DOI: https://doi.org/10.32347/2707-501x.2025.55(1).85-99

UDC 69.02.03:620.91

Guo ZHIYONG[1,2],
Master's degree,Professor
Postgraduate Student
ORCID: 0009-0007-2696-0287
Viacheslav DZHEDZHULA[2],
Doctor of Economic Sciences, Professor
ORCID: 0000-0002-2740-0771
[1]*Jiuquan Vocational and Technical College, JiuQuan, China*
[2]*Vinnytsia National Technical University, Vinnytsia, Ukraine*

RESEARCH ON THE INFLUENCING FACTORS OF ENERGY CONSUMPTION OF RURAL RESIDENTIAL BUILDINGS IN SEVERE COLD AREAS

Energy consumption of rural residential buildings was a key issue addressed in global sustainable development efforts. In this study, a typical rural self-built house in the severely cold climate of Jiuquan, China, was selected, and a dynamic energy consumption model was established using DesignBuilder software. The model was used to systematically analyze how six factors – building orientation, storey height, window-to-wall ratio, facade construction, roof construction, and external window materials-affected heating energy consumption through a one-factor experiment and an L25(5^6) orthogonal test. The results revealed that external wall insulation performance played the most significant role in energy consumption regulation, with EPS insulation facades saving 20.4% more energy than traditional clay brick walls. Low-E coated heat-breaking aluminum windows reduced energy consumption by 18.3% compared to single-pane wood frame windows, and using a 100 mm XPS insulation roof saved 9.8% of energy. The sensitivity ranking showed that the thermal parameters of the envelope (facade > windows > roof) had a stronger influence than building form parameters (floor height > window-to-wall ratio > orientation). The optimal combination scheme (WA4+WI5+RO5) achieved an annual energy consumption of 27,707 kWh, a 24.3% reduction from the baseline model. The study proposed a synergistic design strategy prioritizing high-performance envelope retrofits while limiting incremental storey heights and window-to-wall ratios, providing a quantitative basis for locally adapted energy efficiency policies for rural buildings.

Keywords: rural residential buildings; energy efficiency retrofit; heating energy consumption; orthogonal experiment; envelope optimization; building performance simulation.

Introduction. Structural differences in energy consumption patterns between urban and rural areas have exacerbated the global challenge of emissions reduction, with per capita carbon emissions rising in urban households as a result of the energy transition, while rural buildings face problems such as poor thermal performance of the envelope and inefficient use of biomass, resulting in a long-term substandard indoor thermal environment. In northern China, the average room temperature in farm houses is only 16°C in winter and 28°C in summer, resulting in a double thermal discomfort of “cold in winter and hot in summer". In response to the lack of adaptability of urban energy-saving technologies in rural areas, this study quantitatively evaluates the effects of building orientation, floor height, window-to-wall ratio, façade/roof construction, and exterior window materials on heating energy consumption by using dynamic simulation and orthogonal experiments with DesignBuilder, targeting farm houses in the cold region of Jiuquan, China.

The one-way analysis shows that the most significant energy saving effect is achieved by the exterior wall construction (EPS/rock wool insulation) (20.4% lower than the baseline), followed by the exterior window material (Low-E coated heat-breaking aluminum window saves 18.3% energy), and the roof construction (100mm XPS saves 9.8% energy). The energy consumption rises by 5.2% for every 0.3m increase in storey height, and a window-to-wall ratio of more than 0.5 needs to be matched with high-performance external windows. Orthogonal experiments show that the regulation effect of thermal performance of the envelope is better than the building form parameters, and the sensitivity ranking is exterior wall structure＞exterior window material＞roof structure＞storey height＞window-to-wall ratio＞orientation. The optimal combination (EPS facade + Low-E window + 100mm XPS roof) reduces the annual heating energy consumption to 27,707 kWh, which is 24.3% lower than the baseline; whereas the combination of thermal defects and high floor height (WA1+FH5) increases the energy consumption by 34.7%. The study proposes a tiered retrofit strategy: prioritize the implementation of exterior insulation (EPS/rock wool), promote Low-E windows and roof XPS retrofit, and control the floor height ≤ 6.0 m and window-to-wall ratio ≤ 0.5. In addition, the affordability of farmers (initial investment ≤ 8,000 RMB) and technical feasibility need to be synergistically broken through the policy subsidies and standardized technical packages, such as the Beijing demonstration project that achieves 30% energy saving rate through community-based retrofit. 30% energy saving rate. The study provides a quantitative basis for the energy-saving design of farm houses in cold regions, and in the future, it is necessary to integrate renewable energy and behavioral interventions to build a multi-scale synergistic rural energy transition path.

Analysis of research and publications.

Structural differences in urban and rural energy consumption patterns and carbon emission characteristics significantly contribute to the difficulty of implementing global emission reduction targets. While per capita CO_2 emissions from urban households continue to rise due to the immediate need for winter heating and the transition of the energy mix from coal to electricity/natural gas (Guan et al., 2023), the rural building sector presents a more complex energy efficiency dilemma: existing buildings generally suffer from thermal deficiencies in the envelope (heat transfer coefficients exceeding the standard by a factor of 2.3-4.1), and the inefficient use of traditional biomass (thermal efficiency of less than 35%), directly contributing to the persistent failure of the indoor thermal environment to meet the WHO recommended standards (Li et al., 2010). The common defective thermal performance of the envelope (heat transfer coefficient 2.3-4.0 times higher than the standard) and inefficient utilization of traditional biomass energy (thermal efficiency less than 35%) in existing buildings have directly contributed to the long term failure of the indoor thermal environment to meet the WHO recommendations (Li et al., 2020; Jiang et al., 2021). Measured data show that the average room temperature in farm houses in northern China is only 16°C in winter (6°C below the standard), but as high as 28°C in summer (4°C above the standard), accompanied by fluctuations in relative humidity of more than 75%, resulting in the double thermal discomfort of "cold in winter and hot in summer" and "humid and stuffy" (Li et al., 2020). This unique paradoxical demand structure determines that the urban-oriented energy efficiency retrofit paradigm is not sufficiently adapted to rural scenarios (Cao et al., 2021), and there is an urgent need to construct technical solutions based on the genetics of rural buildings.

