *et al.*, 2009). Therefore, to reduce the pressure of building energy

demand and carbon dioxide emissions, one not only needs to pay attention to the energy consumption of new buildings in the construction stage. How to save the operation energy consumption of existing buildings has more practical significance for energy saving in buildings. During the last decades, architects have gradually embraced a trend that energy efficiency should be maximized as much as possible, resulting in the growing number of passive houses being built (Szirtesi and Igaz, 2016).

A substantial part of the energy demand of residential buildings is due to fossil-fuel-powered space and domestic hot water heating (Pinto and da Graça, 2018). Improving the thermal envelope of these buildings can effectively reduce the energy use. Building an envelope serves a function other than just being a structural or architectural component (Al-Qahtani and Elgizawi, 2020). It can be designed to provide a healthy and comfortable environment for users.

Studies of the energy-saving renovation and building envelope are progressing a lot. Zhou *et al.* (2018) investigated the energy-saving potential from the building envelope design and actual operation optimization. Baglivo *et al.* (2017) highlighted the usefulness of the envelope design optimization that is characterized by high values of heat storage capacity, enabling internal temperature fluctuations to be kept under control, especially during summer. Ahmed and Asif (2020) proposed a three-level energy retrofit scheme, including enhancing the efficiency of air conditioning system and thickening envelope insulation. Results indicated that annual energy consumption in a villa is reduced by 13.79%, 19.27% and 56.9%, and in the apartment building by 22.84%, 28.85% and 58.5% through different retrofit levels. Tan *et al.* (2019) identified that the energy-saving rate of building envelope integrating green plants is 25%. Chen *et al.* (2017) concluded key energy-saving measures on the reconstruction of envelope enclosure, water supply, drainage system and lighting system, and renewable energy use for existing residential buildings in hot summer and cold winter zone. And the envelope renovation should be given a high-priority order.

Energy relates to economic growth by being a basic necessity that fuels the daily consumption of an economy (Lee and Rosalez, 2017). The combustion of a large number of fossil fuels leads to excessive emissions of CO₂. At present, the amount of CO₂ in the atmospheres is nearly 50% higher than in 1750 (Su *et al.*, 2020). CO₂ emissions have globally received more and more attention, including greenhouse effects, health of ecosystems, radiative forcing, global carbon cycle, reduction of CO₂ emissions, as well as CO₂ capture and geological storage (Cai *et al.*, 2019; Xiang *et al.*, 2019; Yang *et al.*, 2019). Atmospheric quality deterioration has occurred in Asian, European and North American cities in recent years, and especially in some rapidly developing regions and countries (Li *et al.*, 2018).

Existing buildings in southern Jiangsu Province, China, have large stocks. Meanwhile, the people here have higher requirements for living comfort. In this study, the existing residential buildings in southern Jiangsu Province are taken as the research object, the effect of building envelope renovation on energy consumption is analyzed by energy consumption simulation software BES1, and the economy of renovation schemes is analyzed through orthogonal test method.

2 METHODS

2.1 Project Overview

The building is located in the city of Wuxi, Jiangsu Province, with a total height of 23.75 m, a total area of 5197.12 m² and a shape coefficient of 0.244. Sustainable buildings and building information modeling are two future cornerstones of the architectural, engineering and construction industry (Liu *et al.*, 2020a). The software BES1 is used to extract the building data of the established model. The area of window and wall in each direction of the existing building, the practice of envelope enclosure and the current situation of annual energy consumption and carbon dioxide emissions are shown in Tables 1, 2 and 3. The layout and simulation model of the building standard floor are shown in Figs. 1 and 2.

2.2 Parameter Setting

The simulation of energy consumption does not consider the energy consumption required by lighting equipment, considers the annual change of energy consumption caused by the structural change of building envelope alone. The average personnel density of the building is 30 m² person⁻¹.

Table 1. Table of the area of window and wall of the existing building.

Orientation	The Area of the External Window (m ²)	The Area of the External Wall (m ²)	The Area of the Roof (m ²)
East	70.84	329.18	0.22
South	427.20	1080.80	0.40
West	75.72	416.68	0.19
North	343.56	1201.20	0.29

Table 2. Components of building envelope before renovation.

