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# Optimization of the Thermal Insulation Level of Residential Buildings in the Almaty Region of Kazakhstan

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**Abstract:** Kazakhstan is country rich in energy resources, but to raise the living standards of the country's population, the government regulates prices of heating energy, which are significantly lower comparing to those in the global energy market. Such an approach encourages the construction of residential buildings without concern for their energy efficiency, which significantly increases energy consumption in the sector and leads to the increase of greenhouse gas emissions into the environment. Therefore, the aim of this study was to analyze the impact of regulated low prices of heating energy on long-term energy use in buildings, to determine optimal levels of building thermal insulation at current energy prices and following global energy price trends, and to demonstrate the impact of more efficient building thermal insulation on heating energy consumption from a long-time perspective. The cost-optimal method used in EU countries was chosen for the optimization of building thermal insulation and energy consumption to compare the impact of energy prices on the optimal thermal insulation of buildings. The results of the study showed that maintaining low energy prices hinders the implementation of energy-efficient solutions in buildings and does not provide an economic justification for prolonging the heating season by ensuring the quality of the indoor microclimate. As a practical result of this study, a recommendation was made to introduce optimal thermal insulation requirements in building regulations and to redistribute part of the energy subsidies for implementation of energy-efficient measures in the residential building sector.

**Keywords:** energy efficiency; cost optimal calculations; energy consumption in buildings

## 1. Introduction

In Kazakhstan, the residential building sector consumes about 14% of produced electricity and about 25% of thermal energy [1]. In the southern Almaty region, where the population has increased over the past 15 years, from 1.15 to 1.85 million [2], there is a shortage of energy to ensure the functioning of buildings. Due to the continued expansion of the residential building sector, both energy demand for buildings and air pollution have increased, and energy consumption in buildings must be reduced by increasing their energy efficiency. This has been provided by a government program [3], and new energy performance requirements for buildings were approved in 2019 [4]. However, these requirements are not justified by calculations; rather, the requirements were implemented only in comparison to buildings that meet the lowest requirements of functionality and hygiene. At the present time, during a period of stabilization of Kazakhstan's economy, it has become relevant to establish an economically reasonable level of building thermal insulation.

Currently, government-regulated thermal energy prices in the Almaty region differ significantly from energy prices in the global market. Maintaining low energy prices for building heating is linked to the state's desire to raise the living standards of the country's population, but it hinders the construction of energy-efficient buildings. The thermal insulation level of partitions in residential buildings currently under construction is significantly lower than the optimal level that is applied in EU countries with a similar climate, in which there is a free energy market. The duration of the heating season, in which heating starts when the three-day average outdoor temperature falls below +10 °C, also reduces the quality of the indoor microclimate.

The objective of this work is to find out the impact of increasing the thermal insulation of partitions on the total energy consumption and total costs of residential buildings over a period of 30 years and to provide recommendations for the thermal insulation of new construction residential buildings in the Almaty region. In most investigations in this area, building thermal insulation is optimized using global energy market set prices for energy, construction work and building materials. In Kazakhstan, energy prices are artificially reduced and the prices of construction works and materials, especially innovative ones, are left to the market regulation. The study of this situation will provide new results and will help to clarify the impact of artificial regulation of energy prices on the energy consumption of buildings in the long perspective.

A number of methodologies for optimizing the energy performance of buildings have been developed, but their essence is similar—investments in energy efficiency improvement measures for buildings must be based on their payback over a set period of time, ensuring the functionality and interior comfort of the buildings. The general steps involved in the cost-optimal methodology are presented in the scientific literature. Previous research [5] demonstrates that building age and investment costs have an important impact on the cost-optimal results; in particular, it is essential that the choice of the thermal insulation, its thickness and conductivity, and the thermal properties of windows be considered to reach a compromise between performance and investment costs.

The simplest method for determination of optimal thermal insulation of walls is presented in reference [6]. In this study, the environmental impact on optimum insulation thickness of external walls was investigated. Optimal thermal insulation was determined for the minimal annual total cost, which is a sum of insulation cost and used energy cost. One financial analysis method is the Simple Payback Period. This method is based on the time required to repay the initial capital investment with the operating savings attributed to that investment. The main drawback of this simple analysis is that it does not take into account the change in the value of money, which is an important financial consideration [7].

