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Research on Low-Carbon Retrofitting Technology for Existing Rural Buildings in Southern Henan Based on DeST

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Abstract

The development of low-carbon technology in urban construction is rapid, whereas in rural and other economically underdeveloped areas, the development of low-carbon buildings is relatively lagging behind. Achieving the low-carbon retrofitting of rural buildings is crucial for reaching the "dual carbon" strategic goals. This study conducted an in-depth investigation into the current situation, energy consumption levels, and factors affecting carbon emissions of rural buildings in Nanyang City. Using DeST simulation software, the energy consumption of a rural building in Wolong District of Nanyang City was simulated and analyzed, examining the impact of factors such as building exterior walls, roofs, external windows, orientation, and window-to-wall ratio on building energy efficiency.

Keywords

Rural buildings; Energy efficiency improvement; Low-carbon technology; Energy consumption simulation.

1. Introduction

National energy consumption data shows that the carbon emission intensity of urban residential buildings has decreased by 21% in recent years, while that of rural residential buildings has increased by 31%. This indicates that rural building carbon emissions are a key area for achieving the “dual carbon” goals. Located in the southwest of Henan Province, at the intersection of Henan, Hubei, and Shaanxi provinces, Nanyang City has both northern and southern climate characteristics, with hot and humid summers, and winters that are dry and sunny with a short cold period. The energy consumption of rural buildings in Nanyang is mainly concentrated on summer shading and winter heating. Traditional rural houses differ significantly from urban houses, so reducing rural building carbon emissions should not simply replicate the carbon reduction strategies of urban high-rise residences and rural buildings in other regions. Instead, a comprehensive analysis that considers local building structures and natural conditions is necessary.

2. Field Research

With the improvement of living standards in rural areas of our country, the demand for housing quality among rural residents has been increasing. The total existing building area in Nanyang City is approximately 508 million m^2, of which rural areas account for about 326 million m^2, or 64%, making them a key focus for low-carbon technology retrofitting.

A survey of 40 villages in the area found that rural buildings lack professional guidance and standard specifications during construction, resulting in exterior walls, roofs, external windows,

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and window-to-wall ratios that do not meet energy-saving standards. Despite the variety of architectural styles, the materials and construction methods are similar, mostly using reinforced concrete or brick-concrete structures. The proportion of building structure types is shown in Figure 1.Existing rural house exterior walls are mostly 240mm thick clay perforated bricks, and the roofs are mostly accessible flat roofs, convenient for crop drying. The external protective structures generally lack effective insulation measures, leading to severe cold air leakage in winter. External windows are mostly single-layer aluminum alloy glass, and about 65% of external doors are single-layer wooden doors, with poor air tightness, which is not conducive to indoor thermal comfort in winter. South-facing windows are generally large, while north-facing windows are smaller or not installed, which is beneficial for lighting but results in excessively high indoor temperatures in summer.

