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Article

Heat transfer-based analysis of building energy demand and energy systems

Aida Nazarova[1], Gulzhan Tleukenova[2], Yer-Targyn Tleukenov[3,*]

[1]School of Science and Humanities, Nazarbayev University, Astana, Kazakhstan
[2]Bau International Deutsche Energie-Agentur GmbH (DENA), Berlin, Germany
[3]Nazarbayev University Research Administration, Nazarbayev University, Astana, Kazakhstan
*Correspondence: yertargyn.tleukenov@nu.edu.kz

Abstract. This study examines the thermal performance of buildings and the efficiency of alternative energy supply systems under cold climatic conditions, with a focus on Eastern Kazakhstan. The objective is to quantify the impact of building envelope insulation and energy system configuration on heating demand, primary energy consumption, carbon emissions, and economic performance. An analytical methodology based on standardized building physics approaches was applied to determine heat demand, accounting for transmission and ventilation losses as well as internal and solar heat gains. Climatic conditions were incorporated using the heating degree-day method. Several energy supply configurations, including conventional fossil-based systems and renewable-integrated solutions, were evaluated in terms of energy, environmental, and economic indicators. The results indicate that improving the insulation standard reduces the specific heating demand from approximately 185 kWh/m²·a to 63 kWh/m²·a, corresponding to a reduction exceeding 60%. Transmission losses represent about 70% of total heat losses. Primary energy consumption decreases from approximately 280 kWh/m²·a for coal-based systems to about 110 kWh/m²·a for renewable-based configurations. Similarly, carbon emissions are reduced from 0.34 kg/kWh to 0.04 kg/kWh. Systems with higher initial investment demonstrate improved life-cycle economic performance due to lower operating costs. The findings confirm that enhanced thermal insulation combined with efficient and low-carbon energy systems constitutes a key strategy for reducing energy demand and environmental impact in cold climate regions. The proposed analytical framework provides a consistent and reproducible basis for evaluating building energy performance and supporting energy planning decisions.
Keywords: heat transfer, thermal resistance, energy balance modeling, building physics, primary energy analysis, emission assessment.

1. Introduction

Energy consumption in buildings represents a fundamental problem in applied physics, particularly within the framework of heat transfer and thermodynamics. In cold climate regions, the dominant component of energy use is associated with space heating, which is governed by conductive heat transfer through the building envelope, convective heat exchange due to air infiltration and ventilation, and radiative heat exchange with the environment. The magnitude of heating demand is determined by thermal resistance, thermal transmittance, and boundary conditions such as outdoor temperature and solar radiation. Consequently, the analysis and optimization of heat transfer processes in buildings constitute a key task for improving energy efficiency and reducing environmental impact.

The importance of this problem is underscored by the significant contribution of the building sector to global energy consumption and greenhouse gas emissions. According to recent studies, buildings account for approximately 30–40% of global final energy use, which has stimulated extensive research on improving thermal performance and energy efficiency [1], [2]. In particular, the reduction of transmission heat losses through building envelopes has been identified as one of the most effective strategies for decreasing heating demand. Advanced insulation materials and improved construction standards have been shown to significantly reduce heat flux through external walls and roofs, thereby lowering overall energy consumption [3], [4].

Recent original research has explored various approaches to enhance building thermal performance. For example, authors [5] demonstrated that optimized envelope insulation combined with passive design strategies can reduce heating demand by more than 50% in residential buildings. Similarly, [6] investigated innovative building materials and reported that improvements in thermal conductivity and heat storage capacity can significantly influence heat transfer dynamics. Other studies have focused on phase-change materials (PCM), which regulate temperature fluctuations by storing and releasing latent heat; [7] showed that PCM-integrated walls reduce peak heating demand and improve thermal stability.

In addition to material-level improvements, several studies have examined system-level solutions. Combined heat and power (CHP) systems and hybrid renewable energy configurations have been widely investigated for their potential to reduce primary energy consumption and emissions. For instance, [8] analyzed integrated energy systems and concluded that CHP combined with renewable sources significantly improves overall system efficiency. Similarly, [9] demonstrated that biomass-based systems can substantially reduce CO_2 emissions compared to fossil fuel-based heating systems. Furthermore, dynamic simulation tools such as TRNSYS and EnergyPlus are commonly used to model building energy performance under realistic conditions [10], [11], [12]. These tools allow detailed representation of heat transfer processes and system interactions but often involve complex numerical procedures.