Economic and environmental benefits of thermal insulation of external walls were analyzed in reference [8]. Optimal thickness of different thermal insulation materials was determined, using an approach for cost-optimal calculation in which total cost was the sum of insulation and energy costs. The optimum thermal insulation thickness was chosen to minimize the total cost [9].

In a previous study, the optimization of building thermal insulation has been expanded to the optimization of building energy performance [10]. This study presents a methodology and a new tool with the goal of assisting in the choice of economically efficient net zero energy buildings (NZEB) solutions for residential building in any climate, for different energy resources, and the local economic conditions. Lowest Initial Cost (LIC) solutions are defined for the energy end uses with relevance to space heating and cooling, water heating (domestic hot water), lighting, cooking, refrigeration, and other appliances.

Many researchers have used reference buildings for optimization of thermal insulation and energy consumption [11]. The considered building was designed in compliance with Italian regulations regarding the envelope insulation level and characterized by common construction techniques. Since terraced housing is currently very widespread in Southern Europe, the analysis was applied to this building type by addressing simple corrective solutions, such as thick thermal insulation, use of low-emissivity glazing and window shadings, high level of air tightness and ventilation with heat recovery, solar collectors for domestic hot water (DHW), and heat pumps for space heating. The multi-story reference NZEB model with 10 renewable energy systems has been used to examine the cost-optimal combination of energy efficiency and renewable energy generation [12]. For investigation of optimal energy retrofit strategies, as base case for cost/benefit analysis, the sampled school buildings of different educational level, age of construction and typological design were divided in homogeneous clusters, each of which was represented by a reference building [13].

The optimal thickness of thermal insulation is determined by the following factors: type of the building, its use, size and structure, type of the insulated component (wall, floor, etc.), climatic characteristics, type of the thermal insulation applied, insulation costs: materials and labour, type and manner of energy supply, fuel and operating prices [14]. The change in the value of money has a significant impact on the optimization process. To assess the diversity of the building materials market, economic costs of each intervention were estimated by averaging the prices presented by different companies for the same intervention [15].

The optimal energy efficiency level also depends on annual operation and maintenance cost which is the sum of the energy costs (for each energy carrier), the operation costs (securities, services etc.), the maintenance cost (inspection, cleaning, overhaul, consumables) and the costs associated with periodic replacement of equipment [16].

Energy efficiency optimization results vary between different climate zones across European countries. In colder climates, thermal insulation and building air tightness appear much more important as thermal improvements are strongly dependent on heating loads. In warmer, sunny locations, Solar irradiance could be evaluated as Solar heat gains and reduce the heating loads [17]. Given the significant climatic variations that exist in different parts of Turkey, 16 cities from four climate zones of Turkey were selected for analysis of optimal thermal insulation thickness. The results showed variation of optimum thermal insulation thicknesses between 2 and 17 cm [18]. However, increasing the thickness of the thermal insulation layer does not always give positive results of building energy efficiency. The energetic and economic influence of external thermal insulation is evaluated for a case study for various cities in Italy, and the results demonstrated the need to avoid excessive thermal insulation of buildings to obtain the highest energy savings [19]. The provided results highlight the different challenges and opportunities presented by the large variation in thermal conditions and solar availability across European climates.

The building energy efficiency design and evaluation process is dependent on life cycle assessment methodologies [20]. The authors expand the traditional understanding that constructions are mostly concerned with cost, time, and quality. To these criteria, sustainable construction adds the consideration of the building's life cycle because the minimization and reduction of the impacts on the environment depends on the performance of the building during all its phases. Following these considerations, authors of this article presents an overview of life cycle methodologies: life cycle assessment (LCA), life cycle energy analysis (LCEA), life cycle ZEB (LC-ZEB), and life cycle costs (LCCA). Life cycle cost analysis is an economic method of project evaluation in which all costs arising from owning, operating, maintaining and disposing of a project are considered to be potentially important to that decision [21]. The main goal of the LCCA in construction sector is to define the cost-effective energy efficiency measures and renewable energy technologies for energy efficient buildings [22]. The LCCA conducted for multi-family Net ZEB helped answer the questions: how far should we go with energy efficiency measures and when should we start to apply renewable energy technologies?

A multi-objective analysis is often used to obtain optimal energy efficiency of buildings, through the analyses of combinations of various structural solutions, energy systems, and building materials [23]. The optimization methodology for NZEB design to enhance its energetic and economic performance includes four steps: building simulation, optimization process, multi-objective analyses and testing solution's robustness [24].