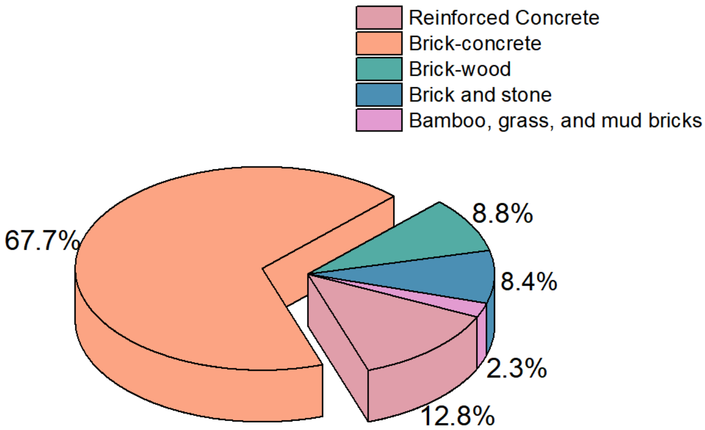

Figure 1. Structure of Rural Buildings in Nanyang City

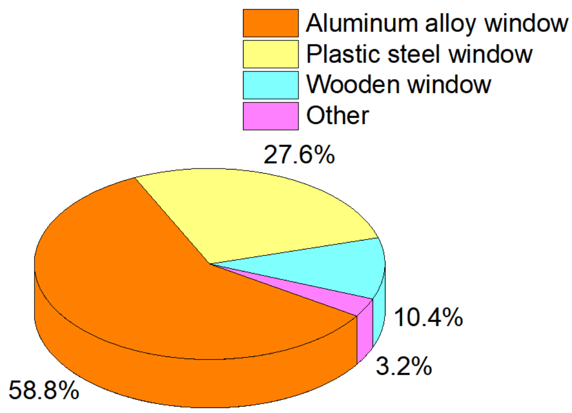

Figure 2. Proportion of Window Materials in Rural Areas

3. Energy Consumption Simulation and Optimization

3.1. Building Overview and Model Extraction

3.1.1. Geographical and Climatic Characteristics

The Nanyang region experiences hot summers, which last from mid-May to mid-September, with daily average temperatures exceeding 28°C and high humidity. Winters are cold, ranging from late November to late February of the following year, with daily average temperatures below 13°C and a dry climate. July is the hottest month, with temperatures reaching up to 28.5°C; January is the coldest month, with average temperatures ranging from-2 to 5°C. The average dry bulb temperatures and daily average temperature variations for each month are shown in

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Figures 3 and 4, respectively. The seasonal variation of solar radiation is significant, with daily shortwave radiation ranging from 3.4 to 6.2 KW, indicating abundant solar energy resources.

