

Research on Energy Consumption Optimization and Carbon Emission Prediction of Traditional Residential Buildings in Hehuang, Qinghai Province

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Abstract

Improving the energy efficiency of traditional residential buildings is a crucial pathway toward achieving carbon neutrality in China's building sector. Traditional dwellings in the Hehuang region of Qinghai suffer from poor thermal performance and excessive energy consumption, making optimization an urgent necessity. This study investigates such dwellings through field surveys, energy simulations using DeST-H, orthogonal experimental design, and multiple regression modeling to analyze the influence of key building parameters on energy use. Range analysis from orthogonal tests identified the optimal retrofit strategy as: applying interior insulation with 70 mm rock wool boards and 12 mm gypsum boards to ordinary exterior walls; 80 mm rock wool boards and 12 mm gypsum boards to roofs; and 50 mm rock wool boards and 12 mm gypsum boards to Zhuangkuo-style exterior walls; adopting a south-facing window-to-wall ratio of 0.5; orienting the building 15° west of due south; and using double glazing with a thermal transmittance of 2.1 W/(m²·K). This configuration achieved a 76.6% reduction in both energy consumption and carbon emissions, demonstrating substantial energy-saving and decarbonization potential. A multiple regression-based carbon emission prediction model was developed and validated for the Hehuang traditional dwellings, offering quantitative guidelines and strategic references for optimizing energy performance in similar climatic and cultural contexts. The findings provide a robust decision-making basis for parameter optimization in practical energy retrofits.

Keywords

Hehuang Traditional Dwellings; Building Energy Performance; DeST-H Simulation; Orthogonal Design; Carbon Emission Prediction.

1. Introduction

With the advancement of the economy and the improvement of living standards, people are placing increasing emphasis on the thermal comfort and energy efficiency of residential buildings. According

to the International Energy Agency, energy consumption during building operation accounts for approximately 30% of global total energy use and 28% of global carbon emissions^[1].

As one of the world's largest economies, China faces substantial energy demand. The number of buildings constructed continues to grow annually, making the building sector one of the country's three largest energy-consuming industries and a major contributor to carbon emissions^[2]. The Hehuang region of Qinghai Province is home to approximately 67% of the province's total population. Traditional Zhuangkuo dwellings in this region feature advantages such as wind resistance and heat retention, while also embodying distinctive historical and cultural value. Conducting research on energy consumption optimization for traditional residential buildings in the Hehuang region is therefore of great significance for improving the local living environment and promoting sustainable development.

In this study, a representative traditional residential building in the Hehuang region of Qinghai was selected as the research object. Building energy consumption was simulated using the DeST-H software. The effects of exterior wall thermal transmittance, roof thermal transmittance, window thermal transmittance, building orientation, and south-facing window-to-wall ratio on building energy use were analyzed. The parameters were then optimized, and carbon emissions were predicted. The results aim to provide a scientific reference and basis for energy retrofits of existing traditional dwellings in the Hehuang region and other areas with similar climatic and cultural characteristics.

2. Establish a Building Energy Consumption Model

2.1 Overview of Hehuang Traditional Dwellings

The Hehuang region is located in the eastern part of Qinghai Province and serves as the political, economic, and cultural center of the province. The annual average temperature in this region ranges from 3 °C to 9 °C, with long and cold winters, where the average monthly temperature in the coldest period is -7.3 °C. Due to its high altitude, the region experiences strong solar radiation. According to China's building thermal design zoning, the area falls within the Severe Cold Zone C. Local buildings must therefore provide adequate thermal insulation to meet winter heating demands. Traditional Zhuangkuo dwellings are a common residential type shared by multiple ethnic groups in eastern Qinghai. Their construction techniques embody unique local wisdom, shaped by the region's distinctive natural environment, cultural traditions, and economic conditions^[3]. These dwellings hold significant practical as well as cultural value.

