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[Ainur Tukhtamisheva](#), Aiganym Ismailova*, [Zhangazy Moldamuratov](#)*

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Article

Thermal Performance and Energy Renovation Potential of a Soviet-Era Multi-Apartment Residential Building in a Cold Climate: A Case Study of Kazakhstan

Ainur Tukhtamisheva ^{1,2}, Aiganym Ismailova ^{1,2,*} and Zhangazy Moldamuratov ^{1,2,*}

¹ International Educational Corporation, Ryskulbekov st. 28, Almaty 050043, Kazakhstan

² Kazakh Leading Academy of Architecture and Civil Engineering, Ryskulbekov st. 28, Almaty 050043, Kazakhstan

* Correspondence: ismile0787@gmail.com (A.I.); zhanga_m_n@mail.ru (Z.M.)

Abstract

Improving the energy efficiency of existing residential buildings is a key challenge for reducing energy consumption in cold climate regions. A considerable proportion of the housing stock in Kazakhstan consists of Soviet-era multi-apartment buildings characterized by high heat losses and low thermal performance. The aim of this study is to assess heat losses and evaluate the energy-saving potential of a typical multi-apartment residential building located in a cold climate. A comprehensive energy audit was conducted, including an analysis of the thermal performance of building envelopes, calculation of heat losses through walls, windows, roof, and heating system pipelines, thermographic inspection, and air infiltration measurements using blower door testing. The results show that the largest share of heat losses occurs through external walls, windows, and uninsulated heating pipelines. The implementation of thermal modernization measures, such as wall insulation, window replacement, and pipeline insulation, can significantly reduce the building's heat consumption and improve overall energy performance. The findings of this study demonstrate the high potential for improving the energy efficiency of existing residential buildings and may be useful for developing renovation strategies for similar buildings in cold climate regions.

Keywords: energy efficiency; heat losses; residential buildings; thermal modernization; energy audit; cold climate; building renovation

1. Introduction

Improving the energy efficiency of existing residential buildings is one of the key priorities for achieving sustainable development and reducing global energy consumption. The building sector accounts for approximately 35–40% of total energy use worldwide [1], with a significant share associated with space heating in regions characterized by cold climates. Therefore, reducing heat losses in residential buildings represents an important opportunity for decreasing energy demand and greenhouse gas emissions.

A substantial proportion of residential buildings in Eastern Europe and Central Asia were constructed during the Soviet period between 1950 and 1990. These buildings were designed according to outdated thermal protection standards and are characterized by insufficient thermal insulation of building envelopes, inefficient heating systems, and significant air infiltration [2,3]. As a result, such buildings demonstrate increased energy consumption and require comprehensive thermal modernization and energy renovation.

In regions with severe continental climates, heat losses through walls, windows, roofs, and heating system components significantly increase the demand for thermal energy. Previous studies

have shown that deficiencies in building envelopes and uncontrolled air infiltration are among the main factors affecting energy performance [4–6]. Thermographic surveys and blower door testing are widely used methods [2,7]. However, most existing studies focus on European and North American building stocks, while detailed investigations of residential buildings in Central Asian countries remain limited.

Previous studies have also investigated energy efficiency and optimal insulation strategies for residential buildings in Kazakhstan [11]. Kazakhstan is characterized by a sharply continental climate with long and cold winters, where outdoor temperatures can fall below $-30\text{ }^{\circ}\text{C}$. Under these conditions, improving the energy performance of existing residential buildings is essential for reducing heat consumption and improving indoor comfort. Despite the relevance of this issue, there is still insufficient research based on detailed energy audits and in-situ measurements of heat losses in existing residential buildings in the central region of Kazakhstan.

The aim of this study is to assess heat losses and evaluate the energy-saving potential of a typical Soviet-era multi-apartment residential building located in a cold climate region of central Kazakhstan. The research is based on a comprehensive energy audit including analysis of the thermal performance of building envelopes, thermographic inspection, and air infiltration measurements using blower door testing. The obtained results allow for the identification of the main sources of heat losses and evaluation of the effectiveness of proposed thermal modernization measures for improving building energy efficiency.

Despite numerous studies on building energy efficiency, detailed investigations of Soviet-era residential buildings in Central Asian cold climate regions remain limited. This study contributes to the existing body of knowledge by providing an integrated assessment combining thermographic inspection, blower door testing, and economic evaluation of energy-saving measures for a representative residential building in Kazakhstan.