Building Envelope	Overview of Components (from Top to Bottom)	Heat Transfer Coefficient (W m ⁻² K ⁻¹)
External wall	Mixed mortar: 20 mm Solid clay brick: 240 mm Mixed mortar: 20 mm	1.74
External window	Single glazed aluminum window	6.40
Slope roof	Cement tile Roof batten Waterproof layer Plank sheathing Purlin	1.59
Flat roof	Cement mortar: 20 mm Waterproof layer Vermiculite concrete: 40 mm Roof board: 120 mm Lime mortar: 10 mm	1.76

Table 3. Annual energy consumption status and carbon dioxide emissions of buildings before renovation.

	Energy Consumption (kWh m ⁻²)	Power Consumption (kWh m ⁻²)	Carbon Dioxide Emissions (t)
Cooling	40.35	17.54	90.89
Heating	25.87	13.62	70.57
Total	66.22	31.16	161.46

The built-in parameters of the model are set according to the local climate conditions and the “Energy-saving Design Standard for Residential Buildings in Hot Summer and Cold Winter Areas.” The indoor designed temperature and humidity in summer are separately 40% and 26°C, while in winter, the indoor designed temperature and humidity are 60% and 24°C. The air conditioning system parameters are set as shown in Table 4.

According to the recommended value of heat transfer coefficient of building envelope in the “Technical Guidelines for Passive Ultra-Low Energy Consumption Green Building (Trial) (Residential Building)” (hereinafter referred to as the “Guidelines”), the upper limit of heat transfer coefficient of building envelope in the hot summer and cold winter area is taken as the reference value of this test. Reference value of upper limit of heat transfer coefficient of external wall and roof are both 0.2–0.35, which of external window is 1.0–2.0.

3 RESULTS AND DISCUSSION

3.1 Analysis of Effect of Energy-saving Transformation of Building Envelope

3.1.1 Analysis of effect of energy-saving renovation of external wall

The area of the external wall takes a large proportion in total area of the building envelope. In

Fig. 1. Layout plan of existing building standard floor.

Fig. 2. Layout plan of existing building standard floor.

Table 4. Parameter setting of air conditioning system.

Function	Equipment	COP	Operation Schedule of Air Conditioning
Cooling	Household split air conditioning	1.9	December 1 (current year)–February 28 (next year)
Heating	Household split air conditioning	2.3	June 15 (current year)–August 31 (next year)

order to explore the impact of the energy-saving reconstruction degree of the external wall on the building energy consumption, the energy-saving renovation effect of the external wall is analyzed separately. When analyzing the effect of external wall renovation, the specification of the roof and the external window before renovation is kept to realize the qualitative analysis of a single variable.

In this study, expanded polystyrene (EPS) insulating board is applied to renovating the external wall of existing buildings. Determination of the thickness of EPS insulating board and its corresponding heat transfer coefficient should take advantage of the reference value of upper limit of heat transfer coefficient of building envelope and the formula of average heat transfer coefficient, as shown in Eq. (1). For example, when the heat transfer coefficient of the external wall is $0.198 \text{ W m}^{-2} \text{ K}^{-1}$, the thickness of EPS insulation board of the external wall is 220 mm:

$$K_m = \frac{K_p \cdot F_p + K_{B1} \cdot F_{B1} + K_{B2} \cdot F_{B2} + K_{B3} \cdot F_{B3}}{F_p + F_{B1} + F_{B2} + F_{B3}} \quad (1)$$

where K is equal to K_m (in areas with hot summers and cold winters); K_m is the mean heat transfer coefficient of external wall; K_p is the mean heat transfer coefficient of the main part of external wall; K_{B1} , K_{B2} , K_{B3} are the heat transfer coefficient of thermal bridges; F_p is the area of the main part of external wall; F_{B1} , F_{B2} , F_{B3} are the area of thermal bridges.

Starting at the external wall before renovation, taking 20 mm as the step length, the external wall renovation scheme Q_1 – Q_{12} is obtained. The relevant data of the relationship between the heat transfer coefficient of the external wall of the existing building and the thickness of the insulation board are shown in Table 5.

After the analysis of each plan, the trend of data change is shown in Fig. 3. It can be seen that the heat transfer coefficient of external wall generally decreases when the thickness of insulation layer increases. However, with the continuous increase of the thickness of insulation layer, the change trend of heat transfer coefficient slows down gradually, and even reaches the result of a straight line. According to the curve trend, when the thickness of EPS insulation board reaches more than 200 mm, the change range of heat transfer coefficient is small.