The main goal of all methods is to determine the cost-optimal solution from different alternatives. These alternatives are comparable only with the same economic assumptions, study period, and service date. According to [22], cost-optimal solutions can be estimated in present-value and annual-value terms. The calculation method requires that all future costs be discounted to their present-value equivalent.

The first data on the optimal management of Kazakhstan's energy resources were provided in a study about the need to decrease greenhouse gas investment [25]. This study provides an analysis of the recent situation and identifies the reasons for energy inefficiencies: outdated heat generating companies, low energy prices, and low incentives for efficient energy use.

The latest data on the energy performance of buildings in Kazakhstan are provided in the Law of Republic of Kazakhstan on Energy Saving and Energy Efficiency [26]. It is stated that efficient use of energy resources must be compatible with technical possibilities and economic justification. The law provides support for the development of methodological and normative measures that increase the energy performance of buildings.

## 2. Methodology, Initial Data, and Boundary Conditions for Optimization of Thermal Insulation of Residential Buildings

### *2.1. Methodology for Determination of the Optimal Thermal Insulation Level*

This methodology is detailed in an official Regulation delegated by the EU commission [27] and essentially corresponds with many of the methods given in the scientific and technical literature.

The essential points of the methodology are:

1. For optimization of thermal insulation of the building envelope, reference buildings were chosen as an example of a real building that corresponds to a typical building geometry, with typical elements of the envelope and energy systems and typical cost structure, corresponding to climatic conditions of the geographical location.
2. Thermal insulation improvements for building envelope elements were defined in steps of thickness of thermal insulation materials. This procedure was chosen due to the nomenclature of thermal insulation materials and the step-by-step publication of the installation cost of thermal insulation layers.
3. The annual energy consumption was calculated as heat losses through 1 square meter of the enclosure element during two heating seasons of different duration. Heat losses through walls and roofs were calculated as heat transfer through these structures, through windows—as difference of heat transfer and solar heat gains through windows, and through floor—primarily for the whole floor of reference building and for optimization as an average value per 1 $m^2$ of floor area were used. The influence of thermal bridges was evaluated in calculation of energy characteristics of reference buildings with optimized thermal insulation.
4. The total cost of each thermal insulation improvement was calculated as the sum of the initial investment, maintenance and replacement costs, if declared life cycle of the structure is shorter when calculating period. For envelope structures, of which declared life cycle is longer when calculating period, the total cost was calculated as the sum of the initial investment and maintenance cost, and residual value of structure was deducted.

Figure 1 shows a graphical presentation of the building insulation optimization model: by increasing the insulation thickness of partitions, the lowest amount of total investment in construction and energy over a 30-year service life is found.

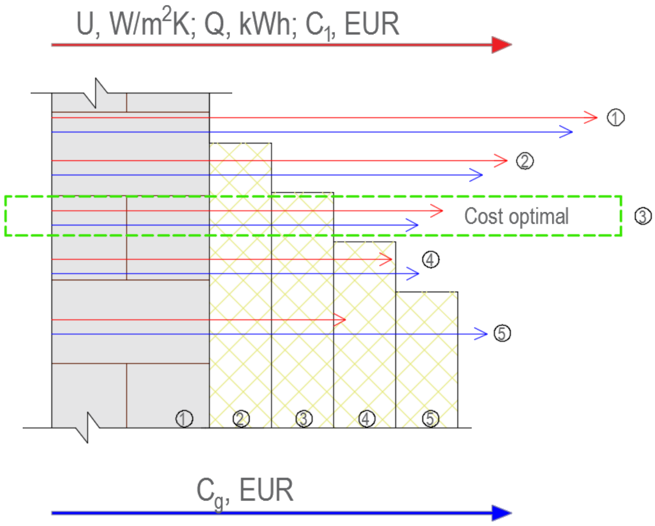


**Figure 1.** Graphic presentation of the model of thermal insulation optimization of building partitions.

The optimization of the thermal insulation of buildings and their elements took account of the expected life cycle of the building elements; the calculation period; the costs of energy, construction products and systems; labor costs; building maintenance; and usage costs. The optimal level of thermal insulation of a building element in terms of energy consumption was considered, and was based on the minimum total cost of installation of thermal insulation materials, maintenance and replacement, and cost of consumed thermal energy during the calculation period. Assumptions concerning changes in energy prices and changes in monetary value over the calculation period were adopted.