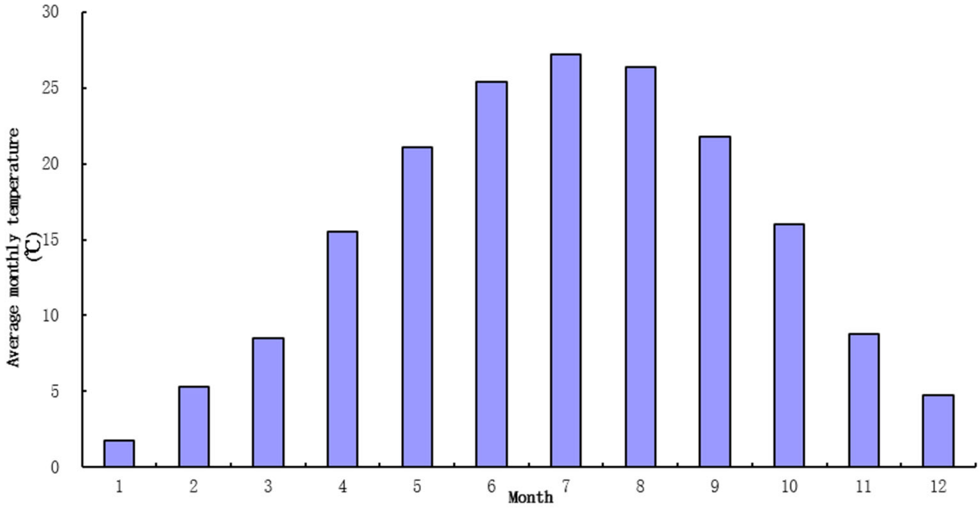

Figure 3. Monthly Average Dry Bulb Temperature

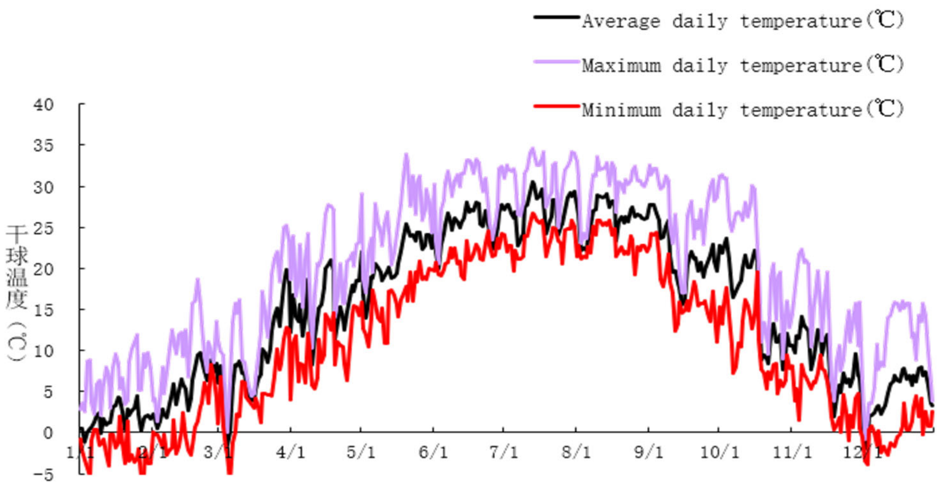

Figure 4. Daily Dry Bulb Temperature

3.1.2. Typical Residential Building Model

Based on the survey data of rural residential buildings in the Nanyang area, a commonly used brick-concrete structure residence was selected as the research subject. This study analyzed the impact of factors such as building floor height, orientation, and opaque envelope (including exterior walls, roofs, and the window-to-wall ratio of south- and north-facing rooms) on energy consumption. The selected residential building has a floor area of 282.03 square meters, is a two-story structure with a total height of 8.85 meters, a first-floor height of 3.6 meters, and a second-floor height of 3.2 meters. The architectural floor plans are shown in Figures 5 and 6, and the elevation is shown in Figure 7.

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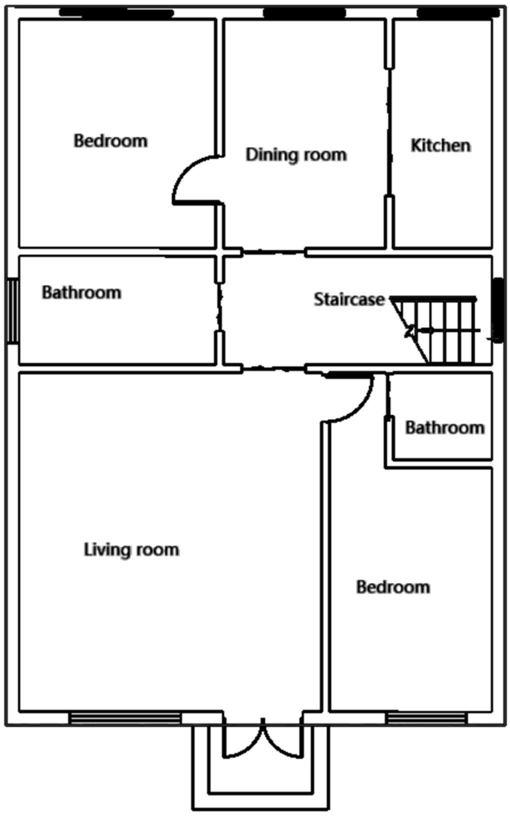