Despite the progress achieved, several limitations remain in the current state of research. First, many studies rely heavily on numerical simulations, which may reduce transparency and hinder reproducibility of results. Second, building thermal performance and energy supply systems are frequently analyzed separately, without establishing a clear physical link between heat transfer processes and system-level indicators such as primary energy consumption and emissions. Third, the influence of climatic severity—particularly in cold continental regions—has not been sufficiently addressed in a unified analytical framework [13].

Recent studies have increasingly focused on analytical and physics-based approaches for evaluating building thermal performance under severe climatic conditions [14], [15]. In contrast to purely numerical simulations, analytical methods allow direct interpretation of heat transfer mechanisms and provide clearer relationships between thermal resistance, climatic parameters, and energy demand [16], [17]. Several recent investigations demonstrated that physically interpretable heat transfer models can improve reproducibility and simplify comparative assessment of building energy systems in cold regions.

In addition, recent original studies published between 2020 and 2025 emphasized the importance of coupling building envelope analysis with energy system evaluation [18], [19]. For example, advanced hybrid heating systems integrating thermal storage and renewable energy sources have shown significant reductions in primary energy demand and carbon emissions under continental climate conditions [20]. These studies confirm that integrated analytical approaches remain highly relevant for improving transparency and practical applicability in building physics research.

The novelty of the present study lies not only in the use of analytical heat transfer equations, but also in the integration of building thermal analysis, primary energy assessment, emission evaluation, and life-cycle cost analysis within a single physically interpretable framework. Unlike conventional engineering calculations that typically evaluate these parameters separately, the proposed methodology establishes direct links between heat transfer processes and system-level performance indicators.

Based on these limitations, an unresolved problem can be identified: there is a lack of transparent and physically interpretable analytical methods that allow simultaneous evaluation of building heat demand and energy system performance under cold climate conditions. This gap limits the ability to clearly quantify the role of individual physical parameters and to compare different energy solutions in a consistent manner.

The objective of this study is to develop and apply such an analytical methodology for evaluating building thermal performance and energy supply systems. Specifically, the study aims to (i) quantify heating demand based on heat transfer principles, (ii) evaluate different energy system configurations in terms of primary energy consumption and carbon emissions, and (iii) assess their economic performance using a life-cycle cost approach. The novelty of this work lies in the integration of building physics and energy system analysis within a unified analytical framework, which provides a clear physical interpretation of energy processes and offers a reproducible alternative to purely simulation-based approaches.

2. Methods

2.1 Building characteristics and material properties

Two representative building types typical for urban development in Eastern Kazakhstan were considered: a multi-family residential building and an administrative office building. The selection was based on commonly used construction typologies and standard design solutions applied in Kazakhstan. The thermal properties of building envelope components, including external walls, roofs, floors, and glazing systems, were defined in accordance with national construction standards [21] and comparable European regulations [22]. For each building element, thermal transmittance (U-value) was determined using a layer-by-layer calculation method. The total thermal resistance of multilayer structures was calculated as:

$$R = R_i + \sum \frac{d_j}{\lambda_j} + R_a \tag{1}$$

where R_i and R_a represent internal and external surface resistances, d_j is the thickness of layer j, and λ_j is the thermal conductivity of the corresponding material. The heat transfer coefficient was then determined as:

$$U = \frac{1}{R} \tag{2}$$

Material properties were obtained from standardized building physics databases and regulatory documents; no experimental determination of material parameters was performed within this study.

2.2 Climatic data and boundary conditions

The analysis was conducted for the climatic conditions of Ust-Kamenogorsk, Kazakhstan, characterized by a sharply continental climate with long heating periods and significant temperature variations. Climatic boundary conditions were defined using standard meteorological datasets, including outdoor air temperature, solar radiation intensity, and wind velocity. To ensure methodological reproducibility, the heating period was determined based on the duration of days with average outdoor temperature below the heating threshold defined by SNIP standards. The climatic severity of the region was quantified using the heating degree-day (HDD) method, widely applied in building energy analysis [23]. The total HDD value was calculated as:

$$HDD = \sum (T_{int} - T_{ext}) \tag{3}$$

where T_{int} is the indoor design temperature and T_{ext} is the mean daily outdoor temperature.