For calculating the total cost of buildings elements, the estimated annual costs were multiplied by the discount factor so that the cost was expressed as the value of the initial year of the calculation before summing.

The total costs of thermally insulated building element from the beginning of the calculation period $\tau_0$, $C_g(\tau)$, EUR, were calculated according to the equation:

$$C_g(\tau) = C_1 + \sum_j \left[ \sum_{i=1}^{\tau} (C_{a,i})(j) \times R_d(i) - V_{f,\tau}(j) \right] \quad (1)$$

where:

1. $\tau$—calculation period, years;
2. $C_1$—initial investment costs related to thermal insulation step $j$, EUR;
3. $C_{a,i(j)}$—annual costs of energy in year i related to particular thermal insulation step, $j$, EUR;
4. $V_{f,\tau(j)}$—residual value of thermal insulation at the end of the calculation period related to the particular thermal insulation step of building element $j$, EUR;
5. $R_d(i)$—discount coefficient in year i, matching discount rate $r$ and calculated as follows:

$$R_d(p) = \left( \frac{1}{1 + r/100} \right)^p \quad (2)$$

$p$—number of years since the beginning of the period; $r$—the actual discount rate.

*2.2. Data for Calculation of the Optimal Thermal Insulation of Building Elements and Energy Performance Indicators of Reference Buildings*

2.2.1. Climate Data for Heat Transfer Calculation

Almaty is a sub-region of Central Asia with an average altitude of 690 m. Its position is 43°19′12′′ north latitude and 76°55′12′′ east longitude. Climate data for calculations were taken from the Regulation of Building Climatology SNiP RK 2.04-01-2001 [28]. The climate data of this source indicates that air temperature in Almaty can rise to +43 °C and may drop to −30 °C, average daily air temperature is below +10 °C for 182 days, and the average temperature of this period is −0.8 °C. Wind blows predominantly from the south. Table 1 shows the average outside air temperatures for each month and year.

**Table 1.** Monthly average outside air temperatures $\theta_{e,m}$ (°C).

| Average temperature, °C | Month of the year | | | | | | | | | | | | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | 8.9 |
| | −6.5 | −5.1 | 2.0 | 10.8 | 16.2 | 20.7 | 23.5 | 22.3 | 17.0 | 9.5 | 0.9 | −4.5 | |

The orientation of the buildings and the arrangement of the windows in building facades are diverse. The Almaty region's new building area is dominated by a north–south and east–west oriented rectangular street layout system, so the facades of buildings are mostly oriented to the south and east. For calculations, it is assumed that 33% of windows face south, 32% of windows face east, 15% of windows face north, and 20% face west. The average amount of solar radiation calculated on monthly basis for these proportions is shown in Table 2.

**Table 2.** Monthly average amount of solar radiation.

| Solar radiation, to vertical surfaces kWh/m$^2$ | Month of the year | | | | | | | | | | | | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | 1230 |
| | 87 | 92 | 117 | 114 | 112 | 104 | 108 | 110 | 111 | 103 | 88 | 82 | |

2.2.2. Indoor Air Temperature in Residential Buildings

The indoor air temperature of residential buildings is given in the interstate standard GOST 30494-96 "Residential and public buildings. Building microclimate parameters" [29]. This document describes the different optimal indoor air temperature limits for a residential building: 20–20 °C for living and resting areas, 19–21 °C for kitchens, 16–18 °C for staircases and corridors, 24–26 °C for bathrooms. There is no clear reason to design differently insulated walls depending on the purpose of the premises, therefore the indoor air temperature of 21 °C was chosen for the calculation of the optimal thermal insulation of the building envelope elements.

2.2.3. Calculation Period and Economic Life Cycles of Building Materials and Elements

A calculation period of 30 years was used for calculation of the optimal thermal insulation of residential buildings. The economic life cycles of buildings and their elements used in the calculations were determined according to EN 15459:2008 [30]. This standard specifies the economic life cycle of the structural elements of a new residential building of 80 years. The life cycle of the thermal insulation of walls, roofs, and floors of a building, with the exception of their finishing and protective layers, is set at 50 years.

The residual value of building elements is determined using the linear depreciation rate from the initial investment costs until the end of the calculation period and discounted at the beginning of the calculation period. As the finishing is not related to the energy efficiency measures of the building, it is assumed that after 30 years of operation, the residual value of building envelope structures is 62.5%

of the initial value, the residual value of the thermal insulation layers will be 40%. The life cycle of windows and doors is 30 years, so the residual value of these building elements after the calculation period is 0.