Thermal performance improvement of the building envelope system has become the core path to reduce the cooling and heating loads of buildings. Studies have shown that the implementation of exterior wall/roof composite insulation ($\lambda \leq 0.035$ W/(m-K)) with Low-E insulating glass (U-value ≤ 1.2 W/(m²-K)) integrated retrofit in cold climate zones can reduce heating energy consumption by 42%-58% (Zhang et al., 2024; Jiang et al., 2023). Innovative solutions such as additional sunrooms coupled with phase change material (PCM) systems can even achieve a breakthrough of 92.17% in the comprehensive energy saving rate of rural houses (Ma et al., 2020). The multi-objective optimization model effectively balances the technical economics through parameter synergy (insulation thickness δ = 80-120 mm, window-to-wall ratio control at 25%-30%) (Wang et al., 2024; Cao et al., 2024). However, the sensitive thresholds of farmers' initial investment (average affordable limit for rural households ≤ 8,000 RMB) and payback period (expectation ≤ 5 years) still need to be broken through policy subsidies and community-based renovation models (Han et al., 2023; Huang & Lin, 2022). The Beijing New Rural Retrofit Demonstration Project has achieved an overall energy saving rate of 30% through the promotion of standardized technology packages, providing a replicable engineering paradigm for similar climate zones (Deng et al., 2023).

The international academic community contributed solutions from different technical dimensions: Kalhor et al. (2020) established qualitative optimization guidelines for the selection of envelope parameters and insulation materials through COMcheck energy simulation; Huang et al. (2021) developed a coupled optimization model for the thermal performance of envelope units based on the LCCA methodology, which revealed the synergy law of the wall/door/window system; Homod et al. (2021) MATLAB/Simulink material simulation, on the other hand, quantitatively verified the sensitive weighting of building materials' thermal conductivity on building energy consumption ($R^2 = 0.89$). Notably, Huang et al.'s (2020) rural social research shows that farmers' willingness to pay (WTP) for low-cost envelope retrofits can be up to 1.8 times that of the traditional solution, subject to the constraints of investment ≤ 5000 RMB and construction period ≤ 15 days.Hamooleh et al. (2024) experiments on PCM walls (with ΔT attenuation of 62%) are in line with the results of the rural energy efficiency investment by Kaya et al. (2021) rural energy efficiency investment analysis (subsidy dependency ≥75%) further reveal that technical feasibility and economic acceptability remain the double helix constraints for rural energy efficiency retrofits. Follow-up studies by Han et al. (2023) and Zhang et al. (2024) show that farmers' acceptance of low-cost solutions such as "thin plaster + internal insulation" is 45% higher than that of traditional solutions, which provides important insights for technology transformation.

Problem statement.

The structural contradiction between urban and rural energy consumption patterns poses a serious challenge to global emissions reduction: the urban energy transition has pushed up per capita carbon emissions, while rural buildings' indoor thermal environments have long deviated from WHO standards due to thermal deficiencies in the envelope and inefficient use of traditional biomass, creating a double dilemma of “energy efficiency and comfort”. Although composite thermal insulation, Low-E glass and other technical solutions have been proposed, the urban-oriented retrofit paradigm faces insufficient adaptability in rural areas: on the one hand, farmers are highly sensitive to the initial investment and payback cycle, and it is difficult to match the economics of the existing technologies; on the other hand, the interaction mechanism between envelope parameters (e.g., thermal insulation thickness, window-to-wall ratio) and the building morphology (storey height, orientation) has not yet been clarified, which restricts the development of a differentiated retrofit strategy. The mechanism of interaction between envelope parameters (e.g., insulation thickness, window-to-wall ratio) and building form (floor height, orientation) is not yet clear, restricting the differentiation of retrofit strategies. How to quantify the key factors influencing the energy consumption of farm buildings in cold regions and balance the technical effectiveness and economic feasibility have become the core issues to solve the bottleneck of rural energy efficiency improvement. The aim of this study is to reveal the key influencing factors and their interaction mechanisms of rural residential heating energy consumption in cold regions, and to propose economically feasible energy-saving optimization paths. By establishing a DesignBuilder dynamic energy consumption model of a typical rural house in Jiuquan area, using a combination of single-factor analysis and multi-factor orthogonal experiments to systematically evaluate the quantitative impact of six types of design parameters on energy consumption, constructing an orthogonal matrix containing 25 sets of experiments, and combining polar analysis and variance analysis to clearly define the sensitivity ranking and synergy law of each factor. It provides data support for cracking the technical and economic barriers to energy efficiency improvement in rural buildings, and has important practical value for the formulation of differentiated subsidy policies and the promotion of suitable energy-saving technologies in rural areas.

Research models and methods.