Figure 5. First Floor Plan

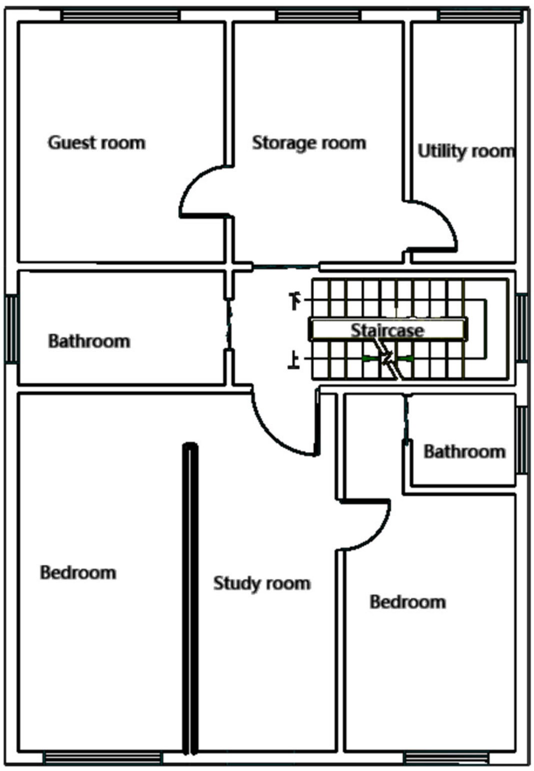

Figure 6. Second Floor Plan

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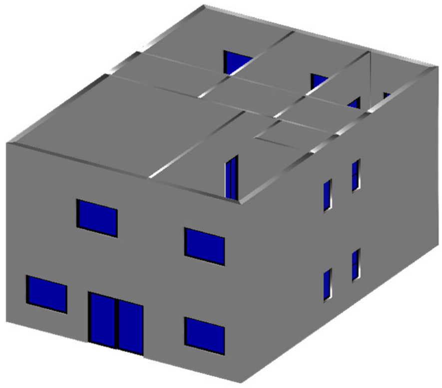

Figure 7. Building Elevation

3.1.3. Energy Consumption Simulation Analysis

Based on the above parameter settings, the building's energy consumption was simulated. The calculation results for the typical building are shown in Table 1. By comparing the calculation results, it can be concluded that the energy consumption of the building's exterior walls and windows accounts for a significant portion of the total energy consumption. Therefore, optimizing these high-energy-consuming areas in rural buildings is essential for achieving low-carbon goals.

Table 1. Simulated Building Load

Statistical Value	Unit	Statistical Value
Annual Maximum Heat Load	kW	56.15
Annual Maximum Cooling Load	kW	39.39
Annual Cumulative Heat Load	kW·h	28393
Annual Cumulative Cooling Load	kW·h	2867.29
Annual Maximum Heat Load Index	W/m2	212.2
Annual Maximum Cooling Load Index	W/m^2	148.85
Annual Cumulative Heat Load Index	$kW·h/m^2$	107.31
Annual Cumulative Cooling Load Index	$kW·h/m^2$	10.84

3.2. Optimization Scheme for Existing Building Envelope Structures

The building envelope is divided into two parts: transparent and opaque. The opaque envelope includes exterior walls, roofs, floors, ceilings, etc., while the transparent envelope includes windows, skylights, balcony doors, glass partitions, etc[1].

3.2.1. Energy-Saving Optimization for Opaque Envelope Structures

Exterior walls and roofs are the foundation of the building envelope. They not only separate the external environment from the interior but are also closely related to the indoor cooling and heating loads. Uninsulated walls and roofs can result in about 65% of energy loss, whereas this proportion can be reduced to 20%-35% with insulation treatment[2]. Therefore, optimizing the thermal insulation performance of exterior walls and roofs is crucial to prevent the loss of indoor heat and cooling and to reduce the building's cooling and heating loads.

Envelope insulation technologies include structural self-insulation and the addition of external insulation layers[3]. For existing rural houses, it is recommended to prioritize the method of adding external insulation materials. Common insulation materials include extruded

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polystyrene boards, expanded polystyrene boards, YT new-type wall insulation materials, polystyrene particle insulation mortar with glue powder, and foam polystyrene boards. The performance characteristics of various insulation materials are shown in the following table.

Table 2. Properties of Common Insulation Materials

Insulation Material	Thermal Conductivity W/(m·K)	Advantages	Disadvantages
Extruded Polystyrene (XPS)	0.028	Waterproof,good thermal insulation	High cost, prone to cracking
Expanded Polystyrene (EPS)	0.042	Economical,good thermal insulation, simple installation	High water absorption, poor fire resistance
Graphite Polystyrene	0.032	Good fire resistance,durability	Strong stability, low mechanical strength
Rock Wool Board	0.038	Good fire resistance, very low heat absorption, no capillary permeability	High cost, complex installation,long construction period
Polyurethane Foam	0.024	Lightweight, good adhesion, convenient and fast installation	Poor fire resistance, high cost, difficulty in achieving