The above external wall energy-saving renovation scheme is calculated and analyzed one by one, in order to obtain the energy-saving effect on each thickness of EPS insulating board. The calculation of energy consumption of the building's annual cooling consumption, heating consumption, total energy consumption and carbon dioxide emissions of the external wall renovation schemes are shown in Table 6.

According to the results of energy consumption of each renovation scheme, the total energy consumption of each plan and the energy-saving effect achieved are compared, as shown in Fig. 4. For the energy-saving transformation of the external wall, the increase of the thickness of EPS insulation layer can bring the decline of the total annual energy consumption of the building, which also shows that the better the energy-saving effect. However, with the continuous increase of insulation layer thickness, the growth rate of energy-saving rate slows down gradually and tends to a linear state. It shows that increasing the thickness of insulation layer will not increase

Table 5. Energy-saving and carbon dioxide emissions reduction renovation scheme of existing building external wall.

Renovation Scheme	The Thickness of EPS Insulation Board (mm)	Heat Transfer Coefficient ($\text{W m}^{-2} \text{ K}^{-1}$)
Before renovation	0	1.736
Q_1	20	1.018
Q_2	40	0.72
Q_3	60	0.557
Q_4	80	0.454
Q_5	100	0.383
Q_6	120	0.332
Q_7	140	0.292
Q_8	160	0.261
Q_9	180	0.236
Q_{10}	200	0.215
Q_{11}	220	0.198
Q_{12}	240	0.183

Fig. 3. Trend of the heat transfer coefficient of external wall.

Table 6. Annual energy consumption and carbon dioxide emissions after external wall renovation.

Renovation Scheme	Total Energy Consumption ($kWh m^{-2}$)	Cooling Consumption ($kWh m^{-2}$)	Heating Consumption ($kWh m^{-2}$)	Energy-saving Efficiency (%)	Carbon Dioxide Emissions (t)
Pre-renovation	66.22	40.35	25.87	0.00	161.46
Q_1	60.12	38.29	21.83	9.21	146.59
Q_2	57.48	37.42	20.06	13.20	140.15
Q_3	56.00	36.94	19.05	15.43	136.54
Q_4	55.05	36.64	18.41	16.87	134.22
Q_5	54.40	36.43	17.97	17.85	132.64
Q_6	53.92	36.28	17.64	18.57	131.47
Q_7	53.55	36.16	17.38	19.13	130.57
Q_8	53.25	36.07	17.18	19.59	129.84
Q_9	53.02	36.00	17.02	19.93	129.28
Q_{10}	52.81	35.93	16.88	20.25	128.76
Q_{11}	52.66	35.88	16.78	20.48	128.40
Q_{12}	52.51	35.93	16.68	20.70	128.03

the energy-saving benefit of external wall significantly, and the increase of insulation layer thickness will cause higher reconstruction cost. Therefore, the economic analysis of insulation thickness should be considered when the existing buildings are reformed for energy conservation.

3.1.2 Analysis of effect of energy-saving renovation of roof

Although the area of roof only accounts for a small part of total area of the building envelope, due to its special location, the roof will produce a large difference between indoor and outdoor temperature, resulting in more energy consumption than the external wall of the same area. In addition, in hot summer and cold winter area, energy-saving renovation of the roof can directly improve the indoor environment of the top floor.

In order to find out the impact of roof renovation on the total annual energy consumption, a separate analysis should be carried out on the roof. When analyzing the effect of roof renovation, the specification of the external wall and window before renovation is kept to realize the qualitative analysis of a single variable. The building has flat roof and slope roof, and the heat transfer coefficient of the two is different before reconstruction. However, after energy consumption simulation, the thickness change of EPS insulation board has similar effect on their heat transfer coefficient.

According to the external wall energy-saving renovation analysis and the ceiling reference value of the roof heat transfer coefficient, the roof transformation plan W_1 – W_{12} is formulated. The concrete values of the roof energy-saving transformation plan are shown in Table 7.

Fig. 4. Change diagram of total energy consumption and energy-saving efficiency of external wall renovation scheme.

Table 7. Energy-saving renovation scheme of existing building roof.