Baseline model engineering overview.The research object is a rural self-built residence, brick structure, north-south orientation, two floors above ground, local first floor, first floor height of 2.7m, second floor height of 2.7m, building height of 5.4m. indoor and outdoor height difference of 0.30m. the first and second floors are equipped with a living room, bedrooms, kitchens and stairwells, with a total floor area of 209.41m^2, the roof form of four-sloped roofs, the external wall is made of 370mm clay bricks, and the internal wall is made of 240mm clay bricks, and the roof is made of 120mm cast-in-place reinforced concrete. 240mm clay bricks are used for external walls, 240mm clay bricks are used for internal walls, and 120mm cast-in-place reinforced concrete is used for the roof. The architectural baseline DesignBuilder model is shown in Figure1.

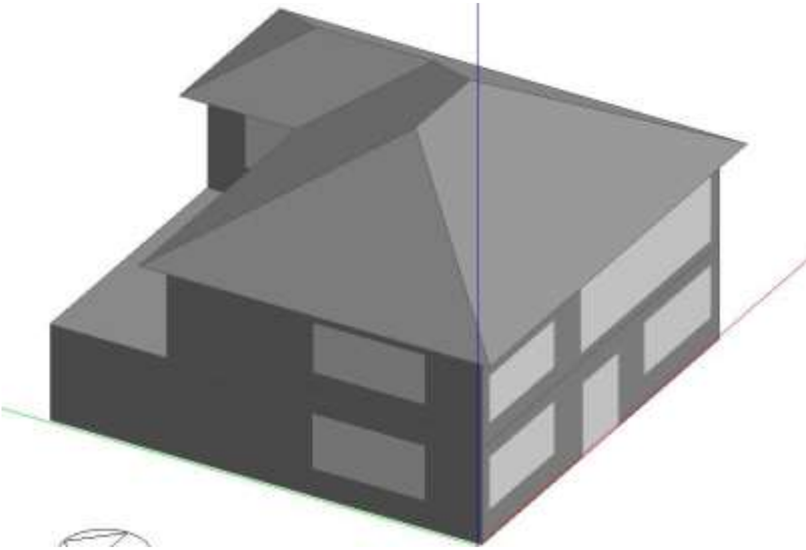

Figure 1. Baseline DesignBuilder model

Meteorological condition parameters.The outdoor climate is based on the Chinese Standard Weather Data (CSWD) JIUQUAN typical meteorological data, which comes with the DesignBuilder software. Jiuquan area is located in the northwest of China, with the longitude of 98°20'~99°18' East and the latitude of 39°10'~39°59' North. Jiuquan is located in northwest China, between 98°20'~99°18'E and 39°10'~39°59'N, in the northwest of Gansu Province. Affected by the continental arid climate conditions, Jiuquan region has a long and cold winter, with a frost-free period of 127-158 days, and the lowest temperature in history reaching -24.4℃, and a strong sunshine and dry heat in summer, with the highest temperature in history reaching 43.1℃, and the temperature difference in the whole year peaking at 67.5℃, and the average number of hours of sunshine in a year is 3056.4 hours.

Winter and summer air-conditioning parameter settings.According to the thermal comfort level classification standard of this residential building and the corresponding indoor design parameter limit value of air conditioning, the indoor calculated temperature of this winter and summer air conditioning energy simulation takes 18℃ and 26℃ respectively, the calculated heating period of this region is 151 days, and the number of air changes takes 1 time/h.

Selection of energy consumption simulation software.The use of Energy Plus can be widely used in building energy consumption simulation analysis, the results of which have accuracy and reasonableness, DesignBuilder is a comprehensive user interface simulation software for building energy consumption dynamic simulation program Energplus. DesignBuilder is a comprehensive graphical user interface simulation software for Energplus, a dynamic simulation program for building energy consumption. It provides performance data to optimize design and evaluation, quickly models complex buildings, and simulates the environment such as light, temperature, and CO_2 in the created model, making it an energy-saving architectural design software that realizes the consideration of the environment from the planning stage onward. In this paper, DesignBuilder software is used to simulate energy consumption.

Selection and value of energy consumption influencing factor level.Combined with the existing research results, this paper is based on the climate characteristics of cold regions and the status quo of typical rural residential buildings, and selects 6 key factors related to heating energy consumption, including building orientation, building height, window-to-wall ratio, exterior wall construction, roof construction and exterior window materials, and selects 5 levels for each factor, and adopts single-factor analysis and multi-factor orthogonal experimental method to study the impact of the changes in the levels of each factor and the interactions on the energy consumption of the building. The values of factors and levels affecting energy consumption are shown in Table 1, the roof structure and thermal parameters in Table 2, the exterior wall structure and thermal parameters in Table 3, and the exterior window materials and thermal properties in Table 4.

Table 1 Influencing factors and levels of energy consumption of rural residential buildings Table

Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Orientation (OR)	OR1 (0°due south)	OR2 (15°)	OR3 (30°)	OR4 (60°)	OR5 (90°)
Floor Height (FH)	FH1 (5.4m)	FH2 (5.7m)	FH3 (6.0m)	FH4 (6.3m)	FH5 (6.6m)
Window-to-wall ratio (WWR)	WWR1 (0.3)	WWR2 (0.4)	WWR3 (0.5)	WWR4 (0.6)	WWR5 (0.7)
Exterior Wall (WA)	WA1 (baseline)	WA2 (grass board composite)	WA3 (aerated concrete)	WA4 (EPS insulation)	WA5 (rock wool insulation)
Roof (RO)	RO1 (baseline)	RO2 (grass board insulation)	RO3 (Color Steel Sheet)	RO4 (50mm XPS)	RO5 (100mm XPS)
Exterior Window (WI)	WI1 (single-pane)	WI2 (double-layer common)	WI3 (double thick glass)	WI4 (Blue Glass)	WI5 (Low-E coating)