(1) Exterior Wall Insulation: The thickness and thermal conductivity of the insulation material are directly related to the building's annual cooling and heating loads. According to related literature[4], in hot-summer and cold-winter regions, the thickness range of exterior wall insulation materials is 60-120mm. The lower the thermal conductivity of the insulation material, the better the energy-saving effect. When selecting exterior wall insulation materials, factors such as construction flatness, crack resistance, and water absorption rate need to be considered. In rural areas, material cost is also a significant factor. Therefore, in terms of material selection, the order is: graphite polystyrene board > expanded polystyrene board > polyurethane foam > extruded polystyrene board > rock wool board. Graphite polystyrene board has better thermal insulation properties, is economically priced, and is easy to apply smoothly, making it the preferred choice for exterior wall insulation systems.

(2) Roof Insulation: Unlike exterior wall insulation, flat roof insulation materials need to consider compressive strength and thermal insulation effects. Graphite polystyrene board is not suitable for this purpose. Polyurethane foam plastic is superior to extruded polystyrene board, but its construction difficulty and cost are significantly higher than extruded polystyrene board. Compared to expanded polystyrene board, extruded polystyrene board has higher compressive strength, better waterproof performance, is moisture-resistant, lightweight, and corrosion-resistant, and virtually does not degrade over time. For roof insulation material selection, extruded polystyrene board is preferred over expanded polystyrene board. The thickness range for roof insulation materials is selected to be 80-140mm.

3.2.2. Energy-Saving Optimization for Transparent Envelope Structures

(1) Door and Window Material Optimization: The door and window materials in existing rural buildings are typically simple and feature poor thermal insulation, with the energy consumption rate of doors and windows being about four times that of walls and five times that of roofs[5]. However, optimizing these elements is relatively straightforward . Most rural

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buildings use ordinary aluminum alloy doors and windows, which do not offer high thermal insulation. For buildings where it is easy to remove and replace doors and windows, they can be upgraded to insulated glass broken bridge aluminum doors and windows. This involves changing the window glass from single-layer to double or triple layers to create a relatively sealed air layer, thereby improving thermal insulation. The window renovation scheme is detailed in Table 3.

Table 3. Common External Window Materials and Their Properties

Material	Thermal Conductivity (W/㎡·K)	Solar Heat Gain Coefficient (W/㎡·K)
Vacuum Glass (3+0.1+3)	3.0	0.713
Ordinary Double-Glazed Glass (6+9A+6)	3.1	0.722
Ordinary Triple-Glazed (Double-Glazed+Single-Glazed)	2.3	0.513
Double-Glazed Glass with Low-E Coating (Low-Transmittance Type)	2.1	0.426

(2) Window-to-Wall Ratio Control:Typically, the heat transfer coefficient of windows is higher than that of walls facing the same direction. The cooling and heating load of a residence increases with the increase in the window-to-wall area ratio. From the perspective of building energy consumption, the smaller the window-to-wall ratio, the lower the overall building load. However, considering human comfort, an appropriate window-to-wall ratio is beneficial for indoor lighting and ventilation [6], making it an important aspect of energy-saving design for new buildings. By analyzing the impact of window-to-wall ratios for different orientations, optimal window-to-wall ratio solutions and their results are presented in Table 4.

Table 4. Window-to-Wall Ratio

Window-to-Wall Ratio	A	B	C	D
South	0.3	0.4	0.5	0.6
North	0.2	0.25	0.3	0.35

4. Multifactor Coupled Energy-Saving Retrofit Scheme

4.1. Orthogonal Experiment Design

Building energy consumption is influenced by various factors such as exterior walls, doors and windows, roofs, and occupant behavior habits. Therefore, the energy-saving retrofit of existing buildings must address multiple aspects to meet the energy-saving standards. By consulting relevant literature and selecting the appropriate range of factors, an orthogonal experiment method is used to screen various experimental schemes [7]. Through the analysis of factors affecting building energy consumption, five influencing factors were ultimately selected, as shown in Table 5, including exterior walls(A), roofs (B), exterior windows(C),south-facing window-to-wall ratio(D), and north-facing window-to-wall ratio (E). Each influencing factor was assigned four levels to establish an orthogonal experiment table.