Renovation Scheme	The Thickness of EPS Insulation Board (mm)	Heat Transfer Coefficient ($\text{W m}^{-2} \text{K}^{-1}$)	
		Flat Roof	Slope Roof
Pre-renovation	0	1.761	1.587
W_1	20	1.026	0.965
W_2	40	0.724	0.693
W_3	60	0.559	0.541
W_4	80	0.456	0.443
W_5	100	0.385	0.376
W_6	120	0.333	0.326
W_7	140	0.293	0.288
W_8	160	0.262	0.258
W_9	180	0.237	0.233
W_{10}	200	0.216	0.213
W_{11}	220	0.198	0.196
W_{12}	240	0.184	0.182

Combined with Fig. 5, the analysis of scheme W_1 – W_{12} in Table 7 shows that although the heat transfer coefficients of flat roof and slope roof are slightly different before renovation, the heat transfer coefficients of both have the same changing trend with the increase of insulation layer thickness, and even almost coincide with each other. Therefore, when considering and analyzing the roof later, the two can be considered as one. The roof is transformed separately, and the trend of change is similar to that of the external wall. When the thickness of EPS insulation layer increases, the heat transfer coefficient of the roof shows a continuous downward trend, but the change of the heat transfer coefficient caused by the increase of the thickness of insulation layer gradually decreases, and even appears in a nearly straight-line state.

Calculating all the schemes of the roof energy-saving renovation one by one, the total energy consumption, cooling consumption, heating consumption and carbon dioxide emissions of the building with different thickness of EPS insulation board are shown in Table 8.

Combined with Fig. 6, the results of roof energy-saving reconstruction schemes W_1 – W_{12} in

Fig. 5. Trend of the heat transfer coefficient of roof.

Table 8. Annual energy consumption and carbon dioxide emissions after roof renovation.

Renovation Scheme	Total Energy Consumption (kWh m ⁻²)	Cooling Consumption (kWh m ⁻²)	Heating Consumption (kWh m ⁻²)	Energy-saving Efficiency (%)	Carbon Dioxide Emissions (t)
Pre-renovation	66.22	40.35	25.87	0.00	161.46
W ₁	62.71	38.71	24	5.30	152.90
W ₂	61.13	38	23.13	7.69	149.05
W ₃	60.24	37.6	22.64	9.03	146.88
W ₄	59.66	37.35	22.31	9.91	145.47
W ₅	59.25	37.17	22.09	10.53	144.47
W ₆	58.96	37.04	21.92	10.96	143.76
W ₇	58.73	36.94	21.79	11.31	143.20
W ₈	58.54	36.86	21.69	11.60	142.73
W ₉	58.4	36.79	21.6	11.81	142.39
W ₁₀	58.27	36.74	21.54	12.01	142.08
W ₁₁	58.17	36.69	21.48	12.16	141.83
W ₁₂	58.09	36.66	21.43	12.28	141.64

Table 8 are analyzed. When the thickness of EPS insulation layer increases, the total building energy consumption will decrease, bringing better building energy-saving effect. However, in the process of increasing the thickness of insulation layer, the decline range of building energy consumption gradually decreases. The variation of energy-saving rate can more directly show the overall situation of the total building energy consumption changing with the thickness of insulation layer. When the insulation layer reaches a certain thickness, the change of energy-saving rate tends to be in a straight-line form. This shows that the energy-saving effect achieved by increasing the thickness of insulation layer is not very outstanding, and the energy-saving benefit is not improved much, but will lead to higher reconstruction cost.

3.1.3 Analysis of effect of energy-saving renovation of external window

Windows could act as a mediator capable of not only reducing the load on the building but also improving the indoor environment by either allowing or blocking the passing of solar radiation

Fig. 6. Change diagram of total energy consumption and energy-saving efficiency of external wall renovation scheme.

(Park *et al.*, 2019). There are many factors to be considered in the energy-saving transformation of external windows, including heat transfer performance of external window glass and window frame profiles, shading performance of external windows and air tightness of external windows. In this study, only the heat transfer and energy absorption of the window are considered.

When analyzing the effect of external window renovation, the specification of the external wall and roof before renovation is kept to realize the qualitative analysis of a single variable. According to the common window frame profiles and glass configurations provided for reference in the “Guidelines” and in combination with the common window specifications and models on the market, six external window renovation schemes C_1 – C_6 are selected, with the corresponding heat transfer coefficient of 2.4–1.0. The specific renovation schemes and their thermal performance are shown in Table 9.

The total energy consumption, cooling consumption, heating consumption and carbon dioxide emissions of each external window renovation schemes are shown in Table 10.

