ЕНЕРГОЗБЕРЕЖЕННЯ В БУДІВНИЦТВІ

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COMPARATIVE STUDY OF ENERGY CONSUMPTION OF RURAL RESIDENTIAL BUILDING ENVELOPES IN HIGH-TEMPERATURE DIFFERENCE AREAS

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As most rural buildings lack effective thermal insulation measures, heat loss is severe, and the increase in carbon emissions exacerbates environmental pollution. This study aimed to improve the thermal insulation performance of rural residential buildings and reduce energy consumption and carbon dioxide emissions. The study methodology involved selecting a typical rural residential building in a high-temperature difference area as the research subject. Expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane foam boards were selected for analysis as wall and roof insulation materials. Meanwhile, single-pane, double-pane insulated, and low-emissivity (low-E) glass were chosen as exterior window materials. Building energy consumption under different wall insulation and exterior window materials was simulated and analysed using DesignBuilder software. The study showed that during the region's cold January period, models using highly efficient insulated wall materials significantly reduced building energy consumption compared to conventional buildings without insulation. When comparing the three insulation materials – XPS, EPS, and polyurethane foam board – XPS insulation demonstrated superior performance: energy savings of 25.7% were achieved when XPS insulation was applied to exterior walls and up to 32.2% when used on the roof. In addition, external window materials were also critical in influencing building energy consumption during this period. The energy savings achieved by the building model using a double-insulating glass of 6+12A+6 specification reached 24.92%. The results of this study provide an important foundation for the energy-efficient design and renovation of both existing and new buildings in areas with high-temperature differences. These findings have significant implications for improving energy efficiency and reducing emissions in rural residential buildings

Keywords: *insulation materials; energy efficiency improvement; simulation analysis; energy-saving renovation; environmental impact*

Introduction

With the continuous rise in rural economic income and the improvement of farmers' living standards, rural self-built housing has gradually evolved from traditional civil structures to **multi-storey** buildings with brick-concrete and frame structures. As rural residential buildings are typically single-family dwellings and their surroundings are directly exposed to the outdoor environment, both existing and newly constructed buildings exhibit poor thermal insulation performance, outdated heating facilities, and low thermal efficiency. Therefore, optimising the envelope materials and structural forms in rural residential buildings in high-temperature difference regions and enhancing the thermal insulation performance of individual buildings are crucial measures for improving residential comfort and reducing energy consumption.

According to Q. Du *et al*. (2021), technological advancements in energy efficiency are often considered an effective means of addressing climate change. However, the expected energy efficiency levels in both urban and rural residential buildings have not been achieved, and building energy consumption continues to rise. As noted by X. Guan *et al*. (2023), the supply of residential energy is gradually transitioning from coal and biomass to electricity, heat, and natural gas, while the use of fossil fuels and the resulting carbon dioxide emissions exert an increasing impact on the environment. In rural residential buildings, factors such as building orientation, aspect ratio, window-to-wall ratio, and envelope structure significantly influence energy consumption during the heating period, with the envelope structure being the most influential factor (Jiang *et al*., 2021). Since envelope energy consumption constitutes a large proportion of total building energy usage, enhancing envelope energy efficiency has become a key aspect of building energy-efficient design and retrofitting (Timchenko *et al*., 2022). The building design and energy consumption patterns of rural households differ from those of urban households, and the indoor thermal environments of most rural buildings are substandard, failing to meet energy efficiency and insulation requirements (Li *et al*., 2020). Furthermore, differences exist between indoor thermal environments and human thermal comfort levels in residential buildings across cities, towns, and rural areas, with rural residents tolerating a lower temperature range than urban residents (Yang *et al*., 2022). As noted by J. Nie *et al*. (2021), under the same indoor air temperature, different envelope materials exhibited significant variations, and building thermal comfort was primarily influenced by the indoor-outdoor temperature difference. To improve the energy efficiency of rural buildings and enhance residential comfort, scholars worldwide have proposed solutions from different perspectives. K. Kalhor & N. Emaminejad (2020) analysed building energy performance using the COMcheck programme and provided recommendations for qualitatively optimising thermal insulation materials based on different building envelope types and systems. J. Huang *et al*. (2021), based on life-cycle cost analysis, developed a thermal performance optimisation model for the envelope structure to improve the energy efficiency of existing residential buildings and determined the optimal thermal performance relationship between envelope units. R.Z. Homod *et al*. (2021) simulated the energy consumption of different building materials using the MATLAB/Simulink environment and found that building materials significantly affected energy consumption. O. Kaya *et al*. (2021) investigated energy efficiency adoption in economically disadvantaged rural areas and found that high-investment and long payback-period programmes for energy efficiency upgrades were unpopular among farmers unless supported by government subsidies and investments. However, rural residents were receptive to energy-efficient building envelope designs and retrofits when lower-cost investments were required (Han *et al*., 2023; Zhang *et al*., 2024).