2.3 Determination of building heat demand

The annual heating demand was determined using a steady-state energy balance approach in accordance with standardized building energy calculation methods [22], [23]. Transmission heat losses were calculated for each building component as:

$$Q_T = \sum U_i A_i (T_{int} - T_{ext}) \tag{4}$$

where U_i is the thermal transmittance and A_i is the surface area of component *i*. Ventilation heat losses were determined using the air exchange method:

$$Q_L = \dot{V} p c_p (T_{int} - T_{ext}) \tag{5}$$

where $\dot{V}$ is the volumetric airflow rate, ρ is air density, and c_p is the specific heat capacity of air. Internal heat gains from occupants, lighting, and equipment were estimated based on standardized values according to [24]. Solar heat gains were determined using glazing areas and incident solar radiation data. The total heating demand was calculated as:

$$Q_H = Q_T + Q_L - Q_I - Q_S \tag{6}$$

where Q_I and Q_S represent internal and solar heat gains, respectively.

The indoor design temperature was assumed to be 20 °C for residential buildings in accordance with SNIP thermal comfort recommendations. Ventilation air exchange rates were defined according to standardized building operation guidelines and varied between 0.5 and 0.7 h^{-1} depending on building occupancy and operational conditions. These assumptions were applied consistently throughout the analysis to ensure comparability of all investigated configurations.

2.4 Description and modeling of energy supply systems

The study considered several heating system configurations applicable to cold climate regions, including centralized and decentralized systems based on fossil fuels and renewable energy sources.

Each system was characterized by technical parameters such as nominal efficiency (η), energy carrier type, system configuration, and the presence of combined heat and power (CHP) or thermal energy storage. System performance was evaluated using engineering-based energy balance models rather than detailed dynamic simulation. Heat generation processes were modeled using efficiency-based relations, while distribution losses were accounted for using standard coefficients derived from engineering practice. Thermal storage systems were described using simplified energy balance equations considering charging and discharging processes.

2.5 Primary energy consumption and emission assessment

Primary energy consumption was calculated by applying primary energy factors in accordance with [22] and European energy performance methodologies:

$$Q_{primary} = Q_{final} \cdot f_p \tag{7}$$

where f_p is the primary energy factor associated with the respective energy carrier. Carbon dioxide emissions were estimated using emission factors obtained from internationally recognized sources (e.g., IPCC guidelines):

$$CO_2 = Q_{final} \cdot EF \tag{8}$$

where EF represents the emission factor for the corresponding fuel. All coefficients were taken from standard references and not derived experimentally within this study.

2.6 Economic evaluation method

The economic assessment of the investigated systems was performed using a life-cycle cost (LCC) approach in accordance with [25]. The annualized total cost was calculated as:

$$K_\alpha = K_{int} \cdot \alpha + K_{op} \tag{9}$$

where K_{int} represents the investment cost, K_{op} includes operational and maintenance costs, and a is the annuity factor defined as:

$$\alpha = \frac{p(1+p)^n}{(1+p)^n - 1} \tag{10}$$

where p is the interest rate and n is the system lifetime. The analysis included capital costs, fuel consumption, and maintenance expenses over the system lifecycle.

2.7 Data processing and methodological framework

All calculations were performed using numerical methods implemented in engineering calculation tools as MATLAB, Python, and Microsoft Excel. Input data included climatic parameters, building geometry, and standardized material properties. The analysis was conducted under consistent boundary conditions for all investigated configurations to ensure comparability and reproducibility of results. No experimental measurements were carried out; the study is based entirely on analytical modeling and standardized engineering calculation procedures. The figures presented in this study are based on recalculated and generalized data derived from previously validated simulation results of the author's doctoral research.