As we can see from Fig. 7 and Table 10, as the heat transfer coefficient of the external window gradually decreases, the total annual energy consumption of the building will decrease and the energy-saving rate will increase accordingly. However, different from the changing trend of the energy-saving transformation of the external wall and roof, the decrease of the heat transfer coefficient of the outer window will make the building energy consumption continue to decrease from 2.4 to 1.0 $\text{W m}^{-2} \text{K}^{-1}$. It can be seen from the change of energy-saving rate that the energy consumption decreases with the decrease of the heat transfer coefficient, and the energy-saving rate gradually increases. When the heat transfer coefficient of the external window reaches 1.0 $\text{W m}^{-2} \text{K}^{-1}$, the building energy-saving rate still keeps an upward trend, which can be speculated that the heat transfer coefficient of the external window of the building has a further downward space, and has a considerable potential for energy-saving transformation.

3.1.4 Analysis of change rate of energy-saving renovation effect of building envelope

According to the analysis of the energy-saving transformation effect of building external wall and roof, when the thickness of insulation layer increases to a certain extent, the decline rate of building energy consumption will gradually slow down. In order to explore the degree of its change, the external wall and roof energy-saving reconstruction was further analyzed.

Table 9. Energy-saving and CO₂ emissions reduction renovation scheme of existing building window.

Renovation Scheme	Specification (from Top to Bottom)	Heat Transfer Coefficient (W m ⁻² K ⁻¹)
Pre-renovation	Single glazed aluminum window	6.4
C ₁	Single-silver low-emissivity glass: 5 mm	2.4
	Air layer: 12 mm	
	Normal glass: 5 mm	
C ₂	Double-silver low-emissivity glass: 5 mm	2.1
	Air layer: 12 mm	
	Normal glass: 5 mm	
C ₃	Triple-silver low-emissivity glass: 5 mm	1.9
	Air layer: 12 mm	
	Normal glass: 5 mm	
C ₄	Single-silver low-emissivity glass: 5 mm	1.6
	Air layer: 12 mm	
	Normal glass: 5 mm	
	Air layer: 12 mm	
	Normal glass: 5 mm	
C ₅	Triple-silver low-emissivity glass: 5 mm	1.3
	Air layer: 12 mm	
	Normal glass: 5 mm	
	Air layer: 12 mm	
	Normal glass: 5 mm	
C ₆	Normal glass: 5 mm	1.0
	Air layer: 12 mm	
	Double-silver low-emissivity glass: 5 mm	
	Vacuum layer	
	Normal glass: 5 mm	

Table 10. Annual energy consumption and carbon dioxide emissions after external window renovation.

Renovation Scheme	Total Energy Consumption (kWh m ⁻²)	Cooling Consumption (kWh m ⁻²)	Heating Consumption (kWh m ⁻²)	Energy-saving Efficiency (%)	Carbon Dioxide Emissions (t)
Pre-renovation	66.22	40.35	25.87	0.00	161.46
C ₁	54.74	38.93	15.82	17.34	133.47
C ₂	53.25	35.89	17.36	19.59	129.84
C ₃	52.54	35.85	16.69	20.66	128.10
C ₄	51.41	35.78	15.62	22.36	125.35
C ₅	50.19	35.35	14.84	24.21	122.38
C ₆	49.01	35.3	13.7	25.99	119.50

When the temperature of indoor and outdoor air exists difference, the process of heat transfer will be appeared. Under stable conditions, through the heat of the envelope, basic heating consumption, so the basic heating consumption of the envelope can be calculated according to Eq. (2):

$$Q = \frac{a \cdot F \cdot \Delta t}{R_1 + \frac{\delta}{\lambda}} \quad (2)$$

where Q is the basic heating consumption of envelope structure; a is the temperature difference correction coefficient of envelope structure; F is the area of envelope structure; Δt is the temperature difference between indoor and outdoor; R_1 is the thermal resistance of building

Renovation schemes of external window

Fig. 7. Change diagram of total energy consumption and energy-saving efficiency of external window renovation scheme.

envelope other than insulation layer; δ is the thickness of insulation layer; λ is the heat transfer coefficient of insulation layer.

According to Eq. (2), the basic heating consumption of the envelope is related to the thickness of insulation materials. In order to analyze the impact of the thickness change of insulation layer on energy consumption and reasonably select the thickness of insulation layer, the concept of change rate of energy-saving is introduced. The relevant definition is shown in Eq. (3):

$$\varphi = \frac{Q - Q_i}{\delta_i} \quad (3)$$

where φ is the energy-saving change rate; Q is the energy consumption before renovation; Q_i is the energy consumption with insulation thickness δ_i ; δ_i is the thickness of insulation layer. The change rate of energy saving of external wall and roof are shown in Table 11.