This study aimed to improve the energy efficiency of rural residential buildings. To achieve this, the research compared and analysed the energy efficiency of 100-mm EPS insulation board, 100-mm XPS insulation board, and 100-mm polyurethane foam board applied to external walls and roofs, based on a typical rural residential building lacking thermal insulation measures. It also evaluated the energy-saving benefits of four types of glass: 3-mm single-pane, 3+6A+6 double-pane, 6+12A+6 double-pane, and 6-mm low-emissivity +12+6 outer double-pane glass. The energy-saving rates of commonly used insulation materials and glass types in rural residential buildings were determined, providing solutions for the energy-efficient design and renovation of both new and existing buildings.

Materials and methods

This study examined rural buildings in areas with significant temperature differences. Based on the meteorological conditions and typical housing types in the region, an energy consumption simulation model was developed using DesignBuilder. Wall insulation materials with different heat transfer coefficients and glass windows with different structural designs were selected for energy consumption simulation analysis, and an optimisation strategy for building energy consumption and conservation under different conditions was formulated.

2.1 Climatic conditions

The study site is located in Jiuquan City, China, between 98°20'-99°18' E longitude and 39°10'-39°59' N latitude. The frost-free period lasts 127-158 days, and the historical lowest temperature recorded -24.4°C. Summers are characterised by strong sunshine, dry conditions, and high temperatures, with a historical maximum of 43.1°C. The maximum annual temperature difference is 67.5°C, and the average annual sunshine duration is 3,056.4 hours.

2.2 Project overview

The study focuses on a two-storey rural residential building with a brick structure. The first floor includes a hall, bedroom, kitchen, and an agricultural tools room, covering a floor area of 124.75 m^2. The building plan is shown in Figure 1.

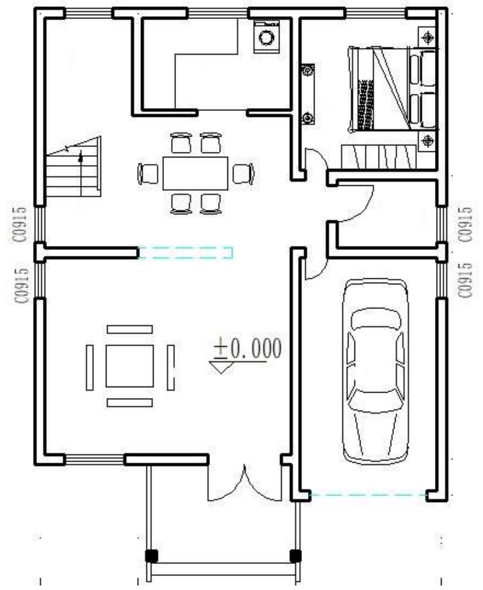

Figure 1. First-floor plan

The second floor consists of a living room, bedroom, and sun terrace, with a floor area of 90.54 m2. The building plan is shown in Figure 2. The roof has a four-pitch design. In winter, heating is provided by a steam boiler fuelled by coal, diesel, steam, and water. In summer, natural ventilation is achieved through open windows. The external walls are constructed from 370 mm standard clay bricks, while the internal walls use 240 mm clay bricks. The roof is composed of concrete glazed tiles without effective insulation.