2. Materials and Methods

2.1. Case Study Building and Initial Data

A typical Soviet-era multi-apartment residential building located in the central region of Kazakhstan (severe continental climate) was selected as a case study. The building was constructed in 1959 and has three above-ground floors with a basement and an attic space. The building includes four stairwell entrances and comprises 25 apartments, with a small commercial unit on the ground floor. The external walls are brick masonry with an exterior plaster finish.

According to technical documentation and field inspection, the building has an external volume of approximately $10,791\text{ m}^3$, a total floor area of 2648.3 m^2 , and a heated floor area of 1772.9 m^2 . The building footprint area is 863.3 m^2 , and the ceiling height is approximately 2.5 m . The reported physical deterioration level is about 40%.

The total area of envelope elements is approximately 3440.6 m^2 , including external walls (1433.6 m^2), glazing (260.6 m^2), door openings (19.8 m^2), floor (863.3 m^2), and ceiling/roof slab (863.3 m^2). Two window types are installed: traditional double wooden frames (42%) and single-chamber plastic glazing units (58%). The building has a pitched slate roof with an attic; the attic insulation consists of a slag layer with an approximate thickness of 100 mm .

The building is connected to a centralized district heating network. The heating system is radiator-based with an upper distribution layout and includes an elevator (jet-pump) unit in the basement. Cast-iron radiators are installed in apartments, while pipe registers are used in common areas. Field inspection indicated that heating pipelines located in the basement and attic spaces, as well as the elevator unit, are largely uninsulated. No hydraulic balancing and no automatic control of heat supply were identified.

Climatic and indoor conditions were considered as follows: the average outdoor temperature during the heating season is approximately $-7\text{ }^{\circ}\text{C}$, the design outdoor temperature is $-32\text{ }^{\circ}\text{C}$, and the

indoor design temperature is +20 °C. Thermographic inspection was conducted at an outdoor air temperature of approximately -10 °C.



Figure 1. Multi-apartment residential building as an object of technical condition assessment of building structures.

2.2. Energy Audit Framework

A comprehensive energy audit was performed to assess the thermal performance of the case study building and to identify the dominant sources of heat losses. The audit framework included: (i) on-site visual inspection of the building envelope and engineering systems; (ii) calculation-based assessment of heat losses through envelope components and heating system elements; (iii) infrared thermographic inspection to detect thermal defects and thermal bridges; and (iv) air infiltration evaluation using pressurization/depressurization testing (blower door) with analysis of airflow parameters at a pressure difference of 50 Pa.

The audit outputs were used to quantify the contribution of individual components (walls, windows, roof/ceiling, and heating pipelines) to the total heat loss and to support the evaluation of retrofit measures [6].

2.3. Heating Load Calculation

The design heating load of the building was determined using a standard engineering approach based on aggregated indicators and the building's external volume. The heating load was calculated using:

$$Q = \alpha \cdot q_0 \cdot V \cdot (t_{in} - t_{out}) \cdot 10^{-6}, \quad (1)$$

where Q is the design heating load (Gcal/h), α is a climatic correction coefficient, q_0 is the specific thermal characteristic of the building (kcal/(m³·h·°C)), V is the external building volume (m³), and t_{in} and t_{out} are indoor and outdoor temperatures (°C), respectively.

For the studied building, $V \approx 10,791\text{m}^3$. The indoor design temperature was assumed as $t_{in} = +20$ °C. The climatic correction coefficient was taken as $\alpha = 0.95$, and the design outdoor temperature was $t_{out} = -32$ °C. The value of q_0 was selected according to building type and construction period. The calculated heating load values were subsequently used to interpret the relative shares of component heat losses and to evaluate the potential impact of retrofit measures.

2.4. Heat Loss Assessment for Envelope and Heating Pipelines

Heat losses through the building envelope were assessed by calculating heat loss rates for major elements (windows, walls, and roof/ceiling) based on their areas and heat loss intensities under representative heating-season temperature differences. For each component, the general form was applied:

$$Q_i = S_i \cdot q_i \quad (2)$$

where Q_i is the heat loss rate (W), S_i is the element area (m²), and q_i is the heat loss intensity (W/m²) determined for the corresponding construction type under a specified temperature difference.