According to Table 11, when the thickness of EPS insulation board increases gradually, the change in energy consumption brought by the unit thickness of insulation board decreases gradually. Since the renovation area of the external wall is twice the area of the roof, the change in energy consumption brought by the external wall is significantly higher than the impact of the roof.

For external wall, when the thickness of EPS insulation board changes from 0 to 120 mm, the change rate of energy saving is obvious; when the thickness of EPS insulation board reaches 120 mm, if the thickness of external wall insulation board is increased, the change range of energy-saving rate gradually slows down, while when the thickness of the insulation board changes between 180 and 240 mm, increasing the thickness of the insulation board has a small change rate of energy saving. Even increasing the thickness of the insulation board, the change rate of energy saving remains unchanged and keeps a basically stable state. This indicates that the contribution of insulation board per unit thickness to building energy consumption reduction is getting smaller and smaller. Therefore, 120-mm-thick insulation board was selected as a more appropriate upper limit for the thickness of external wall insulation board. When the thickness of external wall insulation board is 120 mm, the energy-saving change rate is 0.1.

For the roof, similar to the external wall, when the thickness of EPS insulation board changes from 0 to 120 mm, the change rate of energy saving is obvious; the thickness of EPS insulation board ranging from 140 to 240 mm, the energy-saving rate of change to maintain a basically stable state, the change range is small. Therefore, 140 mm is selected as a more appropriate

Table 11. Energy-saving change rate of external wall and roof.

The Thickness of EPS Insulation Board (m)	External Wall			Roof		
	Heat Transfer Coefficient (W m ⁻² K ⁻¹)	Total Energy Consumption (kWh m ⁻²)	Energy-saving Change rate (φ)	Heat Transfer Coefficient (W m ⁻² K ⁻¹)	Total Energy Consumption (kWh m ⁻²)	Energy-saving Change Rate (φ)
0	1.736	66.22	–	1.761/1.587	66.22	–
20	1.018	60.12	0.31	1.026/0.965	62.71	0.18
40	0.72	57.48	0.22	0.724/0.693	61.13	0.13
60	0.557	56.00	0.17	0.559/0.541	60.24	0.10
80	0.454	55.05	0.14	0.456/0.443	59.66	0.08
100	0.383	54.40	0.12	0.385/0.376	59.25	0.07
120	0.332	53.92	0.10	0.333/0.326	58.96	0.06
140	0.292	53.55	0.09	0.293/0.288	58.73	0.05
160	0.261	53.25	0.08	0.262/0.258	58.54	0.05
180	0.236	53.02	0.07	0.237/0.233	58.40	0.04
200	0.215	52.81	0.07	0.216/0.213	58.27	0.04
220	0.198	52.66	0.06	0.198/0.196	58.17	0.04
240	0.183	52.51	0.06	0.184/0.182	58.09	0.03

upper limit for the thickness of roof insulation board. When the thickness of roof insulation board is 140 mm, the change rate of energy-saving is 0.05.

3.2 Economic Analysis of Energy-saving Renovation of Building Envelope

The current European building stock is ageing and requires a “renovation wave” to improve its energy performance and ensure structural safety (Pohoryles *et al.*, 2020). However, the research found that in China, retrofit of existing buildings generally lack of attractiveness to investors from an economic perspective (Liu *et al.*, 2018). Therefore, it is necessary to consider not only the energy-saving effect achieved, but also the economy of the existing residential building envelope. In this paper, through the static payback period and dynamic payback period, the economy of the energy-saving transformation scheme is judged and selected.

3.2.1 Design of orthogonal experiment scheme

In order to meet the standard of passive ultra-low energy consumption for residential building, an appropriate envelope modification scheme was selected by referring to the upper limit reference value of heat transfer coefficient of building envelope in the “Guidelines,” so as to determine the horizontal range of factors for the orthogonal test.

According to the “Guidelines,” the scheme of optional external wall are Q_6 – Q_{12} , the scheme of optional roof are W_6 – W_{12} , the scheme of optional external window are C_3 – C_6 . Each factor is divided into working condition levels, and four working condition levels are selected. The simulation working condition factors and level selection table are shown in Table 12.