2.2 Overview of the Selected Typical Traditional Dwelling

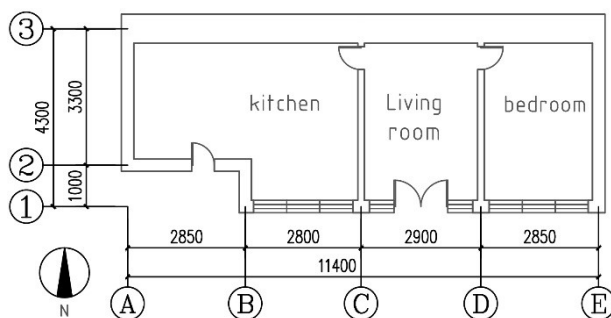


Fig. 1 Floor plan of the house



Fig. 2 Main elevation view of the house

The surveyed dwelling is located in Sanhe Town, Ping'an District, Haidong City, Qinghai Province. It is a single-story rural residence with a north-south depth of 4.3 m, an east-west length of 11.4 m, and an interior height of 3 m, oriented due south. Openings are provided only on the south façade, with a south-facing window-to-wall ratio of 0.4. The exterior windows are single glazing with a thickness of 6 mm. The floor plan consists of one bedroom, one living room, and one kitchen. The north façade is constructed with rammed-earth Zhuangkuo walls, while the other three sides use

conventional brick walls. The floor plan is shown in Fig. 1, and the front elevation is shown in Fig. 2.

2.3 Building Energy Consumption Model Parameter Settings

The parameters of the building envelope in the baseline model are listed in Table 1. The settings for indoor occupant loads, equipment heat gains, and occupancy schedules adopt the default values provided by the software.

Table 1. Typical Parameters of Traditional Residential Enclosure Structure

Structural parts	Thermal resistance /[(m ² ·K)/W]	Heat transfer coefficient /[W/(m ² ·K)]	Standardize the limit of heat transfer coefficient /[W/(m ² ·K)]
Zhuangkou facades	1.05	0.83	0.5
Plain facades	0.34	2.02	0.5
Interior walls	0.27	2.38	/
Roof	0.69	1.19	0.4
Floor	0.06	4.77	/
Exterior windows	/	4.9	2.2

In DeST-H, the outdoor meteorological parameters for the baseline model were configured as follows: heating equipment consists of electric radiators and electric blankets; the heating season extends from October 15 to April 15 of the following year; heating operation time is from 08:00 to 22:00; the indoor design temperature is set at 14 °C; and the ventilation rate is 0.5 air changes per hour. The three-dimensional solar shading diagram of the dwelling is shown in Fig. 3.

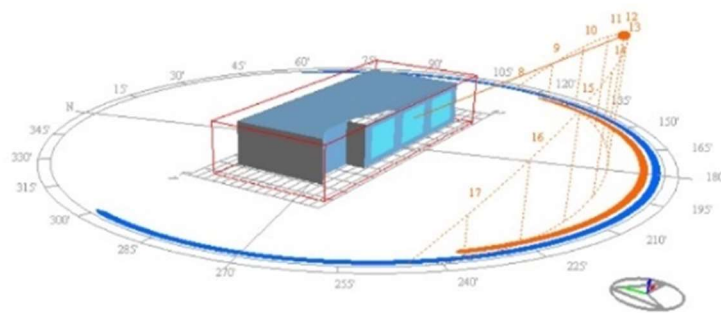


Fig. 3 Solar Radiation Shadow Map

2.4 Energy Consumption Analysis of Hehuang Traditional Dwellings

As shown in Table 1, the measured thermal transmittance values of the envelope components of traditional dwellings in the Hehuang region significantly exceed the corresponding limits specified in the Design Standard for Energy Efficiency of Rural Residential Buildings (GB/T 50824-2013), indicating poor thermal insulation performance. Based on the baseline model, DeST-H simulation results show that the annual building energy consumption of Hehuang traditional dwellings reaches 190.95 kWh/m². This high energy consumption further confirms the low energy efficiency of traditional dwellings. Given Qinghai's alpine climate, the annual cooling load is negligible.

