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SCIENTIFIC FOUNDATIONS FOR IMPROVING THERMAL INSULATION AND ENERGY EFFICIENCY IN MODULAR HOUSES

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Abstract: This article presents the scientific foundations for improving thermal insulation systems and enhancing energy efficiency in low-rise modular residential houses. The study analyzes the influence of temperature fluctuations, high levels of solar radiation, and winter cold loads characteristic of Uzbekistan's sharply continental climate on modular structures. Optimized multilayer wall solutions are proposed to limit heat flow, reduce thermal losses, and eliminate thermal bridges between structural modules. In addition, the thermal conductivity, moisture resistance, and environmental characteristics of insulation materials such as mineral wool, cellulose fiber (ecowool), polyurethane foam, and SIP panels are compared. Calculations demonstrate that selecting the optimal thickness of structural layers in the design of energy-efficient modular homes significantly improves indoor microclimate stability and reduces operating costs. The findings provide a scientific basis for establishing high energy efficiency standards for modular houses constructed across the regions of Uzbekistan.

Keywords: modular houses; thermal insulation; energy efficiency; thermal bridges; multilayer wall construction; thermal conductivity coefficient; continental climate; insulation materials; energy-efficient construction.

Introduction.

In recent years, the demand for modern, efficient, and rapidly constructed residential buildings has grown significantly across Uzbekistan. This trend has accelerated the adoption of modular construction technologies. Since modular houses consist of prefabricated structural blocks manufactured in controlled factory conditions and delivered to the construction site fully or semi-assembled, they allow for shorter construction periods, stable production quality, and enhanced possibilities for increasing energy efficiency. However, Uzbekistan's continental climate—with its sharp daily and seasonal temperature fluctuations, winter cold loads, and intense summer solar radiation—imposes specific requirements on modular house design. Therefore, the proper selection of thermal insulation layers, prevention of thermal bridges between structural elements, and the application of calculation methods that minimize energy consumption require scientifically grounded solutions.

International sources on modular construction widely highlight the superior energy efficiency, manufacturing precision, and thermal performance of prefabricated elements. European and American researchers have extensively analyzed the thermal conductivity, air permeability, and mechanisms of thermal bridge formation in multilayer wall systems used in modular structures. Numerous studies propose various constructive solutions for reducing heat transfer in lightweight steel-framed modules and for applying insulation materials such as polyurethane foam, mineral wool, and wood-based products, especially in cold climates. International publications on energy-efficient construction emphasize that the effectiveness of thermal insulation is one of the primary determinants of a building's overall energy consumption.

Some research conducted in Central Asia investigates how thermal flows change within constructions during temperature fluctuations, the impact of solar radiation on wall assemblies,

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and recommendations for maintaining indoor microclimate stability. Although Uzbekistan's existing regulatory documents define requirements for thermal conductivity, wall thickness, and energy efficiency, they insufficiently address issues specific to modular buildings—such as preventing thermal bridges, calculating joint zones between modules, or adapting prefabricated elements to regional climatic conditions. Therefore, while the existing literature provides general scientific foundations for modular housing, the development of insulation systems and energy-efficiency solutions tailored specifically to Uzbekistan's sharply continental climate highlights the relevance of the present research.

Methods.

In this study, the thermal conductivity coefficients of wall, roof, and floor structures were determined based on SNIP, SP, and O'zDSt standards, and the effect of insulation thickness on energy consumption was calculated. The following characteristics of basalt wool, expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane foam (PUR), and SIP-panel materials were examined:

• thermal conductivity λ;
• moisture absorption capacity;
• density and lightweight performance;
• fire resistance;
• long-term durability.

Therm, Heat2, and Revit Energy modules were used to model heat flow, thermal bridges, and condensation zones in multilayer structures. Additionally, insulation systems and average energy consumption indicators used in modular houses in Kazakhstan, Türkiye, and Russia were compared.

Discussion and Results.

The lightweight structural characteristics of modular houses make them highly sensitive to heat transfer. Therefore, selecting an appropriate insulation material is a key factor not only for energy efficiency but also for indoor microclimate stability, condensation risk prevention, and service life.