In this simulation study of the existing building envelope, only the influence of the heat transfer coefficient of the external wall, the roof and the external window on the building energy consumption are considered, and the interaction between the factors is not considered. The orthogonal design of the three-factor and four-level tests was carried out by using the software SPSS to replace the comprehensive test. The orthogonal table $L_{16}(4^3)$ was selected to conduct 16 simulations. The specific simulation conditions are shown in Table 13.

Table 12. Factors and level selection of simulated working conditions.

Working Condition Level	External Wall (A; mm)	Roof (B; mm)	External Window (C; W m ⁻² K ⁻¹)
1	120	120	1.9
2	160	160	1.6
3	200	200	1.3
4	240	240	1.0

Table 13. $L_{16}(4^3)$ orthogonal array.

Simulated Working Conditions	External Wall (A)	Roof (B)	External Window (C)
1	1	1	1
2	2	2	1
3	3	3	1
4	4	4	1
5	1	2	2
6	2	1	2
7	3	4	2
8	4	3	2
9	1	3	3
10	2	4	3
11	3	1	3
12	4	2	3
13	1	4	4
14	2	3	4
15	3	2	4
16	4	1	4

3.2.2 Economic analysis of energy-saving renovation

An orthogonal experiment is a fast, economical and efficient multi-factor test method. In this paper, the transformation cost refers to the average market price. Among them, the electricity price in Wuxi is USD 0.13 kWh^{-1} , the price of EPS insulation material is USD 76.62 m^{-3} . Price of external window renovation (C_3 – C_6) are separately USD 101.29 m^{-2} , USD 112.78 m^{-2} , USD 151.4 m^{-2} , USD 187.56 m^{-2} . The simulation results and economic analysis of each working condition are shown in Table 14.

According to the total energy consumption, cooling consumption, heating consumption, carbon dioxide emissions and static recovery period, the corresponding orthogonal intuitive optimal scheme and orthogonal horizontal optimal scheme were selected, as shown in Table 15.

Meanwhile, considering the economy of the energy-saving and carbon dioxide emissions reduction renovation, the static payback period was selected as the evaluation index to determine the optimal scheme. The dynamic payback period of the two optimal schemes was calculated, and the optimal scheme of the energy-saving transformation was finally selected. The comparison results of the comprehensive transformation schemes are shown in Table 16.

According to the comparison of the static recovery period and dynamic recovery period of the two schemes, it can be concluded that A1B1C1 is the optimal economic recovery scheme. The specific methods of its transformation scheme are as below. The thickness of EPS insulating board of both external wall and roof is 120 mm. The specification of external window is triple-silver low-emissivity glass (5 mm) + air layer (12 mm) + normal glass (5 mm).

3.3 Analysis of Environmental Benefit

Electricity is a form of energy which is essential in our daily life and electricity generation mainly comes from the burning of coal. According to the analysis above, through renovation of building envelope, energy consumption of heating and cooling during the building operation can be reduced, and the power consumption can be saved, thus reducing the emission of greenhouse gases such as carbon dioxide and dust. China has suffered from extensive air pollution and subsequent severe outcomes, such as impeded socioeconomic development, in recent years (Liu *et al.*, 2020b; Wang *et al.*, 2021; Wu *et al.*, 2021). The software BES1 is used to simulate the actual energy consumption of the above optimal renovation scheme. The comparison of building energy and power consumption before and after renovation can be obtained, as shown in Figs. 8(a) and 8(b). As shown in Fig. 9, the pollutant emission is reduced by a great amount after renovation. According to the simulation, the optimal retrofit scheme can save 16.6 kWh m^{-2} of electricity consumption every year, which has remarkable environmental benefits. Meanwhile, CO_2 emissions could be reduced by 86.01 tons, SO_2 emissions could be by 2.59 tons, and nitrogen oxide emissions could be by 1.29 tons per year.

Table 14. Energy consumption, carbon dioxide emissions and economic analysis results of simulated working conditions.