3. Optimization of Energy Consumption of Traditional Residential Buildings

3.1 Orthogonal Test of Building Energy Consumption Optimization

Table 2. Factors influencing energy consumption and their levels in traditional residential buildings

Numble	Zhuangkou facades Heat transfer coefficient / $[W/(m^2 \cdot K)]$	Exterior windows Heat transfer coefficient / $[W/(m^2 \cdot K)]$	The south-facing window wall is	Plain facades Heat transfer coefficient / $[W/(m^2 \cdot K)]$	Towards	Roof Heat transfer coefficient / $[W/(m^2 \cdot K)]$
1	0.67	4.9	0.2	0.79	(+)30°south-west	0.54
2	0.58	3.4	0.3	0.66	(+)15°south-west	0.48
3	0.51	2.8	0.4	0.57	0°south	0.43
4	0.45	2.5	0.5	0.50	(-)15°south-east	0.39
5	0.41	2.1	0.6	0.45	(-)30°south-east	0.35

Table 3. Structural practices and heat transfer coefficients of traditional residential envelopes

Structural parts	Numble	Constructing Practices (Outside to Inside)	X	Heat transfer coefficient/ $[W/(m^2 \cdot K)]$
Zhuangkou facades	1	500mm rammed earth wall+200 air interlayer+20mm cement mortar+240mm brick wall+20mm cement mortar+Xmm rock wool board+12mm gypsum board	10	0.67
	2		20	0.58
	3		30	0.51
	4		40	0.45
	5		50	0.41
Plain facades	1	10mm tiles+20mm cement mortar+240mm brick wall+20mm cement mortar+Xmm rock wool board+12mm gypsum board	30	0.79
	2		40	0.66
	3		50	0.57
	4		60	0.50
	5		70	0.45
Roof	1	50mm grass mud+100mm loess+10mm wheat straw+40mm firewood splitting wood rafters+Xmm rock wool board+12mm gypsum board	40	0.54
	2		50	0.48
	3		60	0.43
	4		70	0.39
	5		80	0.35

Analysis indicates that multiple factors, including the thermal transmittance of exterior walls and roofs, significantly influence building energy consumption. It is therefore necessary to investigate the combined effects of these factors. However, conducting simulations for all possible parameter combinations would require an extensive workload in both testing and computation. Orthogonal

experimental design offers an efficient, rapid, and cost-effective approach for multi-factor experimental studies. The core concept of the method is to select a representative subset of experimental combinations from the full factorial design based on the principle of “uniform distribution and orthogonality,” thereby greatly reducing the number of experiments and simulation calculations required^[4]. Compared to full factorial testing, orthogonal design can significantly reduce the number of trials, shorten the experimental period, and lower costs. Furthermore, through rational experimental design and rigorous data analysis, orthogonal experiments can accurately reveal the influence patterns of each factor on the target performance indicators, while also determining the optimal combination of parameters.

In this study, six factors were selected for multi-factor analysis of building energy consumption. The values for building orientation, south-facing window-to-wall ratio, and exterior window thermal transmittance were derived from field surveys of common configurations in Hehuang traditional dwellings. The thermal transmittance values for roofs, Zhuangkuo exterior walls, and ordinary exterior walls were obtained from the materials and traditional envelope construction practices commonly used in the Hehuang region. The factors and their corresponding levels are listed in Table 2, while the construction methods and corresponding thermal transmittance values for traditional Hehuang dwelling roofs, Zhuangkuo exterior walls, and ordinary exterior walls are provided in Table 3.

3.2 Orthogonal Test Range Analysis of Building Energy Consumption Optimization

Based on the parameter investigation of traditional dwellings in the Hehuang region and combined with DeST-H building energy simulation, an orthogonal experimental design was developed to systematically study the impact of different factor combinations on building energy consumption. Within the reasonable value ranges of architectural design parameters, six key factors were identified and denoted as X_i . An L25(56) orthogonal array was then generated following the principles of orthogonal experimental design. This array includes 25 representative experimental schemes, as presented in Table 4.