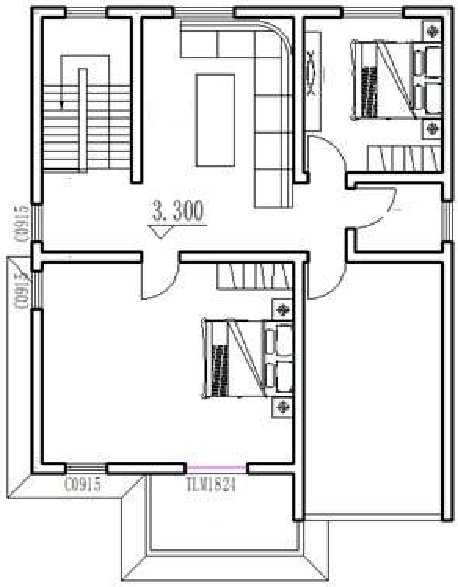

Figure 2. Second-floor plan

2.3 Proposed thermal insulation measures

The external wall area of the building is 257.4 m^2, while the window area measures 21.6 m^2, representing 8.4% of the total external wall area. Because of the low thermal insulation performance of standard clay bricks used in external walls and the lack of thermal insulation measures, push-and-pull single-layer windows exhibit poor sealing performance and high heat loss. The concrete roof is also one of the main contributors to heat loss. Thermal insulation measures primarily involve enhancing roof and external wall insulation, installing double-pane hollow-glass casement windows, and applying external wall reflective natural stone paint. According to the characteristics of the project and local climate conditions, thermal insulation materials with different heat transfer coefficients and glass windows with different structural configurations were selected for analysis, and the optimal renovation scheme was determined. The thermal performance of the insulation materials and glass structures examined in this study is shown in Tables 1 and 2.

Table 1.

Thermal performance parameters of different insulation materials

Roof and exterior wall	Heat transfer coefficient ［$W/m^2 \cdot K$］
Brick wall (370 mm)	0.114
EPS insulation board (100 mm thick)	0.037
XPS insulation board (100 mm thick)	0.024
Polyurethane foam board (100 mm thick)	0.033

Table 2.

Thermal performance parameters of different glass structures

Glass type	Heat transfer coefficient ［$W/m^2 \cdot K$］
3-mm single glass	6.4
3+6A+6 double-pane insulating glass	3.4
6+12A+6 double-pane insulating glass	3.3
6-mm low-E +12+6 outer double-pane insulating glass	1.7

2.4 Energy consumption simulation

In this study, a dynamic simulation program for building energy consumption, DesignBuilder, was used to simulate and analyse the selected building. The model is shown in Figure 3.

Figure 3. Energy consumption analysis model of DesignBuilder

The modelling of the building enclosure structure primarily involved analysing exterior walls, windows, household doors, and roofs. The simulation examined overheating and energy consumption patterns, which were evaluated using DesignBuilder. The impact of insulation materials on energy consumption, and carbon dioxide emissions was optimised.

Results and Discussion

This study adopted 370 mm standard clay bricks with the plaster back layer coated in cement. The energy consumption of four types of thermal insulation materials was analysed, namely, brick walls (370 mm), EPS thermal insulation boards (100 mm thick), XPS thermal insulation boards (100 mm thick), and polyurethane foam boards (100 mm thick), during the normal heating period in rural areas. The indoor temperature was set to 18℃. Figure 4 illustrates the energy consumption of walls with different insulation materials for each month. The analysis indicated that, compared with the original uninsulated wall, in January – the coldest month in the region – EPS insulation boards reduced energy consumption by 23.8%, XPS insulation boards by 25.7%, and polyurethane foam boards by 24.6%.