Table 2 Roof structure and thermal parameters

Level	Structure	Thermal Parameters U-Value (W/m^2-K)	No.
Level 1	Cement tile 20mm + cement mortar 20mm + reinforced concrete 120mm	3.497	RO1
Level 2	20mm cement tile+10mm asphalt linoleum+20mm cement mortar+200mm grass board insulation layer+120mm concrete	0.429	RO2
Level 3	100mm polystyrene sandwich color steel plate	0.300	RO3
Level 4	15mm cement tile+10mm asphalt linoleum+20mm cement mortar+50mm XPS thermal insulation layer+120mm concrete	0.501	RO4
Level 5	15mm cement tile+10mm asphalt linoleum+20mm cement mortar+100mm XPS heat preservation layer+120mm concrete	0.273	RO5

Table 3 Wall structure and thermal parameters

Level	Structure	Thermal Parameters U-Value (W/m^2-K)	No.
Level 1	10mm lime mortar + 370mm common clay brick wall + 20mm cement mortar	1.303	WA1
Level 2	10mm lime mortar + 120 ordinary clay bricks + 100mm grass board + 240mm ordinary clay bricks + 20mm cement mortar	0.580	WA2
Level 3	10mm lime mortar+300mm aerated concrete block+20mm cement mortar	0.679	WA3
Level 4	10mm lime mortar+240 lightweight blocks+100mm EPS insulation board+20mm cement mortar	0.255	WA4
Level 5	10mm lime mortar+200mm aerated concrete block+100mm XPS insulation board+20mm cement mortar	0.228	WA5

Table 4 Exterior window materials and thermal parameters

Level	Structure	Thermal Parameters U-Value (W/m^2-K)	No.
Level 1	6mm single-pane clear glass, wood frame	5.778	WI1
Level 2	Double clear 3mm/13mm Air,Aluminium window frame	2.716	WI2
Level 3	Double clear 6mm/13mm Air,Aluminium window frame	2.665	WI3
Level 4	Double blue 6mm/13mm Air,Aluminium window frame	2.511	WI4
Level 5	Double LOE clear 6mm/13mm Air,Aluminium window frame,with thermal break	1.761	WI5

The main research results.

—Results and Analysis of Single Influencing Factors

Influence of Building Orientation on Energy Consumption. The single-variable energy consumption simulation of building orientation yielded a trend graph illustrating the impact of various orientations on building energy consumption, as depicted in Figure 2. The data reveals that building orientation significantly affects heating energy consumption. As the orientation of the house shifts gradually from due south (0°) to 90°, the heating energy consumption increases from 36,597.71 kWh to 37,434.11 kWh. Due to the maximization of solar radiation heat gain during winter, a due south orientation exhibits the lowest energy consumption. As the orientation deviates from due south, the solar radiation received by the building facade decreases, leading to an increase in the heat load.

Influence of Storey Height on Energy Consumption. The single-variable energy consumption simulation of building floor height produced a trend graph showing the impact of various floor heights on building energy consumption, as presented in Figure 3. An increase in the total floor height from 5.4m to 6.6m results in a 19.5% increase in energy consumption. By using Origin 2021 software to fit the data, a positive relationship between building energy consumption and heating energy consumption was established, with the linear regression equation provided in Equation (1). Each 0.3m increase in storey height leads to an annual increase in energy consumption of approximately 1,800 kWh. Higher storey heights increase the building volume, which enhances the rise of hot air and necessitates additional energy to maintain indoor thermal comfort.

$$Y = 1788.765x + 34793.363 \quad R^2=1 \tag{1}$$

Where: Y is the heating energy consumption (kWh); x is the building height (m)

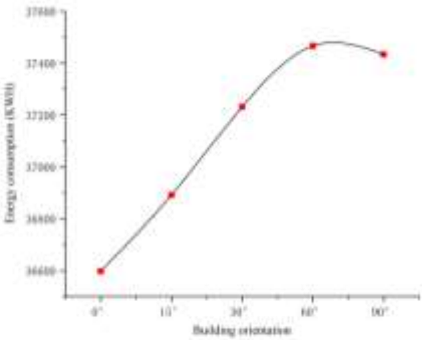

Figure 2. Trend of the effect of house orientation on energy consumption

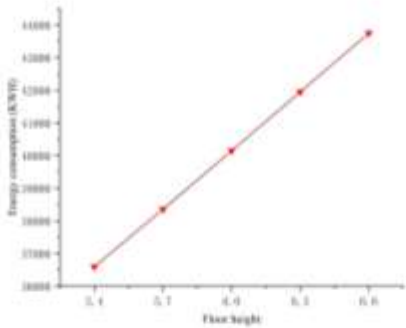

Figure 3. Trend of the effect of building height on energy consumption

Effect of window-to-wall ratio on energy consumption. Through the simulation of energy consumption of a single variable of building window-wall ratio, the trend graph of the impact of building energy consumption with different window-wall ratios is obtained as in Figure 4. The data show that the energy consumption increases from 36,597.71 kWh to 38,222.18 kWh when the window-wall ratio (WWR) is increased from 0.3 to 0.7. The increase in energy consumption of about 2.5% for every 0.1 increase in WWR is mainly due to the poor thermal insulation performance of the single-pane windows. Although increasing the window-to-wall ratio enhances natural daylighting, it leads to significant heat loss in cold regions.

Influence of wall construction on heating energy consumption.Through the single-variable energy consumption simulation of building wall construction, the trend of the impact of different wall constructions on building energy consumption is obtained as shown in Fig. 5, which shows that the energy consumption of the exterior wall with WA4 (EPS insulation) and WA5 (rock wool insulation) is the lowest, and the energy saving is 20.4-20.6% compared with the traditional clay brick wall. the low thermal conductivity of EPS and rock wool significantly reduces the heat loss of wall heat transfer. The energy saving of WA4 was 11.1% compared to WA3 (aerated concrete block), indicating that composite insulation is superior to single material.