As shown in Table 4, among all factors affecting the energy consumption of traditional dwellings, the thermal transmittance of ordinary exterior walls exhibits the largest range value, 38.488 kWh/m², whereas the thermal transmittance of exterior windows shows the smallest range value, 8.692 kWh/m². The proportion of the influence of each factor on building energy consumption is illustrated in Fig. 4. The order of influence on the annual total building load is as follows: thermal transmittance of ordinary exterior walls > thermal transmittance of roofs > thermal transmittance of Zhuangkuo exterior walls > south-facing window-to-wall ratio > building orientation > thermal transmittance of exterior windows. Therefore, when considering the energy performance of traditional dwellings in the Hehuang region of Qinghai, priority should be given to optimizing the thermal transmittance of ordinary exterior walls and roofs.

Table 4. Orthogonal Test Results and Range Analysis

Numble	X ₁ Zhuangkou facades Heat transfer coefficient	X ₂ Exterior windows Heat transfer coefficient	X ₃ The south- facing window wall is	X ₄ Plain facades Heat transfer coefficient	X ₅ Towards	X ₆ Roof Heat transfer coefficient	Y ₁ Test results
1	1	1	1	1	1	1	144.62
2	1	2	2	2	2	2	111.88
3	1	3	3	3	3	3	84.47
4	1	4	4	4	4	4	68.81
5	1	5	5	5	5	5	60.7
6	2	1	2	3	4	5	81.48
7	2	2	3	4	5	1	101.2
8	2	3	4	5	1	2	72.54
9	2	4	5	1	2	3	100.02
10	2	5	1	2	3	4	87.09
11	3	1	3	5	2	4	52.67
12	3	2	4	1	3	5	85.24
13	3	3	5	2	4	1	112.57
14	3	4	1	3	5	2	95.74
15	3	5	2	4	1	3	68.59
16	4	1	4	2	5	3	91.79
17	4	2	5	3	1	4	57.04
18	4	3	1	4	2	5	51.86
19	4	4	2	5	3	1	80.98
20	4	5	3	1	4	3	104.48
21	5	1	5	4	3	2	74.59
22	5	2	1	5	4	3	69.08
23	5	3	2	1	5	4	94.05
24	5	4	3	2	1	5	59.26
25	5	5	4	3	2	1	80.83
Mean1	94.096	89.030	89.678	105.682	80.410	104.040	
Mean2	88.466	84.888	87.396	92.518	79.452	88.688	
Mean3	82.962	83.098	80.416	79.912	82.474	86.405	
Mean4	77.230	80.962	79.842	73.010	87.284	71.932	
Mean5	75.562	80.338	80.984	67.194	88.696	67.708	
Range	18.534	8.692	9.836	38.488	9.244	36.332	

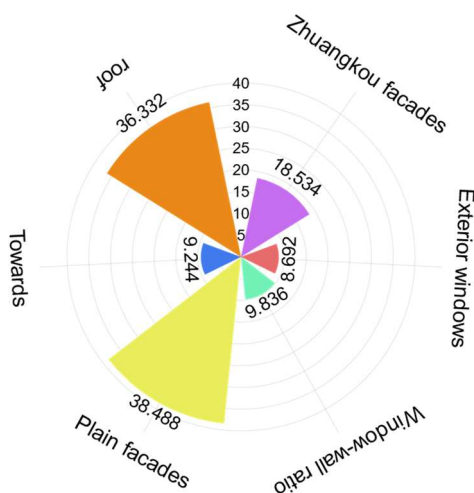


Fig. 4 The impact of various influencing factors on building energy consumption

3.3 Analysis of the Optimal Energy Consumption Scheme

The optimal retrofit scheme was determined by selecting, for each factor, the level corresponding to the lowest mean energy consumption in the orthogonal experiment. As shown in Table 4, the optimal configuration for energy retrofit of Hehuang traditional dwellings is as follows: thermal transmittance of Zhuangkuo exterior walls = 0.41 W/(m²·K), thermal transmittance of exterior windows = 2.1 W/(m²·K), south-facing window-to-wall ratio = 0.5, thermal transmittance of ordinary exterior walls = 0.45 W/(m²·K), building orientation = 15° west of due south, and thermal transmittance of roofs = 0.35 W/(m²·K). The simulated energy consumption under this configuration is 44.69 kWh/m². Compared with the baseline model value of 190.95 kWh/m², the optimal scheme achieves a reduction of 146.26 kWh/m², corresponding to a 76.6% decrease in energy consumption. This demonstrates the significant energy-saving potential of retrofitting traditional dwellings in the region.