The study shows that basalt wool is the most optimal material, as it offers high thermal resistance, fire safety, environmental compatibility, superior sound insulation, and long-term stability without degradation of properties.

Its use improves the thermal efficiency of the building, prevents moisture accumulation inside wall assemblies, and extends the lifespan of the structure.

International experiences in energy efficiency.

Advanced practices in modular construction have primarily developed in Northern Europe, North America, Japan, and Australia. These countries have conducted extensive scientific research and implemented practical projects integrating prefabricated modules into highly energy-efficient residential buildings [5].

In European countries—particularly Sweden, Norway, and Finland—the thermal insulation layers of modular houses are reinforced to withstand extreme cold conditions. Dense mineral wool, wood-fiber boards, and airtight membranes are widely used in wall and roof assemblies. Ventilated facades and dual-layer insulation systems significantly reduce heat losses in energy-

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efficient modules. Standard solutions for minimizing thermal bridges include the installation of structural joints with low heat transfer coefficients.
In North America, polyurethane foam and SIP panels are widely used for modular houses. Due to their high thermal resistance, SIP assemblies drastically reduce energy consumption. Certain U.S. states enforce strict air-tightness requirements for joints between modules, enhancing both energy efficiency and indoor climate stability. Canada and other cold-climate regions apply advanced standards requiring insulation materials with high R-values, helping determine the optimal insulation thickness for regions with prolonged winters.
Factors influencing the overall efficiency of a building include not only insulation but also:

• multi-layer glazing systems;
• roof ventilation design;
• color solutions affecting solar radiation absorption;
• architectural orientation relative to prevailing winds.

Based on average winter temperatures in Uzbekistan, the required thermal resistance of wall structures is $R \geq 3.2–3.5\ m^2K/W$. Calculation results are presented in Table 1.
Table 1

Material	**Thermal Conductivity λ (W/m·K)**	**Required Thickness**
Basalt wool	0.035–0.040	150–200 mm
EPS	0.038–0.040	130–160 mm
XPS	0.030	100–120 mm
PUR	0.025–0.028	80–100 mm

According to the comparative results, basalt wool was identified as the optimal, safest, and most economically reasonable option, offering excellent thermal resistance, non-combustibility, and long service life.

Based on wall-structure modeling:
• metal frame elements increase heat loss through the wall by 12–18%;
• applying an elastic thermal-insulation tape reduces this value to 6–8%;
• adding supplementary insulation at wall–floor junctions completely eliminated condensation.

Heat losses through the roof account for 30–35% of total building heat loss.
The roof-assembly analysis showed that:
• 200–250 mm of basalt wool provides optimal performance;
• incorrect placement of waterproofing and ventilation channels reduces insulation efficiency by 20%;
• a double air cavity lowers summer heat gain by 15%.

Regarding floor and foundation insulation, heat loss through the foundation accounts for 12–18%. When XPS is used:
• 50–80 mm insulation increases the R-value by 20–25%;
• the risk of condensation on the floor surface is fully eliminated.

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Analyzing the overall energy-efficiency model, a modular house built with optimal construction solutions achieves the following:
• winter heating energy consumption decreases by 28–40%;
• summer cooling loads decrease by 18–25%;
• daily indoor temperature fluctuations drop to 2.5–3 °C (compared to 6–8 °C in conventional houses).

Conclusion.
Under Uzbekistan's sharply fluctuating climatic conditions, the following scientifically grounded conclusions were reached regarding thermal insulation for modular houses:

1. **Optimal wall insulation** consists of 150–200 mm of basalt wool.
2. **Roof insulation** of 200–250 mm provides the highest level of energy efficiency.
3. **Floor and foundation insulation** using 50–80 mm of XPS effectively eliminates condensation risks.
4. A **ventilated façade system** increases thermal efficiency by **12–18%**.
5. When an optimal integrated system is applied, total energy consumption decreases by **30–40%**.
6. A **comprehensive energy-efficient model** ensures long-term sustainability for modular housing.

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