Additional heat losses associated with localized thermal defects (e.g., thermal bridges, degraded plaster, leakage zones around window frames) were estimated using a convective heat transfer approach:

$$Q_{def} = S_{def} \cdot \Delta T \cdot h \quad (3)$$

where S_{def} is the defect-affected area (m²), ΔT is the temperature difference (°C) derived from thermographic observations, and h is the heat transfer coefficient (W/(m²·°C)).

Heat losses from uninsulated heating pipelines located in unheated spaces (basement and attic) were estimated by calculating the surface area of the pipes and applying a convective heat transfer model:

$$S_{pipe} = 2\pi RL \quad (4)$$

$$Q_{pipe} = S_{pipe} \cdot \Delta T \cdot h_{cyl} \quad (5)$$

where R is the pipe radius (m), L is the pipe length (m), ΔT is the temperature difference between pipe surface and surrounding air (°C), and h_{cyl} is the convective heat transfer coefficient for a cylindrical surface (W/(m²·°C)).

2.5. Thermographic Inspection

Infrared thermography was used to identify spatial non-uniformities in surface temperatures and to locate thermal bridges and envelop defects. The survey was performed under cold outdoor conditions (approximately -10 °C) to enhance temperature contrast between indoor and outdoor environments. Thermograms were obtained for representative façade areas, window zones, corners, and junctions between envelope elements. The thermographic results were used to (i) qualitatively identify defect locations and (ii) support quantitative estimation of additional heat losses [2,13] in defect-affected areas via temperature gradients and inferred ΔT values.

2.6. Air Infiltration Measurement (Blower Door Test)

Building airtightness was evaluated using fan pressurization/depressurization testing. The test was conducted by creating a pressure difference of 50 Pa between indoor and outdoor environments and recording the airflow rate required to maintain the pressure difference. Both depressurization and pressurization modes were considered. The key reported indicators were: (i) V_{50} , the airflow rate (or air volume flow) at 50 Pa, and (ii) n_{50} , the air exchange rate at 50 Pa, which is commonly used to characterize infiltration-related airtightness [3].

The measured airtightness indicators were compared against normative values applicable to residential buildings to determine whether infiltration-related heat loss reduction measures should be prioritized.

2.7. Data Availability and Ethical Statement

The study does not involve human or animal subjects and does not require ethical approval. The audit-based input data and calculated results supporting the findings of this study are available from the author upon reasonable request.

3. Results

3.1. Structure of Heat Losses in the Building

The comprehensive energy audit and thermal calculations revealed a significant imbalance in heat loss distribution across the building envelope and engineering systems. The analysis demonstrated that the dominant heat losses are associated with the external walls and uninsulated heating pipelines, while windows and roof structures also contribute substantially to the total thermal load.

Table 1 summarizes the calculated heat losses and their relative contribution to the overall building heating demand under typical winter operating conditions.

Table 1. Distribution of heat losses across building components.

Building element	Heat loss (kW)	Share of total heat loss (%)
Windows	≈20	≈16
External walls	≈58	≈46
Heating pipelines	≈41	≈32
Roof/ceiling	≈24.8	≈19

The results indicate that the largest share of heat losses occurs through the external walls due to insufficient thermal insulation and structural degradation. Heating system pipelines located in unheated spaces also represent a significant source of energy loss. Windows and roof structures contribute additional heat losses due to poor airtightness and insufficient insulation.

The calculated average design heating load of the building is approximately 0.11 Gcal/h under typical heating season conditions, which reflects the combined influence of envelope and system-related thermal losses.

3.1.1. Heat Losses Through Windows

The building contains 130 windows of two main types: traditional double wooden frames and single-chamber plastic glazing units. The total glazing area is approximately 260.6 m², representing about 7.6% of the total envelope area.

Heat losses through windows were calculated based on the glazing area and characteristic heat loss coefficients for different window types under representative temperature differences. The calculated heat loss through existing windows is approximately 17.6 kW, corresponding to about 14% of the average design heating load.

Thermographic inspection revealed additional heat losses caused by air leakage through deteriorated sealing elements and insufficient insulation between window frames and wall openings. Local thermal defects around window perimeters resulted in an estimated additional heat loss of approximately 2.9 kW.

