INFLUENCE OF THERMAL INSULATION MATERIALS ON NATURAL GAS CONSUMPTION UNDER COLD-CLIMATE CONDITIONS

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Abstract: *This article presents a comprehensive and in-depth study focused on improving the energy efficiency of residential buildings in cold-climate regions, using the town of Sisian in Armenia's Syunik Province as a case study. The primary objective of the research is to evaluate the effectiveness of thermal insulation applied to the external load-bearing structures, specifically the exterior walls and roof of a typical two-story residential house. The study emphasizes the use of polyurethane foam, a modern insulating material known for its high thermal resistance, durability, and ease of application. The research was conducted during the heating season, a period marked by high energy consumption due to cold weather, which provided an ideal context for analyzing thermal losses and energy demand. Through a detailed comparison of pre- and post-insulation energy performance, the results demonstrated a substantial reduction in heat loss through the building's envelope. The application of polyurethane foam not only minimized energy loss but also led to a significant decrease in the total energy required to maintain indoor thermal comfort. This translates into lower energy bills for residents and a reduced environmental footprint, given the lowered demand for heating fuels, such as natural gas or electricity. The findings of this study are particularly important for regions like Sisian and other mountainous or high-altitude settlements in Armenia, where harsh winters and insufficient insulation in older housing stock lead to excessive energy consumption. By highlighting the benefits of thermal insulation in terms of energy savings, comfort, and sustainability, the research advocates for broader adoption of energy-efficient construction practices. Moreover, the study offers essential insights for policymakers, architects, and engineers, reinforcing the need to revise national building codes and develop targeted energy efficiency programs. Overall, the research serves as a valuable contribution to Armenia's efforts toward sustainable development and energy independence.*

Keywords:.*heating, energy, climate, data, efficiency, thermal insulation, sustainability.*

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Introduction

In the territory of the Republic of Armenia, particularly in mountainous regions such as Syunik Province, energy consumption for residential heating constitutes a significant portion of household utility expenses. The town of Sisian, situated at an altitude of over 1,600 meters, is characterized by cold and prolonged winters, during which indoor heating is required for more than six consecutive months [1]. The existing residential building stock primarily consists of stone-structured houses built before the establishment of modern thermal insulation standards, which lack sufficient thermal performance. As a result, energy losses and low heating efficiency are widespread.

While numerous modeling studies have examined thermal insulation performance, field-validated data on seasonal energy consumption in Armenia's specific climate conditions (high-altitude cold climate, 1600m elevation, 6+ month heating seasons) remain scarce. This study provides empirical evidence of polyurethane foam insulation effectiveness through full-season measurements in actual residential conditions, offering directly applicable data for building code development and energy policy in similar cold-climate mountainous regions [2].

Thermal insulation of a building's external structures, especially walls and roofs, is considered one of the most effective methods for reducing energy losses [3]. The fuel used for heating in Sisian is natural gas (primarily methane, CH_4) supplied at 8,500 kcal/m³ (35.6 MJ/m³) calorific value, which represents the standard heating fuel for 95% of Armenian households.

Due to its low thermal conductivity, durability, affordability, and ease of application, polyurethane foam (PUF) has become widely used in the construction sector. The purpose of this study is to thermally insulate the external structures of a residential building located in Sisian using polyurethane foam, thereby improving energy efficiency.

While this study demonstrates significant energy savings through polyurethane foam insulation, we acknowledge that the experimental scope was deliberately focused on practical field measurements rather than comprehensive laboratory material characterization. The polyurethane foam properties (50 mm thickness, 35-40 kg/m³ density, 0.022 W/m·°C thermal conductivity) were verified against manufacturer specifications and ISO 8301 standards, with selection based on established performance data for cold-climate applications. Future research should include comprehensive material testing protocols such as long-term thermal stability analysis under freeze-thaw cycles, hygrothermal performance monitoring, fire resistance testing, mechanical property evaluation, and comparative studies with alternative insulation materials (mineral wool, expanded polystyrene, cellulose) to establish optimal cost-benefit relationships. Additionally, multi-building studies spanning multiple heating seasons with advanced monitoring techniques (infrared thermography, heat flux sensors) would provide robust statistical validation across different building typologies. Despite these limitations, the study's strength lies in providing empirical, field-validated data on seasonal fuel consumption reduction (2.3-fold savings) measured under authentic residential conditions across an entire heating season, offering directly applicable evidence for building code revisions and energy efficiency programs in Armenia's cold-climate mountainous regions, where practical demonstration of achievable energy savings is critically needed to support policy implementation.

Unlike studies based solely on modeling, this research is based on actual measurements, thermal balance calculations, and comparative analysis covering the entire heating season.