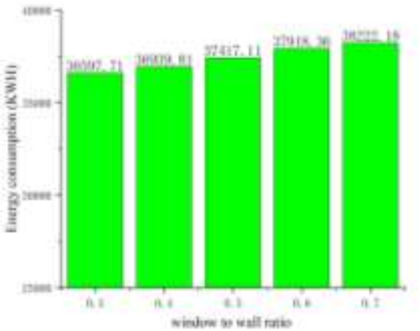

Figure 4. Building energy consumption for different window-to-wall ratios

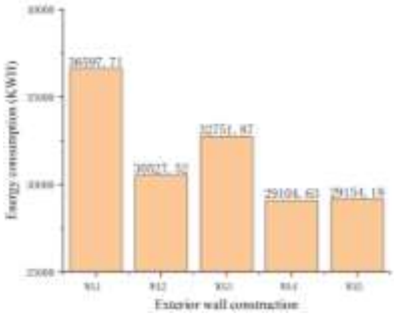

Figure 5. Energy consumption of different exterior wall configurations

Effect of roof construction on heating energy consumption. Through the single-variable energy simulation of roof construction, the trend graph of the impact of building energy consumption of different roof constructions is obtained as in Figure 5.The roof insulation significantly affects the energy consumption, and RO5 (100 mm XPS) consumes the lowest amount of energy, which is reduced by 9.8% compared with the baseline roof RO1.The thermal conductivity of XPS is lower than that of the grass boards and the polystyrene sandwich panels, which effectively suppresses the heat loss. However, the difference in energy consumption between RO3 (color steel sheet) and RO5 is only 0.6%, indicating that lightweight roofs need to trade-off thermal insulation and structural strength.

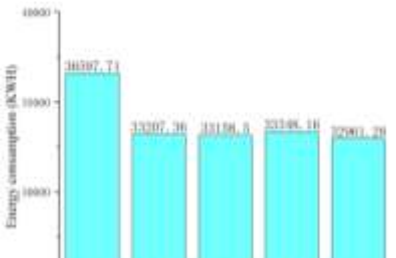

Figure 6. Building energy consumption of different roof constructions

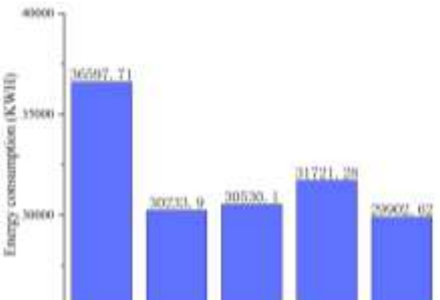

Figure 7. Energy consumption of building with different window materials

Influence of external window materials on heating energy consumption.Through the simulation of single-variable energy consumption of different external window materials, the trend of building energy consumption of different external window materials is obtained in Figure 7.The data show that the energy consumption of using heat-breaking aluminum alloy frame + double Low-E glass (WI5) is the lowest, and the energy saving is 18.3% compared with that of single-pane wooden frame window.The Low-E coating reduces the loss of long-wave radiation, and the heat-breaking aluminum frame lowers the heat-transfer coefficient of the window frame to 1.8 W/m²-K. The energy consumption of the double-glazed energy consumption of 30,233.90 kWh for a regular insulating window (WI2) indicates that synergistic optimization of coating and frame is the key.

Ranking of key factors

Prioritization was determined as follows by ranking the key influencing factors in terms of absolute value of percentage change in energy consumption:

Exterior wall material (-20.5%): thermal insulation dominates, WA4 (EPS insulation) is the most effective.

Exterior window type (-18.3%): thermal bridging + Low-E coating (WI5) significantly reduces heat loss.

Storey height (+19.5%): for every 1m increase in storey height, energy consumption increases by about 3.3%.

Roof structure (-10.0%): Increased thickness of XPS thermal insulation layer enhances energy saving.

Window-to-wall ratio (+4.4%): Increased window area will exacerbate heat exchange and needs to be combined with high-performance external windows.

Orientation (+2.3%): Due south orientation (OR1) has the lowest energy consumption, followed by east-west orientation, and north orientation is the worst.

－Multi-influence factors results and analysis

In order to understand the interaction among the factors, this study simulated the combined effects of six factors on heating energy consumption of rural residential buildings in terms of orientation (OR), floor height (FH), window-to-wall ratio (WWR), facade construction (WA), roof construction (RO), and external window material (WI) by orthogonal experimental design (L25(5^6)). Table 5 demonstrates the energy consumption results of the 25 sets of tests, revealing the sensitivity of each factor and its interaction through analysis of polarity and analysis of variance (ANOVA).

Table 5 Simulation results of orthogonal experiments

Experiment No.	Orientation (OR)	Floor Height (FH)	Window-to-wall ratio (WWR)	External Wall (WA)	Roof (RO)	Exterior Window (WI)	Energy consumption (KWh)
1	OR1	FH1	WWR1	WA1	RO1	WI1	36597.71
2	OR1	FH2	WWR2	WA2	RO2	WI2	26456.96
3	OR1	FH3	WWR3	WA3	RO3	WI3	29646.67
4	OR1	FH4	WWR4	WA4	RO4	WI4	28831.81
5	OR1	FH5	WWR5	WA5	RO5	WI5	27707.37
6	OR2	FH1	WWR2	WA3	RO4	WI5	26313.95
7	OR2	FH2	WWR3	WA4	RO5	WI1	28729.82
8	OR2	FH3	WWR4	WA5	RO1	WI2	31111.55
9	OR2	FH4	WWR5	WA1	RO2	WI3	36165.92
10	OR2	FH5	WWR1	WA2	RO3	WI4	30112.28
11	OR3	FH1	WWR3	WA5	RO2	WI4	24409.02
12	OR3	FH2	WWR4	WA1	RO3	WI5	33332.27
13	OR3	FH3	WWR5	WA2	RO4	WI1	33554.27