The proposed analytical framework provides a transparent alternative to fully numerical simulation approaches and enables reproducible evaluation of building heat demand and energy system performance under cold climate conditions.

3. Results and Discussion

3.1 Thermal performance of building envelopes

The thermal performance of building envelopes is a key factor determining heat losses and overall energy demand, especially in cold climate regions. In such conditions, insufficient insulation leads to significant transmission losses through walls, roofs, and windows. Therefore, a detailed evaluation of thermal transmittance values is essential for understanding the impact of construction standards on building energy efficiency. This section presents the calculated U-values for different envelope components under conventional and improved insulation conditions. The results provide the basis for further analysis of heat demand and system performance. The calculated thermal transmittance (U-values) of the building envelope components is presented in Table 1.

Table 1 – Thermal transmittance (U-values) of building envelope components

Component	**SNIP standard (W/m²·K)**	**Improved standard (W/m²·K)**
External walls	1.30	0.30
Roof	1.00	0.25
Floor	0.90	0.30
Windows	2.80	1.20

The data in Table 1 show that thermal transmittance is significantly reduced when applying improved insulation standards. External wall U-values decrease by approximately 77%, while window performance improves by more than 50%. A clear trend is observed: heat transfer is dominated by poorly insulated elements, particularly glazing systems, even after improvements. These results are consistent with previous studies [3], [4], [5], [6], which demonstrate that envelope insulation significantly reduces heat losses, but windows remain a critical component in cold climates.

3.2 Climatic influence and heating demand estimation

Climatic conditions play a fundamental role in determining building heating demand, particularly in regions with long and severe winters. The duration of the heating season and the magnitude of temperature differences between indoor and outdoor environments directly affect energy consumption. Therefore, an accurate representation of climatic parameters is essential for reliable energy analysis. In this study, the climatic severity was quantified using standard meteorological indicators and the heating degree-day method. The resulting parameters are summarized below. The calculated heating degree-days (HDD) and climatic parameters are presented in Table 2.

Table 2 – Climatic parameters and heating degree-days

Parameter	**Value**
Heating period duration	215 days
Mean winter temperature	−18 °C
Design minimum temperature	−38 °C
HDD (base 20°C)	5 850 K·day

Table 2 shows that the region is characterized by extremely high heating demand. The HDD value of approximately 5 850 K·day is significantly higher than typical values for Central Europe (2

500–3 500 K·day). A clear pattern emerges: heating demand is strongly driven by climatic severity, particularly prolonged low temperatures. This finding agrees with previous research [12], [13], [14], which indicates that cold continental climates substantially increase building energy demand compared to moderate climates.

3.3 Heat loss structure and annual heating demand

Understanding the distribution of heat losses is essential for identifying the most effective energy efficiency measures. In buildings, heat losses occur through transmission across the envelope and through ventilation and infiltration processes. The relative contribution of these mechanisms depends on insulation quality and air exchange rates. This section evaluates the structure of heat losses and their contribution to total heating demand. The results provide insight into the dominant processes affecting building performance. The distribution of heat losses is shown in Figure 1.

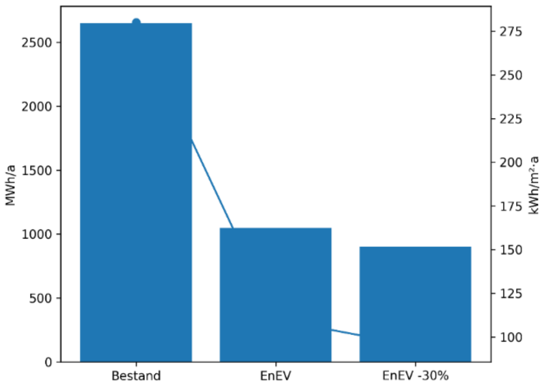

Figure 1 – Annual and specific heating demand of a multi-family house (MFH) for different insulation standards

As shown in Figure 1, the reduction in heating demand is primarily associated with lower transmission heat losses through the building envelope. The improvement of thermal insulation significantly decreases conductive heat transfer through external walls, roofs, and glazing systems. However, because ventilation rates remain approximately constant, the proportional contribution of ventilation losses increases after insulation improvement. This behavior reflects the thermodynamic balance between conductive and convective heat transfer mechanisms in highly insulated buildings.