The total heat loss through windows, including structural and installation defects, is therefore estimated at approximately 20 kW (≈0.02 Gcal/h), representing about 16% of the building's total heat

losses. Thermographic images confirmed the presence of thermal bridges and localized infiltration zones, particularly around plastic window frames and junctions with wall structures.

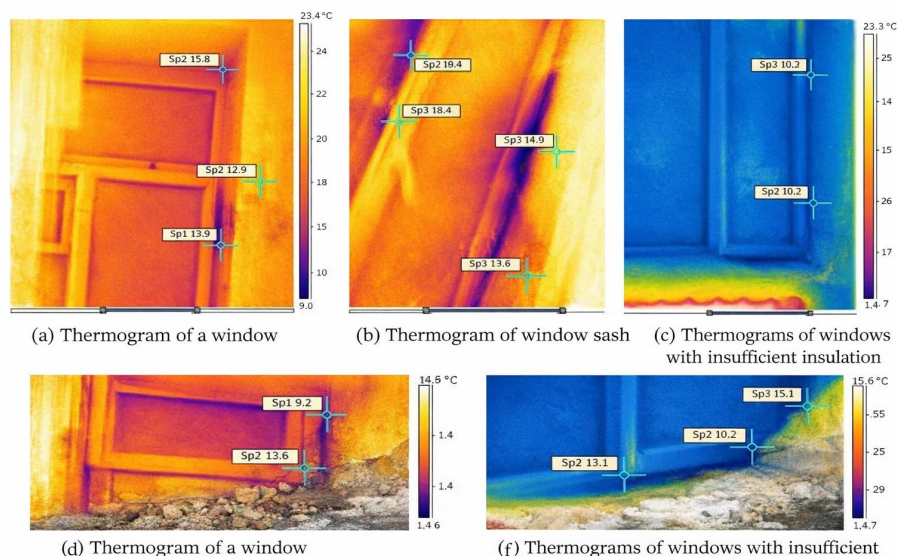


Figure 2. Thermographic examination of window structures revealing heat losses and insulation defects.

3.1.2. Heat Losses Through External Walls

The external walls are constructed of solid brick masonry with an approximate thickness of 0.7 m and external cement plaster. No additional thermal insulation is present. The total wall area is approximately 1433.6 m², accounting for about 41.7% of the total envelope area.

Under standard conditions, calculated heat losses through walls in satisfactory condition would be approximately 29 kW ($\approx 23\%$ of the design heating load). However, visual inspection and thermographic analysis revealed significant structural deterioration, including partial plaster detachment, thermal bridges at wall joints, and freezing of corner zones.

Thermographic measurements indicated extensive “problem areas” with reduced surface temperatures and increased heat flux. The total area affected by thermal defects was estimated at approximately 860 m². Additional heat losses associated with these areas were calculated at approximately 29 kW.

As a result, the total heat loss through external walls is estimated at approximately 58 kW (≈ 0.05 Gcal/h), corresponding to about 46% of the overall building heat loss. This confirms that wall structures represent the dominant source of thermal energy loss due to insufficient insulation and envelope degradation.

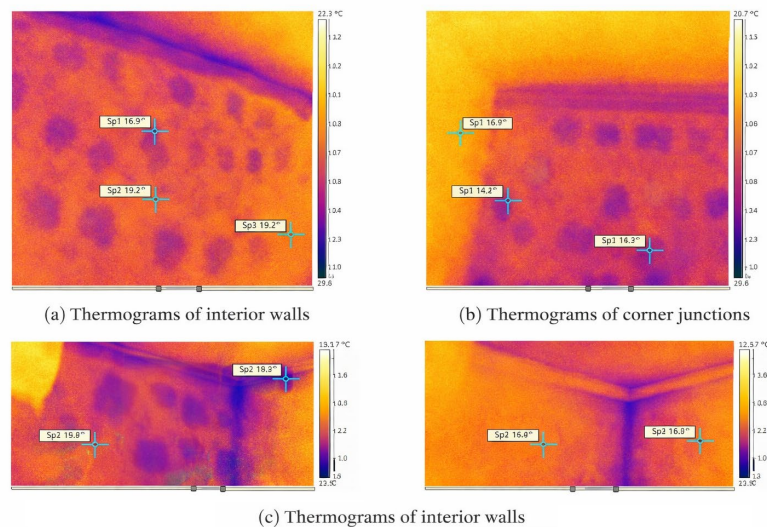


Figure 3. Thermographic assessment of walls and corner junctions.