Table 5 (continued)

Experiment No.	Orientation (OR)	Floor Height (FH)	Window-to-wall ratio (WWR)	External Wall (WA)	Roof (RO)	Exterior Window (WI)	Energy consumption (KWh)
14	OR3	FH4	WWR1	WA3	RO5	WI2	32032.47
15	OR3	FH5	WWR2	WA4	RO1	WI3	32708.44
16	OR4	FH1	WWR4	WA2	RO5	WI3	25974.39
17	OR4	FH2	WWR5	WA3	RO1	WI4	33083.01
18	OR4	FH3	WWR1	WA4	RO2	WI5	27221.12
19	OR4	FH4	WWR2	WA5	RO3	WI1	31606.86
20	OR4	FH5	WWR3	WA1	RO4	WI2	39426.59
21	OR5	FH1	WWR5	WA4	RO3	WI2	25806.21
22	OR5	FH2	WWR1	WA5	RO4	WI3	25844.56
23	OR5	FH3	WWR2	WA1	RO5	WI4	34888.32
24	OR5	FH4	WWR3	WA2	RO1	WI5	33771.33
25	OR5	FH5	WWR4	WA3	RO2	WI1	38609.79

Sensitivity analysis of each factor on energy consumption. In order to evaluate the main factors of orthogonal experiments, Extreme variance analysis was used, and the mean and polar deviation of energy consumption under the level of each factor were calculated from equations (2) and (3) as shown in Table 6.The sensitivity ranking was obtained as follows: exterior wall construction>exterior window material>roof construction>storey height>window-to-wall ratio>facing direction. The results show that the thermal performance of the envelope (external wall, external window, roof) has a significantly stronger role in regulating energy consumption than the building form parameters (floor height, window-to-wall ratio, orientation).

$$\bar{y}_{A_K} = \frac{1}{nA_k}\sum_{i=1}^{N} y_i \cdot I(A_i = k) \qquad (2)$$

Where: nA_k is the number of trials at the kth level of factor A,and I（·） is the indicative function (taking 1 when A_i=k and 0 otherwise).

$$R_A = max(\bar{y}A_1, \bar{y}A_2, \cdots, \bar{y}A_m)\text{-}min(\bar{y}A_1, \bar{y}A_2, \cdots, \bar{y}A_m) \qquad (3)$$

Where: R_A is the extreme variance at each factor level, and y_{Ai} is the average energy consumption at each factor level.

Table 6 Average energy consumption at each factor level (kWh)

Factors	Level 1	Level 2	Level 3	Level 4	Level5	Extreme variance（R）
External Wall (WA	35,597	29,193	32,752	29,105	29,154	7,493.09
Exterior Window (WI)	35,263	31,807	32,455	31,201	29,903	7,371.21
Roof (RO)	35,766	30,295	31,159	30,583	32,961	6,296.34
Floor Height (FH)	30,169	30,869	32,432	32,760	33,920	5,168.29
Window-to-wall ratio (WWR)	31,524	30,859	32,018	32,625	33,280	3,755.82
Orientation (OR)	31,848	30,486	31,507	30,770	32,384	3,438.16

Mechanism of action of key factors.Exterior wall construction (WA).WA4 (EPS insulation) and WA5 (rock wool insulation) reduce energy consumption by 20.4% and 20.3%, respectively, compared to the baseline (WA1), and their low thermal conductivity significantly reduces heat loss .WA2 (grass board composite) is slightly less energy efficient than WA4 due to the inclusion of 100 mm grass board.

Exterior window materials (WI).The energy consumption of WI5 (Low-E coating + thermal break aluminum frame) was 18.3% lower than that of WI1 (single-pane wood frame), which was mainly attributed to the low emissivity of Low-E coating and optimized heat transfer coefficients of the thermal break aluminum frame.The energy savings of WI2 (double-pane regular hollow) and WI4 (blue glass) were 9.8% and 11.5%, indicating that the synergistic design of coating and framing is crucial to reduce longwave radiation loss.Roof construction (RO). RO5 (100 mm XPS) was 9.8% more energy efficient than the baseline roof (RO1), and its thermal conductivity was significantly lower than that of RO2 strawboard insulation. However, RO3 (colored steel sheet) consumes only 5.4% less energy than RO1 due to the lack of effective insulation, confirming the law of diminishing marginal benefit of roof insulation thickness on thermal resistance.

In addition, some combinations show significant interaction effects, with energy consumption decreasing to 27,707.37 kWh when WA4 (EPS insulation) is used with WI5 (Low-E windows), which is 12% higher than the single-factor energy saving stacking effect, while the combination of WA1 (baseline external wall) and FH5 (6.6 m storey height) leads to a surge in energy consumption to 39,426.59 kWh, reflecting the thermal defects and the synergistic negative impact of space volume expansion. Based on the sensitivity analysis, the energy efficiency priorities for rural buildings are proposed: adopting EPS or rock wool exterior wall insulation (WA4/WA5); promoting Low-E coated heat-breaking aluminum windows (WI5); and laying ≥50 mm XPS insulation on the roof (RO4/RO5). It is also necessary to avoid the combination design of high window-to-wall ratio (WWR>0.5) and high floor height (FH>6.0 m).