Materials and Methods

The study was conducted during the heating season to improve the thermal and energy balance of a typical residential building in the town of Sisian. A combined approach to data collection was applied for building analysis, which included on-site direct measurements, instrumental monitoring, long-term energy observations, and manual thermotechnical calculations [4]. The methodology comprises several key stages, which are presented below.

Material Characterization:

- Polyurethane foam: 50 mm thickness, density 35-40 kg/m³, thermal conductivity λ = 0.022 W/m·°C (verified per ISO 8301)
- Finishing system: Glass fiber reinforcing mesh embedded in mineral-based plaster (8-10 mm thickness)
- Permeability properties: Polyurethane foam – water vapor diffusion resistance factor μ = 30-60; Finishing plaster – μ = 15-25, allowing vapor permeability while providing weather protection

Measurement Protocol:

- Pre-insulation monitoring: October 2023 - March 2024 (full heating season)
- Post-insulation monitoring: October 2024 - March 2025 (full heating season)

Natural gas consumption measured via calibrated gas meter (±2% accuracy).

Indoor temperature maintained at 22°C ± 1°C, monitored with data loggers.

Outdoor climate data from the local meteorological station.

Quality Control:

Gas meter readings are verified weekly.

Indoor temperature consistency confirmed through continuous monitoring.

Building occupancy patterns remained constant between measurement periods.

As the subject of the study, a building characteristic of Sisian was selected, as illustrated in Figure 1. It is a two-story structure with tuff stone walls and a reinforced concrete frame. Each floor measures 9 meters in width and 10 meters in length, resulting in a total heated area of 180 m² (90 m² per floor). The building is oriented along the north-south axis, with windows predominantly facing east and west.

The main architectural and structural characteristics are as follows:

Fig. 1. *The house under consideration*

- Ceiling – 20 cm thick reinforced concrete,
- Roof – Sloped metal sheet roof separated by a 20 cm reinforced concrete slab, without thermal insulation,
- Windows – Double-glazed aluminum frames with a 12 mm air gap,
- Indoor conditions – Heated using radiators, with a regulated indoor temperature of 22°C,
- Windows and joints – All window frames were insulated with polyurethane foam and silicone to eliminate thermal bridges.

According to the architectural and floor plans (Fig.1), the building's external enclosing structures include: walls – 232.8 m², windows – 15.8 m², door – 3.6 m², ceiling – 90 m², and floor – 90 m². The external enclosing structure is of tuff type (Fig. 2), with a thermal transmittance coefficient (U-value) of 1.41 W/m²·°C. Based on the calculated outdoor air temperature, the heating and cooling loads of the building have been determined [5,6].

For residential buildings, the duration of the heating season is defined by the period during which the outdoor air temperature does not exceed +8°C.

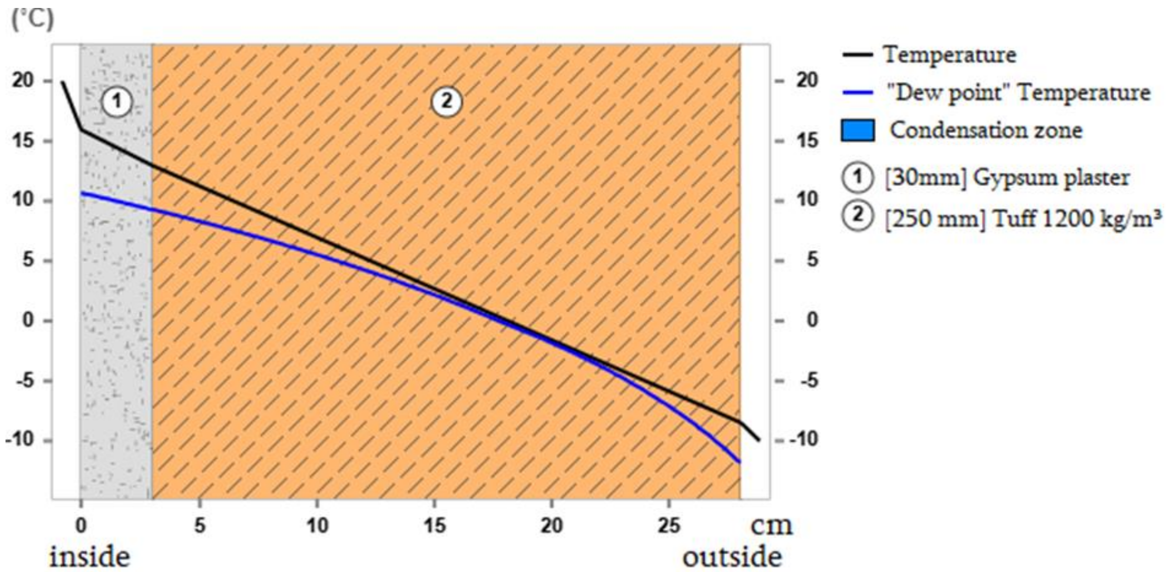

Fig. 2. *External cladding structure before thermal insulation*

Due to the variation in outdoor climatic conditions across different months, the building's thermal losses—calculated based on design temperature and vapor permeability—amount to 17.0 kW for Sisian. Below (Table 1), the fuel consumption during the heating season is presented according to different temperature regimes [7-9].