4. Carbon Emission Forecast of Traditional Houses

4.1 Establish a Carbon Emission Prediction Model

Multiple regression is a commonly used statistical method for examining the relationship between multiple independent variables and a single dependent variable. The application of a multiple linear regression model requires that the relationship between the dependent and independent variables be linear, and that the effect of each independent variable on the dependent variable be independent of the others. Based on measured data, a baseline model of a representative traditional dwelling in the Hehuang region of Qinghai was established using the DeST-H simulation software. On the basis of this model, an orthogonal experiment with six factors and five levels was conducted, yielding 25 sets of building energy consumption data. The six factors influencing building energy consumption were selected as independent variables, while building energy consumption was taken as the dependent variable. These variables satisfy the conditions for applying a multiple linear regression model. A multiple linear regression analysis was conducted to establish the energy consumption prediction model for traditional dwellings in the Hehuang region. The significance (Sig) values associated with all six independent variables were less than 0.05, indicating that all regression coefficients were statistically significant and met the model requirements. Table 5 presents the model summary used for testing the goodness of fit. The adjusted R² value was 0.977, which is close to 1, demonstrating an excellent fit of the regression model. The last item in Table 5 is the Durbin–Watson (D–W) statistic, which evaluates the correlation between independent variables and residuals. The D–W value of 1.979 falls within the acceptable range of 0–4, satisfying the model assumptions.

Table 5. Summary table of multiple regression predictive analysis model

Model Summary					
Model	R	R ²	After adjusting R ²	regression estimation standard error S	D-W
1	0.991 ^b	0.983	0.977	3.31862	1.979

Using the building parameters of traditional dwellings listed in Table 4 as independent variables and the corresponding building energy consumption values as the dependent variable, a multiple linear regression analysis was conducted in the SPSS software using its multiple linear regression module. This analysis examined the linear relationships between each building parameter and energy consumption. The resulting energy consumption prediction model is expressed as:

$$Y_1 = -80.859 + 26.239X_1 + 2.721X_2 - 46.229X_3 + 124.621X_4 - 0.177X_5 + 207.485X_6 \quad (1)$$

In (1), Y_1 - building energy consumption value; X_1 - thermal transmittance of Zhuangkuo exterior walls; X_2 - thermal transmittance of exterior windows; X_3 - south-facing window-to-wall ratio; X_4 - thermal transmittance of ordinary exterior walls; X_5 - building orientation; X_6 - thermal transmittance of roofs.

Carbon emissions refer to the amount of CO₂ emitted per unit time per unit area or per unit of energy consumed, and serve as a key metric for assessing the impact of human activities on global climate change. The Standard for Building Carbon Emission Calculation (GB/T 51366–2019) divides the building life cycle into four stages: design, embodied (material production and transportation), operation and maintenance (O&M), and demolition and recycling. It is generally acknowledged within the industry that the O&M stage exhibits the highest level of carbon emissions; therefore, predicting carbon emissions during this stage is of significant importance. Various methods exist for calculating carbon emissions in the O&M stage, including direct measurement, the carbon emission factor method, material balance calculation, and factor decomposition. Among these, the carbon emission factor method is widely adopted due to its low cost, simplicity, broad applicability, and ease of data acquisition. According to the 2021 Power Grid CO₂ Emission Factors jointly released by the Ministry of Ecology and Environment and the National Bureau of Statistics, the average carbon emission factor for the regional power grid in Qinghai Province is 0.1326 kgCO₂/(kWh·a). The calculation formula is:

$$\text{Carbon Emissions} = \text{Building Energy Consumption} \times 0.1326 \quad (2)$$

The resulting carbon emissions are measured in kgCO₂/m²·a. Given that the heating system in the studied dwelling is entirely powered by electricity, the carbon emission factor method was applied directly by multiplying the predicted building energy consumption by the regional grid's average carbon emission factor of 0.1326 kgCO₂/(kWh·a). The resulting carbon emission prediction model for the traditional dwelling is:

$$Y_2 = Y_1 \times 0.1326 \quad (3)$$

In (3), Y_1 - building energy consumption value; Y_2 - building carbon emissions.