Conclusion

In this study, the key influencing factors of heating energy consumption of rural residential buildings in severe cold areas and their action mechanisms were systematically revealed through the combination of dynamic energy simulation and orthogonal experiments, and the following research results were obtained.

The one-way analysis showed that the exterior wall construction was the primary sensitivity factor, and the use of EPS insulation (WA4) or rock wool composite wall (WA5) could realize energy saving rates of 20.4% and 20.3%, respectively. Improvements in the thermal performance of exterior window materials provided significant marginal benefits, with Low-E coated thermal break aluminum windows (WI5) reducing energy consumption by 18.3% compared to traditional single-pane wood-framed windows. The increased thickness of roofing XPS insulation improved energy efficiency, but the gain in energy efficiency slowed down beyond 50 mm, with 100 mm XPS (RO5) saving 9.8% compared to the baseline roofing. The synergistic effect of building form parameters could not be ignored - every 0.3 m increase in storey height led to a 5.2% increase in energy consumption, and a window-to-wall ratio of more than 0.5 needed to be combined with high-performance windows to avoid a surge in heat loss.

The results of the orthogonal experiments revealed the complex mechanism of multi-factor interaction, and the optimal combination (WA4+WI5+RO5) achieved an annual heating energy consumption of 27,707 kWh, which was 24.3% lower than that of the baseline model, and the energy-saving effect showed a nonlinear superposition feature. Conversely, poor combinations (e.g., WA1+FH5) led to a surge in energy consumption to 39,426 kWh, highlighting the negative coupling effect of thermal defects and space volume expansion. These findings provided a cascading decision-making framework for rural building energy efficiency retrofits: prioritizing the implementation of exterior wall insulation, followed by the promotion of Low-E windows and roof XPS retrofits, while controlling the floor height (≤6.0 m) and window-to-wall ratio (≤0.5) through design optimization.

The results of this study provided a quantitative basis for the energy-saving design of agricultural houses in cold regions, and future research needs to further integrate renewable energy systems and behavioral intervention strategies to construct a multi-scale synergistic rural energy transition path.

References:

[1] Kalhor, K., & Emaminejad, N. (2020). Qualitative and quantitative optimization of thermal insulation materials: Insights from the market and energy codes. *Journal of Building Engineering*, 30, 101275. https://doi.org/10.1016/j.jobe.2020.101275

[2] Li, B., You, L., Zheng, M., Wang, Y., & Wang, Z. (2020). Energy consumption pattern and indoor thermal environment of residential building in rural China. *Energy and Built Environment*, 1(3), 327-336. https://doi.org/10.1016/j.enbenv.2020.04.004

[3] Yang, Z., Zhang, W., Qin, M., & Liu, H. (2022). Comparative study of indoor thermal environment and human thermal comfort in residential buildings among cities, towns, and rural areas in arid regions of China. *Energy and Buildings*, 273, 112373. https://doi.org/10.1016/j.enbuild.2022.112373

[4] Du, Q., Han, X., Li, Y., Li, Z., Xia, B., & Guo, X. (2021). The energy rebound effect of residential buildings: Evidence from urban and rural areas in China. *Energy Policy*, 153, 112235. https://doi.org/10.1016/j.enpol.2021.112235

[5] Guan, X., Guo, S., Xiong, J., Jia, G., & Fan, J. L. (2023). Energy-related CO_2 emissions of urban and rural residential buildings in China: A provincial analysis based on end-use activities. *Journal of Building Engineering*, 64, 105686. https://doi.org/10.1016/j.jobe.2022.105686

[6] Jiang, W., Liu, B., Li, Q., Li, D., & Ma, L. (2021). Weight of energy consumption parameters of rural residences in severe cold area. *Case Studies in Thermal Engineering*, 26, 101131. https://doi.org/10.1016/j.csite.2021.101131

[7] Cao, W., Yang, L., Zhang, Q., Chen, L., & Wu, W. (2021). Evaluation of rural dwellings' energy-saving retrofit with adaptive thermal comfort theory. *Sustainability*, 13(10), 5350. https://doi.org/10.3390/su13105350

[8] Zhang, X., Zhang, X., Chen, B., Zhao, J. R., Sun, J., Zhao, J., ... & Zhu, J. (2024). Thermal Performance Optimization of Building Envelopes in a Low-Cost and Energy-Saving Rural Dwelling in Severe Cold Region—Taking Central Area of Liaoning as an Example. *Buildings*, 14(8), 2505. https://doi.org/10.3390/buildings14082505

[9] Jiang, W., Jin, Y., Liu, G., Li, Q., & Li, D. (2023). Passive nearly zero energy retrofits of rammed earth rural residential buildings based on energy efficiency and cost-effectiveness analysis. *Renewable and Sustainable Energy Reviews*, 180, 113300. https://doi.org/10.1016/j.rser.2023.113300

[10] Ma, L., Zhang, X., Li, D., Arıcı, M., Yıldız, Ç., Li, Q., ... & Jiang, W. (2020).