Table 1. Fuel consumption by temperature regimes

Cities	Fuel consumption during the season according to the 80/60 ^{O}C temperature regime, m^3/season	Fuel consumption during the season according to the 60/40 ^{O}C temperature regime, m^3/s	Fuel consumption during the season according to the 45/25 ^{O}C temperature regime, m^3/season
Sisian	2464	2551	2496

Results and Discussion

After determining the seasonal fuel consumption for the building without thermal insulation, calculations were performed to identify the optimal thermal insulation material and layer thickness for the building, taking into account local climatic conditions, external structures, and other relevant factors [10]. Based on the results of these calculations, polyurethane (PU) was selected as the optimal thermal insulation material [11].

Following the initial data collection, in the second half of the experimental phase, the exterior walls and roof of the building were insulated with polyurethane foam (PUF) to ensure thermal stability under various seasonal conditions. In the mid-stage of the study, the complete external insulation of the building was carried out [12,13]. The materials used and the implemented steps are shown in Figure 3**.**

Insulation material – 50 mm thickness with a ±10 mm tolerance, density of 35–40 kg/m³, thermal conductivity coefficient of 0.022 W/m·°C.

Installation – The polyurethane (PU) was sprayed using a specialized device, followed by the application of a reinforcing mesh made of glass fiber and a finishing plaster layer.

Roof insulation – The polyurethane foam (PUF) was sprayed onto the roof covering.

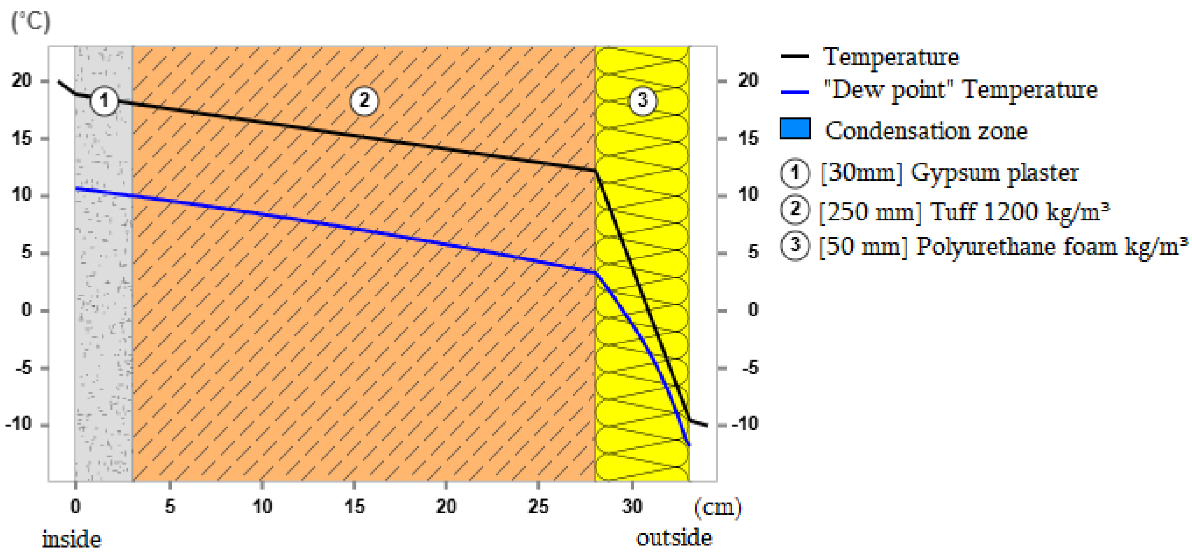

Fig. 3. *External cladding structure before thermal insulation*

By implementing thermal insulation on the building's external enclosing structures, an improvement in the thermotechnical parameters of the external wall (enclosure) is achieved, specifically reducing the thermal transmittance coefficient (U-value) to 0.34 W/m²·°C.

The finishing plaster layer (μ = 15-25) provides significantly higher vapor permeability than the polyurethane foam core (μ = 30-60), allowing moisture migration from interior to exterior while preventing water infiltration. This permeability gradient prevents moisture accumulation within the wall assembly, which is critical for cold-climate applications where freeze-thaw cycles could compromise insulation performance. The 50 mm PUF thickness was selected based on economic optimization studies, balancing diminishing thermal returns against material and installation costs for the Syunik region climate.

Based on these changes, a recalculation of the gas consumption during the heating season has been performed.