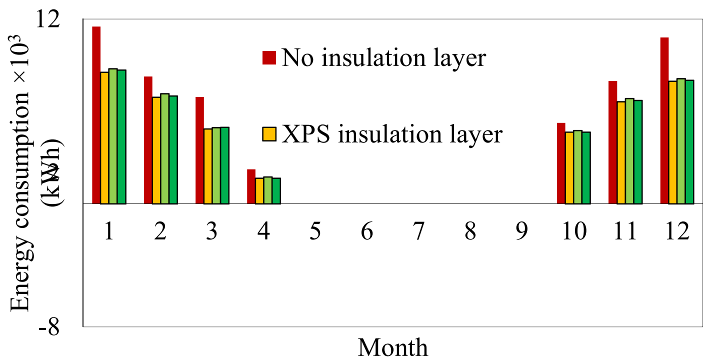

Figure 4. Energy consumption of walls with different thermal insulation materials per month

The original roof structure consisted of a concrete structural layer, a plastering layer, and a glass-tiled surface layer. As no insulation measures had been implemented, heat loss was significant. Four types of thermal insulation materials – concrete (120 mm) without insulation, EPS thermal insulation boards (100 mm thick), XPS thermal insulation boards (100 mm thick) and polyurethane foam boards (100 mm thick) – were examined through simulations. Figure 5 illustrates the energy consumption of roofs with different insulation materials for each month. The analysis demonstrated that in January – the coldest month in the region – EPS panels reduced energy consumption by 29.8%, XPS panels by 32.2%, and polyurethane foam boards by 30.3% compared to the original roof without insulation.

The data indicated that under extremely low temperatures, external walls and roofs insulated with XPS thermal insulation boards achieved the highest energy-saving rates. From a thermophysical perspective, XPS thermal conductivity is slightly higher than the theoretical value of polyurethane. However, its closed porosity and ultra-low water absorption ensure the stability of thermal resistance in high-humidity environments. Conversely, polyurethane prefabricated panels experience thermal resistance loss due to the thermal bridging effect at the joints. Additionally, EPS, due to its open-pore structure, exhibits higher hygroscopicity, which further increases the thermal conductivity coefficient as humidity rises. Regarding construction adaptability, XPS can be seamlessly joined due to its high compressive strength, significantly reducing the thermal bridge effect. Polyurethane, however, is prone to forming heat loss channels at the seams if a non-spraying application method is used. Furthermore, high humidity during rural winters further amplifies XPS's moisture resistance advantage, whereas polyurethane and EPS suffer from reduced thermal resistance due to moisture absorption. This study concludes that XPS's combined advantages in thermal conductivity, moisture resistance, and ease of construction make it the optimal choice for energy-efficient wall retrofitting in low-temperature and high-humidity regions.

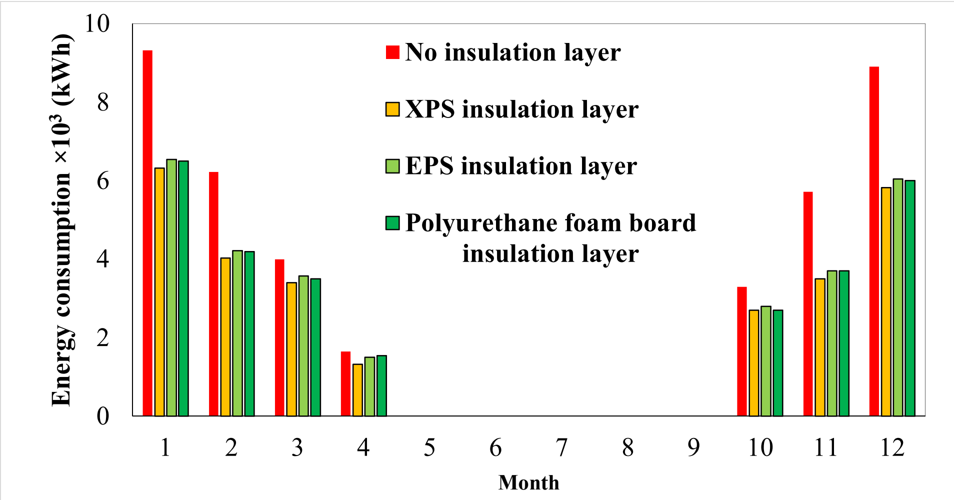

Figure 5. Monthly energy consumption of roofs with different thermal insulation materials