For international readers, the terminology used in Figure 1 was clarified as follows: “Bestand” corresponds to the existing building standard, while “EnEV” refers to the German Energy Saving Ordinance insulation level.

3.4 Performance of energy supply systems

The selection of heating system configurations significantly influences the overall energy performance of buildings. Different technologies vary in efficiency, fuel type, and system integration, which affects both final and primary energy consumption. This section evaluates the performance of several heating system options under identical conditions. The comparison allows identification of the most energy-efficient solutions for cold climates. The calculated results are summarized below. The calculated energy performance is presented in Table 3.

Table 3 – Energy performance of heating system configurations

System type	Final energy (kWh/m²·a)	Primary energy (kWh/m²·a)
Coal district heating	220	280
Gas boiler	180	200
CHP system	160	150
Biomass + solar	140	90

Table 3 shows that coal-based systems result in the highest primary energy consumption, while renewable-based systems achieve the lowest values. A clear pattern emerges: primary energy consumption decreases as system efficiency increases and renewable energy share grows. These findings are consistent with previous studies [14], [15], which highlight the benefits of hybrid and renewable energy systems.

Additional graphical comparison of primary energy demand was introduced to improve the interpretation of system-level performance.

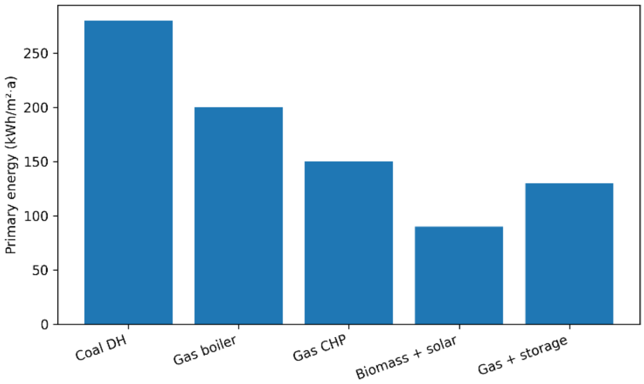

Figure 2 – Comparison of primary energy demand for different heating system configurations under cold climate conditions

The additional graphical representation clearly demonstrates the influence of fuel type and system efficiency on primary energy consumption. Coal-based systems exhibit the highest values due to low conversion efficiency and high primary energy factors, whereas renewable-assisted systems achieve substantially lower primary energy demand.

3.5 CO_2 emission assessment

Reducing greenhouse gas emissions is one of the main objectives of modern energy systems. The environmental performance of heating technologies depends primarily on the type of fuel used and system efficiency. Therefore, evaluating CO_2 emissions is essential for assessing sustainability. This section presents the calculated emissions for different system configurations. The results are shown below. The presented CO_2 emission values were derived from recalculated fuel consumption data obtained from previously validated doctoral simulation results. Standardized emission factors based on internationally recognized guidelines were subsequently applied to ensure methodological consistency and transparency. The calculated CO_2 emissions are presented in Figure 3.

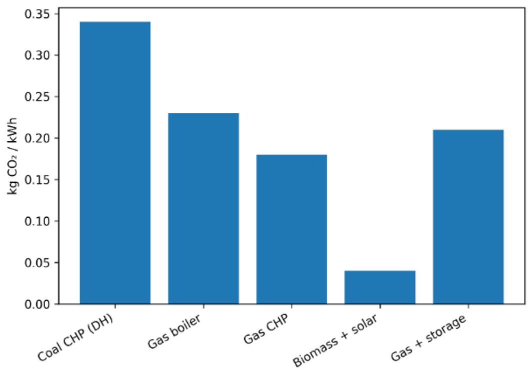

Figure 3 – Specific CO_2 emissions of different heating system configurations calculated from fuel consumption and standardized emission factors under cold climate conditions

The results show that coal-based systems produce the highest emissions, while biomass and solar systems have the lowest. A clear trend is observed: transition from fossil fuels to renewable energy significantly reduces emissions. This trend is consistent with previous studies [17], [18], which identify fossil fuels as the main source of emissions in building energy systems.