4.2 Validation of the Multiple Regression Carbon Emission Prediction Model

To verify the accuracy of the proposed carbon emission prediction model, 10 additional random combinations of independent and dependent variable parameters were selected. As shown in Table 6,

the relative error between the predicted values of the carbon emission model and the simulated values from the software ranged from 0.4% to 4.7%, with an average relative error of 2.46%. The small error margin indicates that the model possesses high predictive accuracy.

Table 6. Comparison of simulated and predicted building energy consumption values

Numble	Simulate carbon emissions	Predict carbon emissions	relative error	Numble	Simulate carbon emissions	Predict carbon emissions	relative error
1	15.26	14.87	2.5%	6	15.26	14.27	3.6%
2	11.84	12.18	2.9%	7	11.84	7.66	3.2%
3	13.99	14.32	2.4%	8	13.99	6.77	1.8%
4	9.68	9.22	4.7%	9	9.68	9.98	1.6%
5	11.74	11.79	0.4%	10	11.74	13.75	1.6%

4.3 Prediction Results and Analysis of Residential Carbon Emissions

By multiplying the simulated energy consumption of the optimal building model (44.69 kWh/m²) and the baseline model (190.95 kWh/m²) by the regional grid average carbon emission factor (0.1326 kgCO₂/(kWh·a)), the corresponding carbon emissions were calculated as 5.93 kgCO₂/(m²·a) and 25.32 kgCO₂/(m²·a), respectively. The optimal scheme thus achieved a reduction of 19.39 kgCO₂/(m²·a), representing a 76.6% decrease in carbon emissions. These results demonstrate the significant carbon-reduction potential of retrofitting traditional dwellings.

The multiple regression-based carbon emission prediction model developed in this study was validated for accuracy and found to be highly user-friendly. Practitioners and residents without advanced building science expertise can predict building energy consumption and carbon emissions by inputting only key design parameters-such as window thermal transmittance and roof thermal transmittance-into the model. By integrating dynamic building carbon emission simulations with static design parameters, the model provides a practical and scientific reference for numerous new construction and renovation projects in the Hehuang region during the design and planning stage, with the dual goals of energy conservation and carbon reduction.

5. Conclusion

Based on extensive field investigations and literature research, this study employed the DeST-H software to perform dynamic simulations of the energy consumption of traditional dwellings in the Hehuang region of Qinghai. The simulation results were analyzed and predicted using orthogonal experimental design and multiple regression modeling. The main conclusions are as follows:

Sensitivity analysis of influencing factors: Range analysis revealed that the thermal transmittance of ordinary exterior walls and roofs are the two most influential factors, both exhibiting strong sensitivity and having a pronounced effect on energy consumption. In contrast, the thermal transmittance of Zhuangkuo exterior walls, south-facing window-to-wall ratio, building orientation, and exterior window thermal transmittance have weaker effects and require only basic compliance with design standards.

Optimal retrofit scheme for energy consumption reduction: The most energy-efficient retrofit scheme for traditional dwellings in the Hehuang region involves: adding interior insulation of 70 mm rock wool boards and 12 mm gypsum boards to ordinary exterior walls; adding 80 mm rock wool boards and 12 mm gypsum boards to roofs; adding 50 mm rock wool boards and 12 mm gypsum boards to Zhuangkuo exterior walls; adopting a south-facing window-to-wall ratio of 0.5; orienting the building 15° west of due south; and using double glazing with a thermal transmittance of 2.1 W/(m²·K). Under

this configuration, building energy consumption is reduced to 44.69 kWh/m², compared to 190.95 kWh/m² for the baseline model, achieving a reduction of 146.26 kWh/m² or 76.6%.

Carbon emission reduction potential: A multiple regression carbon emission prediction model for traditional dwellings in the Hehuang region was established and validated. Under the optimal retrofit scheme, carbon emissions were reduced by 33.05 kgCO₂/(m²·a), equivalent to a 76.6% decrease compared to the baseline model, indicating significant decarbonization potential after retrofitting.

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