Influence of sunspace on energy consumption of rural residential buildings. *Solar Energy*, 211, 336-344. https://doi.org/10.1016/j.solener.2020.09.043

[11] Wang, M., Xu, Y., Shen, R., & Wu, Y. (2024). Performance-Oriented Parametric Optimization Design for Energy Efficiency of Rural Residential Buildings: A Case Study from China's Hot Summer and Cold Winter Zone. *Sustainability*, 16(19), 8330. https://doi.org/10.3390/su16198330

[12] Cao, P., Sun, Q., Li, H., & Jiao, Y. (2024). Optimization Analysis of an Energy-Saving Renovation Scheme for Building Envelopes of Existing Rural Houses Based on a Comprehensive Benefit Evaluation. *Buildings*, 14(2), 454. https://doi.org/10.3390/buildings14020454

[13] Han, T., Liu, P., Niu, C., & Li, Q. (2023). Evaluation of energy-saving retrofit projects of existing rural residential envelope structures from the perspective of rural residents: the Chinese case. *Environment, Development and Sustainability*, 25(8), 8419-8446. https://doi.org/10.1007/s10668-022-02876-5

[14] Huang, M. Q., & Lin, R. J. (2022). Evolutionary Game Analysis of Energy-Saving Renovations of Existing Rural Residential Buildings from the Perspective of Stakeholders. *Sustainability*, 14(9), 5723. https://doi.org/10.3390/su14095723

[15] Deng, Q., Shan, M., Zhang, G., Zhang, S., Liu, Y., & Yang, X. (2023). Effect Evaluation of Large-Scale Energy Saving Renovation of Rural Buildings in Beijing and Implications for Other Cities in the Same Zone. *Sustainability*, 15(6), 5580. https://doi.org/10.3390/su15065580

[16] Huang, J., Wang, S., Teng, F., & Feng, W. (2021). Thermal performance optimization of envelope in the energy-saving renovation of existing residential buildings. *Energy and Buildings*, 247, article number 111103. DOI: 10.1016/j.enbuild.2021.111103.

[17] Homod, R.Z., Almusaed, A., Almssad, A., Jaafar, M.K., Goodarzi, M., & Sahari, K.S. (2021). Effect of different building envelope materials on thermal comfort and air-conditioning energy savings: A case study in Basra city, Iraq. *Journal of Energy Storage*, 34, article number 101975. DOI: 10.1016/j.est.2020.101975.

[18] Huang, M., & Lin, R. (2020). Analysis on the difficulties and countermeasures of energy saving reconstruction of existing rural residential buildings. *IOP Conference Series: Earth and Environmental Science*, 569, 012023. DOI: 10.1088/1755-1315/569/1/012023.

[19] Hamooleh, M.B., Torabi, A., & Baghoolizadeh, M. (2024). Multi-objective optimization of energy and thermal comfort using insulation and phase change materials in residential buildings. *Building and Environment*, 262, 111774. DOI: 10.1016/j.buildenv.2024.111774.

[20] Kaya, O., Klepacka, A.M., & Florkowski, W.J. (2021). The role of personal and environmental factors in rural homeowner decision to insulate; an example from Poland. *Renewable and Sustainable Energy Reviews*, 150, 111474. DOI: 10.1016/j.rser.2021.111474.

Го ЧЖИОНГ, В'ячеслав ДЖЕДЖУЛА

Дослідження факторів впливу на енергоспоживання сільських житлових будинків в умовах сильних холодів

Виявлені ключові фактори впливу та механізми їх взаємодії на споживання теплової енергії в сільських житлових будинках у холодних регіонах, а також запропоновані економічно обґрунтовані шляхи оптимізації енергозбереження.

Шляхом створення динамічної моделі енергоспоживання типового сільського будинку в районі Цзюцюань у DesignBuilder, використання комбінації однофакторного аналізу та багатофакторних ортогональних експериментів для систематичної оцінки кількісного впливу шести типів проектних параметрів на енергоспоживання, побудови ортогональної матриці, що містить 25 наборів експериментів, а також поєднання полярного аналізу та дисперсійного аналізу для уточнення рейтингу чутливості та закону синергії кожного фактора.

Односторонній аналіз показує, що конструкція зовнішніх стін є основним фактором чутливості, а використання ізоляції EPS (WA4) або композитної стіни з кам'яної вати (WA5) дозволяє досягти показників енергозбереження на рівні 20,4% і 20,3% відповідно. Покращення теплових характеристик зовнішніх віконних матеріалів забезпечує значні маржинальні переваги: алюмінієві вікна з низькоемісійним покриттям (WI5) знижують енергоспоживання на 18,3% порівняно з традиційними однокамерними вікнами з дерев'яною рамою. Збільшення товщини ізоляції даху з пінополістиролу (XPS) покращує енергозбереження, але при товщині понад 50 мм приріст сповільнюється: 100-міліметровий шар XPS (RO5) заощаджує 9,8% енергії порівняно з базовим варіантом даху. Не слід ігнорувати синергетичний ефект параметрів форми будівлі – кожні 0,3 м збільшення висоти поверху призводить до збільшення енергоспоживання на 5,2%, а співвідношення вікна до стіни більше 0,5 вимагає високоефективних зовнішніх вікон, щоб уникнути сплеску тепловтрат.

Результати ортогональних експериментів розкривають складний механізм багатофакторної взаємодії, і оптимальна комбінація (WA4+WI5+RO5) досягає річного споживання енергії на опалення 27 707 кВт-год, що на 24,3% нижче, ніж у базовій моделі, а енергозберігаючий ефект має нелінійний суперпозиційний характер. І навпаки, погані комбінації (наприклад, WA1+FH5) призводять до сплеску енергоспоживання до 39 426 кВт-год, що підкреслює негативний ефект зв'язку теплових дефектів і розширення об'єму приміщення.

Це дослідження забезпечує інформаційну підтримку для подолання технічних та економічних бар'єрів на шляху підвищення енергоефективності в сільських будівлях і має велику практичну цінність для розробки диференційованої політики субсидій та просування відповідних енергозберігаючих технологій у сільській місцевості.

Ключові слова: сільські житлові будинки; енергоефективна модернізація; споживання теплової енергії; ортогональні експерименти; оптимізація огороджувальних конструкцій; моделювання характеристик будівлі.