The original project utilised single-glass aluminium alloy sliding windows. In this study, energy consumption simulations were conducted under four scenarios: 3-mm single-pane glass, 3+6A+3 double-pane insulating glass, 6+12A+6 double-pane insulating glass, and 6-mm low-E +12+6 double-pane insulating glass. Figure 6 illustrates the energy consumption of different glazing types for each month. The analysis indicates that the use of double-pane insulating units can significantly enhance the insulation of the house and reduce energy consumption. During the coldest month in the region, energy savings of 16.04% were achieved using 3+6A+3 double-pane units, 24.92% by using 6+12A+6 double-pane units, and 22.89% by using 6-mm low-E +12+6 external double-pane units.

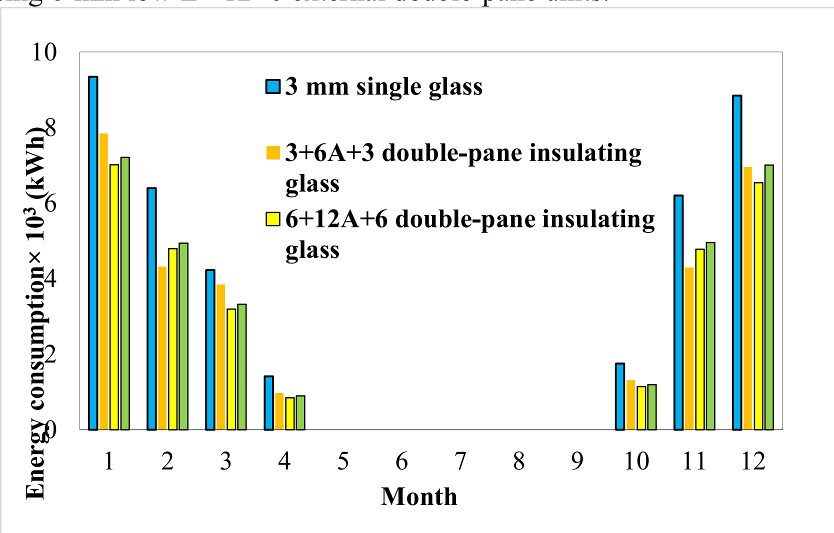

Figure 6. Monthly energy consumption of different glazing types

Simulation results indicate that 6+12A+6 double-pane insulating glass outperforms low-E coated glass in energy savings during the coldest months due to multiple synergistic mechanisms. The 12-mm air layer optimises insulation performance by reducing heat convection and conduction while preventing heat loss, which may increase in thicker air layers due to enhanced gas flow. The region experiences long annual sunshine hours, allowing the solar heat gain coefficient of standard double glazing to effectively utilise solar radiation for passive heating. In contrast, low-E glass, despite its lower heat transfer coefficient, significantly reduces SHGC, leading to higher supplemental heating requirements at night. Furthermore, the higher cost and lower thermal inertia of low-E coatings exacerbate temperature fluctuations. By contrast, 6+12A+6 double glazing enhances thermal stability and reduces heating system loads due to its thicker glass layers. This study reveals that in cold regions with high solar radiation, window material selection should prioritise balancing the coupling effect of U-value and SHGC rather than focusing solely on achieving a low heat transfer coefficient.

Simulation results further demonstrate that energy-saving retrofitting of external walls, roofs, and windows plays a crucial role in improving the energy efficiency of rural residential buildings. By installing high-performance thermal insulation materials on walls and roofs, the heat transfer rate was significantly reduced, and direct heat conduction effects were effectively mitigated. Simultaneously, the double-pane design – insulating properties of its internal air layer – substantially minimised heat exchange between the interior and exterior through conduction, thereby considerably reducing heat loss from the interior. Considering the combined effects of exterior wall and roof insulation retrofitting, window and door upgrades, and optimal utilisation of solar energy resources, it is estimated that rural buildings in cold regions could achieve energy savings of up to 65%.