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Table 5. Influencing Factors and Level Values

Factor/Level	A external walls	B roof	C external windows	D south-facing window-to-wall ratio	E north-facing window-to-wall ratio
1	60	80	Vacuum Glass(3+0.1+3)	0.3	0.2
2	80	100	Ordinary Double-Glazed Glass(6+9A+6)	0.4	0.25
3	100	120	Ordinary Triple-Glazed (Double-Glazed + Single-Glazed)	0.5	0.3
4	120	140	Double-Glazed Glass with Low-E Coating (Low-Transmittance Type)	0.6	0.35

4.2. Optimal Combination Analysis

This study conducts a 5-factor and 4-level orthogonal experimental analysis. Therefore, for this building model, the levels are selected and filled into the orthogonal experimental table accordingly. The experiment ultimately yielded 16 test plans. The simulation calculations for the parameter values of each plan were conducted, and the range analysis results are presented in Table 6.

Based on the simulation results of the orthogonal experiment, the influence weights of various factors on the unit area load of the entire building were determined. Among them, the external wall insulation and external windows have a significant impact on the simulated building, and should be prioritized in energy-saving retrofitting of the building. The test results calculated in this experiment are the annual cumulative load indices. Therefore, by selecting the smaller values of the average level ki (where i = 1, 2, 3, 4), the optimal combination of each individual factor can be determined as A4B4C4D1E1. However, the orthogonal experiment results indicate that plan 14 (A4B2C3D1E4) is the optimal solution. Clearly, among the 16 plans of the orthogonal experiment, the scheme A1B1C1D4E4 is not present, and whether it is the best solution needs to be proven through formal testing. To compare with the best plan selected by the orthogonal experiment, validation tests were conducted using the A1B1C1D4E4 scheme and the A4B2C3D1E4 scheme, resulting in energy-saving rates of 64.88% and 79.73%, respectively. The energy-saving rates of each plan were calculated by comparing the building indices of each factor with the reference building, as shown in Figure 8. It is evident that the 14th plan with the combination of A4B2C3D1E4 has the lowest annual cumulative load index and the highest energy-saving rate, making it the optimal combination plan.

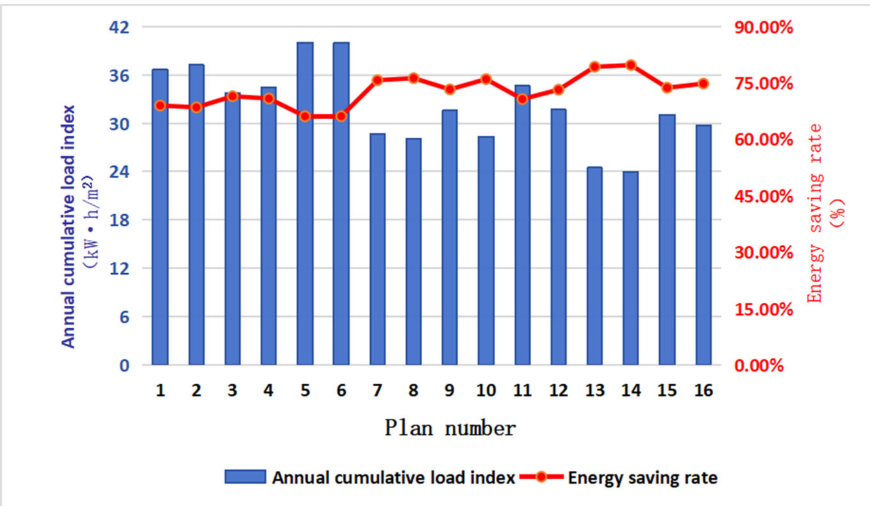

Figure 8. Experimental Results of Various Test Protocols

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Table 6. Orthogonal Experimental Table and Range Analysis Results