Simulated Working Conditions	Working Condition Level			Combined Scheme	Annual Load Index (kWh m ⁻²)				Carbon Dioxide Emissions (t)	Total Renovation Cost (USD m ⁻² a ⁻¹)	Annual Energy-saving Benefit (USD m ⁻² a ⁻¹)	Static Investment Recycling Time (a)
	A	B	C		Total Energy Consumption	Cooling Consumption	Heating Consumption					
1	1	1	1	A1B1C1	32.59	28.37	4.22	75.44	28.69	2.09	13.76	
2	2	2	1	A2B2C1	31.58	27.97	3.61	73.10	31.39	2.15	14.62	
3	3	3	1	A3B3C1	30.94	27.71	3.23	71.62	34.10	2.19	15.59	
4	4	4	1	A4B4C1	30.51	27.53	2.98	70.63	36.80	2.21	16.62	
5	1	2	2	A1B2C2	31.25	28.16	3.09	72.34	31.56	2.17	14.53	
6	2	1	2	A2B1C2	31.05	28.13	2.92	71.88	32.58	2.18	14.91	
7	3	4	2	A3B4C2	29.92	27.61	2.31	69.26	36.96	2.25	16.41	
8	4	3	2	A4B3C2	29.84	27.59	2.24	69.07	37.99	2.26	16.82	
9	1	3	3	A1B3C3	29.89	27.62	2.28	69.19	39.21	2.26	17.39	
10	2	4	3	A2B4C3	29.20	27.32	1.88	67.59	41.91	2.30	18.24	
11	3	1	3	A3B1C3	29.59	27.56	2.03	68.50	41.27	2.27	18.15	
12	4	2	3	A4B2C3	29.01	27.28	1.72	67.15	43.97	2.31	19.03	
13	1	4	4	A1B4C4	28.93	27.54	1.39	66.97	46.43	2.32	20.03	
14	2	3	4	A2B3C4	28.60	27.41	1.19	66.20	47.46	2.34	20.30	
15	3	2	4	A3B2C4	28.51	27.39	1.12	66.00	48.49	2.34	20.68	
16	4	1	4	A4B1C4	28.63	27.47	1.16	66.27	49.52	2.34	21.19

Table 15. Pre-selection of the optimal scheme.

Evaluation Index	Orthogonal Intuitive Optimal Scheme	Orthogonal Horizontal Optimal Scheme
Total energy consumption	A3B2C4	A4B4C4
Cooling consumption	A4B2C3	A4B4C3
Heat consumption	A3B2C4	A4B4C4
Carbon dioxide emissions	A3B2C4	A4B4C4
Static investment recycling time	A1B1C1	A1B1C2

Table 16. Comprehensive comparison of reconstruction schemes.

Scheme Type	Specific Scheme	Total Renovation Cost (USD m ⁻² a ⁻¹)	Energy-saving Benefit (USD m ⁻² a ⁻¹)	Static Investment Recycling Time (a)	Dynamic Investment Recycling Time (a)
Orthogonal intuitive optimal scheme	A1B1C1	28.69	2.09	13.76	22.84
Orthogonal horizontal optimal scheme	A1B1C2	30.72	2.15	14.30	24.50

Fig. 8. Comparison of (a) energy and (b) power consumption before and after the optimal renovation scheme.

4 CONCLUSIONS

We evaluated various energy-saving renovation schemes for an existing residential building in an area with hot summers and cold winters by using the relevant standards and specifications, the software BES1, and the orthogonal test method to set various parameters, simulate the building's energy consumption, and conduct an economic analysis, respectively. Our findings can be summarized as follows.

- (1) Based on our individual analysis of each scheme, the building's energy consumption decreased with the envelope element's heat transfer coefficient. However, the conservation effect gradually diminished as the thickness of the insulation layer for the exterior wall and the roof increased.
- (2) We simulated the effects of combining different schemes by employing the orthogonal test method and setting the static payback period (the time required to recover the invested capital) as the evaluation index. The optimal combination in terms of both cost and energy

Fig. 9. Comparison of air pollutant emissions before and after renovation.

Table 17. The optimal renovation scheme.

Building Envelope	Renovation Scheme	Heat Transfer Coefficient (W m ⁻² K ⁻¹)
External wall	EPS insulation board: 120 mm	0.332
External window	Triple-silver low-emissivity glass: 5 mm Air layer: 12 mm Normal glass: 5 mm	1.900
Roof	EPS insulation board: 120 mm	Flat roof: 0.333 Slope roof: 0.326

efficiency (Table 17) resulted in a cooling capacity, heating consumption, total building energy consumption, static payback period, and dynamic payback period of 28.37 kWh m⁻² a⁻¹, 4.22 kWh m⁻² a⁻¹, 32.59 kWh m⁻² a⁻¹, 13.76 years, and 22.84 years, respectively.

(3) This combination also reduced the annual emissions of CO₂, SO₂, and NO_x by 86.01 tons, 2.59 tons, and 1.29 tons, respectively, which offers substantial environmental benefits.

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