M. Huang & R. Lin (2020) argued that energy efficiency retrofitting of existing rural residential buildings could not only enhance the living environment of rural residents but also contribute to energy savings, emission reductions, and the sustainable development of the construction industry. M.B. Hamooleh *et al*. (2024) stated that phase change materials are among the most effective methods for storing thermal energy, and their incorporation into building walls can significantly improve a building's thermal comfort. Furthermore, the optimal thickness of insulation is influenced by the climatic conditions in which a building is situated.

Q. Deng *et al*. (2023) conducted an extensive study on an insulation retrofitting project involving 710,000 rural houses in Beijing, demonstrating that, in the context of energy-saving retrofits for rural buildings, external wall insulation technology is widely adopted to upgrade the insulation of existing structures. Within these retrofit projects, EPS and XPS were the predominant choices for wall insulation materials across various districts, with thicknesses ranging from 50 to 80 mm. Additionally, the majority of retrofit strategies for external doors and windows involved replacing existing units with insulated double-pane units made of plastic-steel and broken-bridge aluminium alloy. Energy simulation analyses indicate that retrofitting walls, doors, and windows to varying extents (7% to 53%) can effectively reduce building energy consumption by 12% to 31%, which closely aligns with the findings of this study in terms of energy reduction trends.

Q. Li *et al*. (2022) carried out a comprehensive assessment of the effectiveness of energy-saving retrofitting in rural residential sunrooms by integrating orthogonal experiments with the entropy weight method. Considering factors such as energy efficiency improvements, incremental costs, cost-benefit ratios, and carbon reduction potential, the optimal construction strategy was identified: a window-to-wall ratio of 0.9, a sunroom depth of 0.9 metres, a roof comprising 60-mm foam concrete thermal insulation boards, a floor paved with 20-mm extruded polystyrene thermal insulation boards, exterior walls fitted with 120-mm foam concrete insulation boards, and triple-glazed windows as the exterior window material. Although the optimisation strategies proposed in that study share similarities with those in the present study, it is recognised that substantial modifications to window-to-wall ratios in existing buildings pose significant implementation challenges due to the unique characteristics of rural residential structures. W. Cao *et al*. (2021) developed an energy-saving retrofit evaluation framework specifically designed for naturally ventilated buildings, with key retrofit measures including the installation of high-efficiency insulated windows, the addition of exterior wall and roof insulation, and the application of the entropy weight method for multi-objective optimisation analysis of various retrofit options. The study's findings reveal that a combination of 6+12A+6 mm insulating glass windows, 50 mm of exterior wall insulation, and 90 mm of roof insulation yields the most significant energy-saving effect, improving energy efficiency by 23.81% compared to the baseline building. This outcome is consistent with the results of the present study in terms of energy-saving trends, while variations in energy-saving rates can be attributed to differences in building attributes and climatic conditions.

L. Ma *et al*. (2020) examined the solar space efficiency of double-pane units and compared them with single-pane units, highlighting that the energy-saving efficiency of double-pane systems can reach 11.3%. Considering the variability in window-to-wall ratios among buildings, this study shares similarities in energy-saving principles with the present study's conclusion that using 3+6A+3 double-pane units can achieve a 16.04% reduction in energy consumption. P. Cao *et al*. (2024) selected 90-mm-thick XPS boards for exterior wall insulation, and 80-mm-thick XPS boards for roof insulation, and specified 6+12A+6-mm bridge-break insulated windows for exterior window insulation, finding that building energy savings exceeded 50% – a result consistent with the findings of this study. W. Jiang *et al*. (2023) attempted to retrofit existing rural dwellings from three perspectives: thermal insulation, additional daylighting spaces, and the incorporation of phase change materials, achieving an energy-saving rate of up to 92.17%. However, this study takes a cautious approach, recognising that such a high energy-saving rate represents more of a theoretical limit. Given the actual characteristics of rural buildings and the cost constraints associated with retrofitting, achieving this level of energy savings in real-world projects would be highly challenging.