3.1.3. Heat Losses from Heating System Pipelines

Uninsulated heating pipelines located in basement and attic spaces were identified as a major source of heat loss. In the basement, approximately 190 m of pipelines with a diameter of 40 mm were found without thermal insulation. The calculated heat loss from basement pipelines and associated equipment is approximately 14.6 kW.

In the attic, approximately 180 m of pipelines without insulation were identified. Due to high temperature differences between pipe surfaces and surrounding air, heat losses from attic pipelines were estimated at approximately 26.4 kW.

The combined heat loss from heating system pipelines in basement and attic spaces is therefore approximately 41 kW (≈ 0.04 Gcal/h), representing about 32% of the building's total heat losses. These losses occur due to direct heat transfer from uninsulated surfaces to unheated spaces and the outdoor environment.

3.1.4. Heat Losses Through Roof and Ceiling

The building has a pitched roof with an attic space. The ceiling consists of reinforced concrete slabs with roofing felt and a slag insulation layer approximately 100 mm thick. The total ceiling area is approximately 863.3 m².

The calculated heat loss through the ceiling and roof structure is approximately 24.8 kW (≈ 0.02 Gcal/h), corresponding to about 19% of the total heat loss. The relatively high heat loss is attributed to insufficient insulation thickness and degradation of roofing structures.

Thermal calculations indicate that increasing insulation thickness could significantly reduce heat losses through the roof structure.

3.1.5. Air Infiltration and Airtightness Assessment

Air infiltration measurements were conducted using blower door testing under pressurization and depressurization conditions at a pressure difference of 50 Pa. The test provided values for airflow rate (V50) and air exchange rate (n50), which characterize building airtightness.

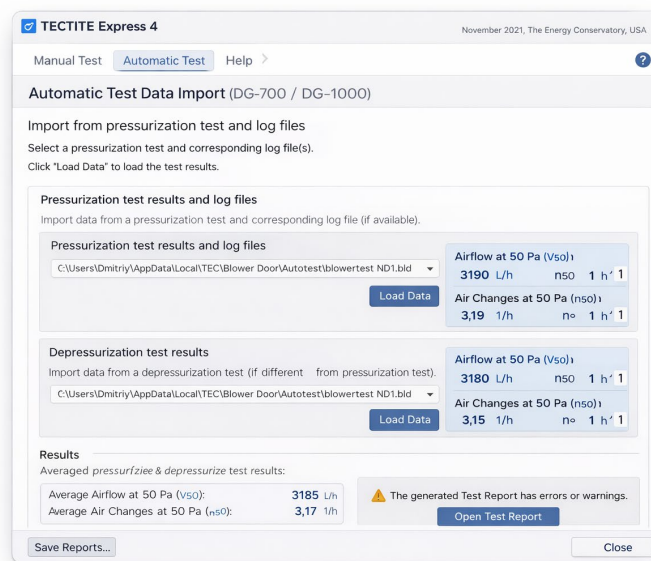


Figure 4. Results of measuring the air infiltration level in building structures.

The measured infiltration values were within recommended limits for residential buildings of similar construction types. This indicates that uncontrolled air infiltration is not the dominant factor in the building's overall heat loss. Consequently, heat losses associated with the building envelope and heating system components represent the primary targets for thermal performance improvement.

3.2. Energy Saving Potential and Economic Evaluation

To evaluate the effectiveness of potential renovation measures, an economic assessment of several energy efficiency improvements was conducted. The analysis included envelope insulation, modernization of the heating system, and installation of control and metering devices aimed at reducing heat losses and improving the overall thermal performance of the building.

The expected reduction in heating load, annual energy savings, implementation costs, and payback periods was estimated for each proposed measure. The calculations were performed using the average district heating tariff in Kazakhstan, estimated at approximately 5500 KZT per Gcal, which represents a typical value for residential buildings connected to centralized heating systems.

The results indicate that the implementation of all proposed measures could reduce the building's annual heat consumption by approximately 573.7 Gcal, resulting in annual financial savings of about 3.15 million KZT. These results demonstrate significant potential for improving the energy efficiency of existing residential buildings through comprehensive thermal modernization.