Number	A	B	C	D	E	Annual Cumulative Load Index	Energy Saving Rate
1	60	80	Vacuum Glass(3+0.1+3)	0.3	0.2	36.62	69.00%
2	60	100	Ordinary Double-Glazed Glass(6+9A+6)	0.4	0.25	37.22	68.50%
3	60	120	Ordinary Triple-Glazed (Double-Glazed + Single-Glazed)	0.5	0.3	33.72	71.46%
4	60	140	Double-Glazed Glass with Low-E Coating (Low-Transmittance Type)	0.6	0.35	34.44	70.85%
5	80	80	Ordinary Double-Glazed Glass(6+9A+6)	0.5	0.35	40.03	66.12%
6	80	100	Vacuum Glass(3+0.1+3)	0.6	0.3	39.98	66.15%
7	80	120	Double-Glazed Glass with Low-E Coating (Low-Transmittance Type)	0.3	0.25	28.70	75.71%
8	80	140	Ordinary Triple-Glazed (Double-Glazed + Single-Glazed)	0.4	0.2	28.04	76.26%
9	100	80	Ordinary Triple-Glazed (Double-Glazed + Single-Glazed)	0.6	0.25	31.56	73.28%
10	100	100	Double-Glazed Glass with Low-E Coating (Low-Transmittance Type)	0.5	0.2	28.35	76%
11	100	120	Vacuum Glass(3+0.1+3)	0.4	0.35	34.62	70.69%
12	100	140	Ordinary Double-Glazed Glass(6+9A+6)	0.3	0.3	31.68	73.19%
13	120	80	Double-Glazed Glass with Low-E Coating (Low-Transmittance Type)	0.4	0.3	24.48	79.28%
14	120	100	Ordinary Triple-Glazed (Double-Glazed + Single-Glazed)	0.3	0.35	23.95	79.73%
15	120	120	Ordinary Double-Glazed Glass(6+9A+6)	0.6	0.2	31.07	73.71%
16	120	140	Vacuum Glass(3+0.1+3)	0.5	0.25	29.76	74.81%
K1	142.00	132.69	140.98	120.95	124.08	Summation	
K2	136.75	129.5	140.00	124.36	127.24		
K3	126.21	128.11	117.27	131.86	129.86		
K4	109.26	123.92	115.97	137.05	133.04		
k1	35.50	33.17	35.25	30.24	31.02	Mean	
k2	34.19	32.38	35.00	31.09	31.81		
k3	31.55	32.03	29.32	32.97	32.47		
k4	27.32	30.98	28.99	34.26	33.26		
R	8.19	2.19	6.25	4.03	2.24	-	-

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5. Conclusion

In order to reduce the energy consumption of existing rural residential buildings, improve energy efficiency, and enhance indoor thermal comfort, this study focuses on low-carbon energy-saving retrofitting. Through literature review, field research, energy consumption simulation, and result analysis, various low-carbon technical retrofitting schemes for rural buildings in the southern Henan region were developed and comprehensively evaluated.

Building energy consumption is related to many factors, and the optimal scheme obtained from individual analysis of factors such as external walls and roofs may ignore the interactions between factors. The optimal results from multi-factor coupling analysis are often the best retrofitting schemes, with the highest energy-saving rate for the building. Analyzing the simulation results, it can be concluded that when the building's external walls use 120mm graphite polystyrene boards, the roof insulation material is 100mm thick extruded polystyrene boards, the external windows are ordinary triple-glazed, and the north-south window-to-wall ratios are 0.3 and 0.35 respectively, the building's total load index is the lowest, and the energy-saving rate reaches 79.73%. For economically underdeveloped areas, the building's external walls and roofs can be insulated with 60mm and 80mm thick materials, respectively, and the windows can be replaced with double-layer hollow glass plastic steel casement windows at a cost of 50-60 yuan per square meter of building area, resulting in the lowest economic cost for the retrofitting scheme.

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