Conclusion

In this study, the effects of different insulation materials and window configurations on the energy consumption of a typical rural house in a high-temperature region were systematically analysed. Based on DesignBuilder simulation data, optimal energy-saving performance was achieved when 100-mm-thick XPS boards were used for exterior wall and roof insulation, leading to a 25.7% and 32.2% reduction in energy consumption under extreme low-temperature conditions in January, respectively. The low thermal conductivity of XPS, due to its closed-cell structure, significantly outperforms polyurethane and EPS in high-humidity environments. For exterior window retrofits, 6+12A+6 double-pane insulating glass achieved a higher energy-saving rate (24.92%) than low-E glass. This advantage stems from the 12-mm air layer's effective suppression of thermal convection, combined with a solar heat gain coefficient (SHGC) of 0.62.

Therefore, in regions with large temperature variations and prolonged sunshine hours, 100-mm XPS boards are recommended for walls and roofs. The construction process should adopt the staggered-seam pasting technique with waterproof and breathable membranes to mitigate high-humidity conditions. For exterior windows, 6+12A+6 double-pane insulating glass with broken-bridge aluminium alloy frames is preferred. These optimised insulation measures have significant potential for reducing energy consumption in both retrofitted and newly constructed rural buildings. While envelope structures play a crucial role in influencing energy consumption, further exploration of innovative building materials in rural residential construction will be necessary to enhance energy efficiency in the future.

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ПОРІВНЯЛЬНЕ ДОСЛІДЖЕННЯ ЕНЕРГОСПОЖИВАННЯ ОГОРОДЖУВАЛЬНИХ КОНСТРУКЦІЙ СІЛЬСЬКИХ ЖИТЛОВИХ БУДИНКІВ В РАЙОНАХ З ВИСОКИМИ ПЕРЕПАДАМИ ТЕМПЕРАТУР

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Оскільки більшість сільських будівель не мають ефективних заходів з теплоізоляції, втрати тепла є значними, а збільшення викидів вуглекислого газу спричиняє значний тиск на забруднення навколишнього середовища. Метою дослідження було покращення теплоізоляційних характеристик сільських житлових будинків та зменшення споживання енергії і викидів вуглекислого газу. Методологія дослідження передбачала вибір в якості об'єкта дослідження типового сільського житлового будинку в зоні з високими перепадами температур. Для аналізу було обрано пінополістирол (EPS), екструдований полістирол (XPS) та пінополіуретанові плити в якості ізоляційних матеріалів для стін та даху. В якості зовнішніх віконних матеріалів були обрані однокамерні, двокамерні склопакети з ізоляцією та склопакети з низьким енергоспоживанням. За допомогою програмного забезпечення DesignBuilder було змодельовано та проаналізовано енергоспоживання будівлі з різними матеріалами ізоляції стін та зовнішніх вікон. Дослідження показало, що протягом холодних січневих місяців у регіоні моделі з високоефективними ізольованими стіновими матеріалами значно знизили енергоспоживання будівлі порівняно зі звичайними будівлями без ізоляції. При порівнянні трьох ізоляційних матеріалів – XPS, EPS та пінополіуретанової плити – ізоляція XPS продемонструвала відмінні показники: 25,7 % економії енергії було досягнуто при використанні ізоляції XPS на зовнішніх стінах, і до 32,2 % – при використанні ізоляції XPS на даху. Крім того, зовнішні віконні матеріали також були одним з ключових факторів, що впливають на енергоспоживання будівлі в той час, і енергозбереження моделі будівлі з подвійним ізоляційним склом специфікації 6+12A+6 досягло 24,92 %. Результати цього дослідження можуть стати важливою основою для енергозберігаючого проектування та реконструкції існуючих і нових будівель в районах з високими перепадами температур, а також мати значні наслідки для підвищення енергоефективності та скорочення викидів в сільських житлових будівлях

Ключові слова: *ізоляційні матеріали; підвищення енергоефективності; імітаційний аналіз; енергозберігаюча реновація; вплив на довкілля*

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