Among the measures analyzed, insulation of heating pipelines demonstrates the shortest payback period (approximately 1.5 years) due to its relatively low implementation cost and substantial reduction of heat losses occurring in unheated spaces such as basements and attics. Measures such as the installation of thermostatic radiator valves and automated heat substations also show favorable economic performance by improving heat distribution and enabling more efficient control of heat supply.

In contrast, window replacement and roof insulation require higher capital investment and therefore demonstrate longer payback periods. Nevertheless, these measures provide additional benefits, including improved thermal comfort, reduction of thermal bridges, enhanced indoor environmental quality, and increased durability of building envelope structures. Economic evaluation of building retrofit measures has been widely discussed in previous studies [24,28].

Overall, the results confirm that a comprehensive renovation strategy combining envelope insulation and modernization of heating systems can significantly reduce heat losses and improve the energy performance of existing residential buildings located in cold climate regions Table 2.

Table 2. Expected results of energy efficiency measures.

Energy-saving measure	Expected load reduction (Gcal/h)	Annual energy savings (Gcal/year)	Implementation cost (KZT)	Expected annual cost savings (KZT/year)	Payback period (years)
Window replacement	≈0.009	46	≈14,300,000	≈253,000	≈56
External wall insulation	≈0.04	196	≈11,600,000	≈1,078,000	≈10.8
Heating pipeline insulation	≈0.02	89	≈740,000	≈489,000	≈1.5
Roof insulation improvement	≈0.005	26	≈3,450,000	≈143,000	≈24
Installation of automated heat substation (AHS)	≈0.015	75.6	≈3,000,000	≈416,000	≈7.2
Installation of balancing valves	≈0.005	25.2	≈886,000	≈139,000	≈6.4
Installation of thermostatic radiator valves	≈0.013	65.5	≈1,380,000	≈360,000	≈3.8
Installation of apartment heat meters	≈0.01	50.4	≈1,815,000	≈277,000	≈6.5
Total	0.117	573.7	≈37,171,000	≈3,155,000	Average payback period ≈12 years

Figure 5 illustrates the potential annual energy savings associated with the proposed retrofit measures. The results indicate that external wall insulation provides the largest reduction in heat consumption, followed by insulation of heating pipelines and installation of automated heat control systems. Measures such as thermostatic valves and apartment heat meters also contribute significantly to reducing energy consumption by improving heat distribution and control within the building.

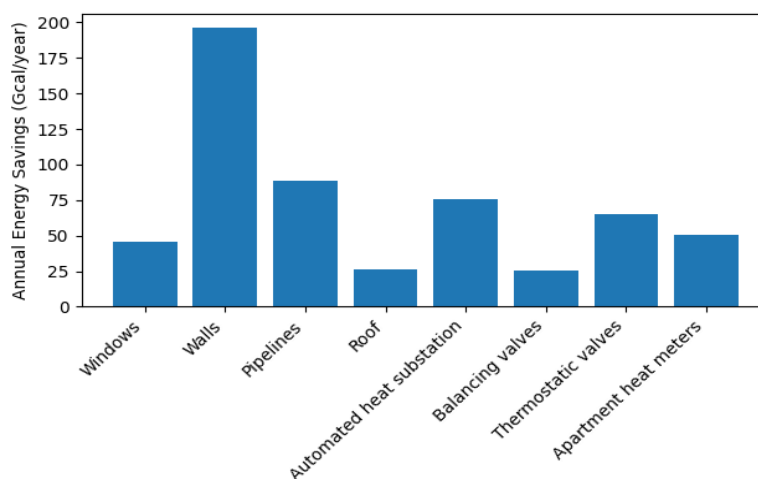


Figure 5. Potential annual energy savings resulting from the implementation of different energy efficiency measures in the studied residential building.

4. Discussion

The results obtained in this study confirm that heat losses in existing multi-apartment residential buildings located in cold climate regions are primarily determined by the thermal performance of

building envelope components and the condition of engineering systems. The quantitative assessment demonstrated that the largest share of heat losses is associated with external walls, followed by heating pipelines, roof structures, and windows.

The dominant contribution of external walls (approximately 46% of total heat losses) is consistent with previous studies conducted in cold climate regions, where poorly insulated masonry structures represent the main pathway of heat transfer to the outdoor environment [4,6,10]. The presence of thermal bridges, degraded plaster layers, and insufficient insulation significantly increases heat flow through wall assemblies and leads to higher heating demand.