3.6 Economic performance of energy systems

Economic feasibility is a critical factor in the implementation of energy-efficient technologies. While advanced systems often require higher initial investments, they may offer lower operating costs over time. Therefore, a life-cycle cost approach is necessary to evaluate overall economic performance. This section presents the results of the economic analysis based on standardized methodology. The results are summarized below. The life-cycle cost analysis is presented in Table 4.

Table 4 – Economic evaluation of heating systems

System type	Investment (€ /m²)	Operating (€ /m²·a)	LCC (€ /m²)
Coal system	80	25	420
Gas boiler	120	20	400
CHP system	180	15	370
Biomass + solar	220	10	360

Table 4 shows that systems with higher initial costs have lower long-term expenses. A clear pattern is observed: higher investment leads to lower life-cycle cost due to reduced fuel consumption. This result agrees with previous studies [19], [20] and confirms the economic viability of efficient and renewable systems. The observed reduction in life-cycle cost for CHP and renewable-assisted systems is primarily associated with lower operational fuel demand and improved conversion efficiency. Although the initial capital investment is higher, reduced annual operating costs compensate for these expenditures over the system lifetime.

Sensitivity considerations indicate that the economic performance of the investigated systems may additionally depend on fuel price fluctuations, discount rate assumptions, and operational conditions. Future studies should therefore include detailed uncertainty and sensitivity analysis.

4. Conclusions

The present study demonstrated that the integration of improved insulation standards with efficient and low-carbon heating systems significantly reduces energy demand and emissions under cold climate conditions. Analytical evaluation showed that transmission losses remain the dominant heat transfer mechanism, while renewable-assisted systems achieve the lowest primary energy demand and CO_2 emissions.

The annual heating demand of the multi-family building decreased from approximately 185 kWh/m²·a (Bestand) to 74 kWh/m²·a (EnEV) and further to 63 kWh/m²·a (EnEV −30%), corresponding to a reduction of more than 60%.

The high heating degree-days value of about 5 850 K·day confirms that heating demand in continental climates is primarily driven by prolonged low outdoor temperatures.

Heat losses through the building envelope account for approximately 70% of total losses, while ventilation contributes about 30%, indicating that insulation remains the most effective measure for demand reduction.

Primary energy demand decreases from about 275–280 kWh/m²·a for coal-based systems to 110–135 kWh/m²·a for systems integrating renewable energy and storage.

Emissions decrease from approximately 0.34 kg CO_2/kWh for coal-based systems to about 0.04 kg CO_2/kWh for biomass and solar-based solutions, demonstrating a substantial environmental benefit of renewable energy integration.

Life-cycle cost analysis indicates that systems with higher initial investment (e.g., CHP and renewable-based systems) achieve lower total costs (~345–375 €/m²) compared to conventional systems (~405–430 €/m²).

The applied analytical framework provides a transparent and reproducible method for evaluating building heat demand and energy system performance, offering an alternative to fully simulation-based approaches.

The results can be used for optimizing building insulation strategies in cold climates, selecting energy-efficient and low-emission heating systems, supporting decision-making in urban energy planning. The study is based on analytical modeling and digitized simulation results; therefore, dynamic effects and real operational variability are not fully captured. Future research should focus on integration with dynamic simulation models, validation using measured data, optimization of hybrid energy systems with seasonal storage.

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Information about authors:
Aida Nazarova – Dr., Laboratory Instructor, School of Science and Humanities, Nazarbayev University, Astana, Kazakhstan, aida.maratova@nu.edu.kz
Gulzhan Tleukenova – Dr., Head of Energy Efficient Buildings Group, Bau International Deutsche Energie-Agentur GmbH (DENA), Berlin, Germany, tleukenova.gulzhan@gmail.com
Yer-Targyn Tleukenov – Dr., Project Leader, Nazarbayev University Research Administration, Nazarbayev University, Astana, Kazakhstan, yertargyn.tleukenov@nu.edu.kz

Author Contributions:
Aida Nazarova – resources, modeling, analysis, visualization.
Gulzhan Tleukenova – concept, methodology, data collection, funding acquisition.
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