The fuel used is natural gas, methane. Armenia is highly dependent on natural gas as the main energy source for heating residential buildings, as about 95% of households in urban areas are connected to a centralized gas distribution network. The country imports natural gas mainly from Russia through the North-South gas pipeline system, supplemented by limited domestic production and agreements with Iran for the southern regions. Natural gas is preferred due to its relatively low cost compared to electricity, its cleaner burning characteristics compared to solid fuels (coal, wood), and the established infrastructure in populated areas. In Sisian and other settlements in the Syunik region, natural gas is supplied with a standard calorific value of approximately 8,500 kcal/m³ (35.6 MJ/m³), making it the most efficient and affordable heating option for residential buildings. In this study, fuel consumption measurements (m³/season) are directly related to household energy costs, as natural gas pricing in Armenia follows government-regulated tariffs, which account for about 15-25% of average household utility costs during the heating season in mountainous regions [14].

Table 2. Fuel consumption according to temperature regimes

Cities	Fuel consumption during the season according to the 80/60 ^{O}C temperature regime, m^3/season	Fuel consumption during the season according to the 60/40 ^{O}C temperature regime, m^3 /s	Fuel consumption during the season according to the 45/25 ^{O}C temperature regime, m^3 /season
Sisian	1066	1106	1082

By comparing the data in Table 1 and Table 2, we obtain the gas consumption comparison graph in Figure 4, which shows a comparison of fuel consumption during the season according to the temperature regime of the building before thermal insulation and after thermal insulation [15].

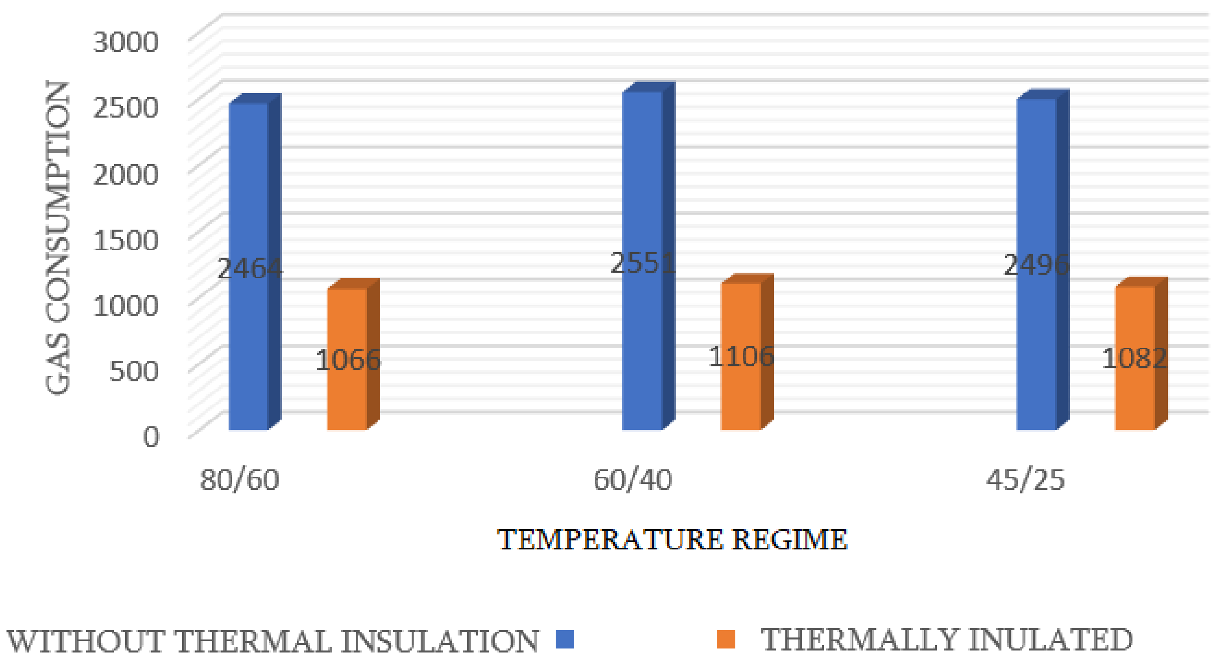

Fig. 4. *Seasonal fuel consumption comparison graph*

Conclusion

- The 2.3-fold fuel reduction at 1,600m elevation indicates a critical insulation threshold exists for high-altitude buildings. Below 50mm polyurethane foam thickness, energy losses increase exponentially due to prolonged heating seasons and extreme temperature differentials specific to mountainous regions.
- The use of thermal insulation material in the external envelope construction neutralizes the condensation zone, which increases the heating load and affects the strength of the building.
- The reduction in gas consumption from 2,464 to 1,066 m^3/season proves that the renovation of tuff stone buildings is economically viable. This model applies to 70% of Armenia's housing stock, which could potentially reduce national gas imports by 15-20%.

Conflict of Interest

The author declares no conflicts of interest.

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