An important finding of this study is the substantial contribution of uninsulated heating pipelines (approximately 32% of total heat losses). Similar observations have been reported in earlier studies; however, the magnitude of these losses in the present case highlights the critical role of internal engineering systems in overall building energy performance [6]. This result suggests that system-level inefficiencies may be underestimated in conventional energy assessments, which often focus primarily on envelope characteristics.

Heat losses through windows (approximately 16%) are associated not only with thermal transmittance of glazing but also with installation defects and air leakage. Thermographic inspection confirmed that infiltration through window joints and insufficient sealing contributes to additional heat transfer, which is consistent with findings reported in previous studies [2,3].

Roof and ceiling structures account for approximately 19% of total heat losses. Although this share is lower than that of walls and pipelines, it remains significant due to insufficient insulation thickness and material degradation. Previous studies have demonstrated that increasing roof insulation can effectively reduce heat transfer and improve overall building energy performance [10].

The economic assessment showed that different energy efficiency measures vary significantly in terms of cost-effectiveness. Insulation of heating pipelines and installation of thermostatic control devices demonstrated the shortest payback periods due to relatively low implementation costs and high energy-saving potential. Similar trends have been reported in recent studies focusing on cost-optimal retrofit strategies for existing buildings [24,28].

In contrast, external wall insulation provides the greatest reduction in heat losses but requires substantial capital investment, resulting in longer payback periods. Nevertheless, this measure is essential for achieving significant long-term improvements in building energy performance. Additional measures, such as roof insulation and window replacement, contribute not only to energy savings but also to improved indoor thermal comfort and durability of building structures.

From a broader perspective, the results of this study highlight the importance of a comprehensive approach to energy renovation that integrates improvements in building envelope performance with modernization of heating systems and implementation of control technologies. This finding is consistent with recent research emphasizing the need for integrated retrofit strategies in existing residential buildings.

It should be noted that this study is based on a single case study building, which may limit the generalization of the results. Building-specific characteristics, construction quality, and operational conditions can influence the distribution of heat losses and the effectiveness of renovation measures. Therefore, future research should focus on analyzing a larger sample of residential buildings and evaluating the long-term performance of combined energy renovation strategies under different climatic conditions.

5. Conclusions

1. This study evaluated the thermal performance and energy renovation potential of a typical Soviet-era multi-apartment residential building located in the cold climate conditions of central Kazakhstan. A comprehensive energy audit was conducted, including heat loss calculations for building envelope components, thermographic inspection, and air infiltration measurements using blower door testing.

2. The results show that the building experiences significant heat losses typical of residential buildings constructed during the mid-20th century. The largest share of heat losses occurs through external walls (approximately 46%), followed by uninsulated heating pipelines (32%), roof structures (19%), and windows (16%). Thermographic analysis revealed multiple thermal bridges and envelope defects that contribute to increased heat transfer and reduced thermal efficiency.

3. The economic evaluation of proposed energy efficiency measures demonstrated that the implementation of renovation strategies could significantly improve the building's energy performance. The total potential reduction in heat consumption was estimated at approximately 573.7 Gcal per year, which corresponds to annual financial savings of around 3.15 million KZT based on the average district heating tariff in Kazakhstan.

4. Among the proposed measures, insulation of heating pipelines and installation of thermostatic control devices showed the shortest payback periods due to low investment costs and high energy-saving potential. External wall insulation provides the greatest reduction in heat losses but requires higher capital investment.

5. Additional measures, including roof insulation and window replacement, contribute to improved thermal comfort, reduced heat losses, and increased durability of building envelope structures.

6. Overall, the results highlight the importance of implementing comprehensive energy renovation strategies that combine building envelope insulation, modernization of heating systems, and improved heat control technologies.

7. The findings of this study may support the development of energy-efficient renovation programs for Soviet-era residential buildings in Kazakhstan and other cold climate regions.

8. Future research should focus on analyzing a larger sample of buildings and evaluating the long-term performance of integrated energy renovation measures under different climatic conditions.

Author Contributions: Conceptualization, A.Z. and Z.M.; methodology, A.Z.; validation, A.Z., A.I. and Z.M.; formal analysis, A.Z.; resources, A.Z.; writing—original draft preparation, A.Z.; writing—review and editing, A.Z., A.I.; visualization, Z.M.; supervision, A.Z. and A.I.; All authors have read and agreed to the published version of the manuscript.

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