#### 2.2.4. Reference Buildings and Structure of Their Envelope

After the analysis of new building projects in the Almaty region, a one-story residential building of 143.5 $m^2$ m total area, with internal volume of 625.8 $m^3$, was selected as a model for this research. The building height was 3.0 m, and the designed air change in the building at 50 Pa pressure difference n50 was once per hour. Window areas were 13.3% of floor area and 12.3% of the wall areas of the building. Window areas in the north, east, south, and west directions represent 2.3%, 19.5%, 9.1%, and 18.4% of the total wall area, respectively. The ratio of the window glazing area to the total window area was 0.8.

The construction of the building was monolithic framework. Exterior walls were made of ceramic bricks, insulated with polystyrene foam or mineral wool, three-layer masonry, or rendered with various finishes. The masonry of the building was reinforced with vertical reinforced concrete inserts, the reinforcement of which was connected at the top of the walls with a monolithic boundary strap. The inner partitions were massive and made of solid ceramic bricks. The ceiling and ventilated attic was made of monolithic reinforced concrete or wood frame, insulated with mineral wool. The roof was pitched, with a ventilated attic. Windows and exterior doors were made of plastic, with insulated glass units. Floors were on compacted ground, of reinforced concrete with various internal finishes. The foundations were continuous, of reinforced concrete on an extruded polystyrene foam pad that was 400 mm wide.

#### 2.2.5. Initial Investment of Certain Thermal Insulation Improvement

The initial investment for each step of thermal insulation of building envelope element is calculated by summing up all the costs that are needed to finish the building. These are the costs of designing the building, purchasing materials, installing structures, including the connections to other building structures. For the purposes of this study, the initial investment was calculated by summing the cost of purchasing and installing thermal insulation materials, including construction overheads at 10% of materials cost and 15% of labor cost; design and maintenance costs at 2% of building value; and value added tax of 12%.

The average prices of thermal insulation materials used for building thermal insulation, depending on their intended use, were taken from the official websites of the trade organizations in the Almaty region (the prices of materials were provided with the value added tax). The installation cost of these materials was taken from the official set of construction norms and prices of Kazakhstan [31] (prices are exclusive of value added tax). The calculated initial investment, related to the particular thermal insulation of the building envelope element, is given in Table 3.

Calculations were made for 1 $m^2$ of a 5 cm thick thermal insulation layer. The cost of the timber frame was added for the installation of a pitched roof, wooden framework ceiling, and wall. The following formula was used to calculate the initial cost of insulation of roofs, walls, and floors:

$$C_1 = 1.02 \cdot (1.1 \cdot C_{ti} + 1.15\, C_{in} \cdot 1.12) \tag{3}$$

where:

1. $C_1$—initial investments for installation of 1 $m^2$ of 5 cm thick thermal insulation layer, EUR;
2. $C_{ti}$—the price of 0.05 $m^3$ thermal insulation material, EUR;
3. $C_{in}$—the price of installation of 1 $m^2$ 5 cm thick thermal insulation layer, EUR.

**Table 3.** Initial investment for thermal insulation of the building envelope elements.

| Building Element | Thermal Insulation Material | Thermal Conductivity W/(m·K) | The Price of 1 m$^2$, EUR | The Price of 1 m$^2$ Installation EUR | Initial Investment of 1 m$^2$ 5 cm Thick EUR |
|---|---|---|---|---|---|
| Pitched roof | Mineral wool | 0.037 | 1.6 + 1.64 * | 0.83 | 4.8 |
| Flat roof | Mineral wool | 0.039 | 2.8 | 0.51 | 3.8 |
| | EPS | 0.037 | 2.0 | 0.51 | 2.9 |
| Wooden framework ceiling | Mineral wool | 0.037 | 1.6 + 1.64 * | 0.51 | 4.3 |
| Reinforced concrete ceiling | Mineral wool | 0.036 | 1.6 | 0.51 | 2.5 |
| Wall with external brickwork | Mineral wool | 0.036 | 1.9 | 1.0 | 3.4 |
| | EPS | 0.041 | 1.4 | 1.0 | 2.9 |
| Wall with external rendering | Mineral wool | 0.036 | 3.2 | 1.0 | 4.9 |
| | EPS | 0.039 | 2.0 | 1.0 | 3.5 |
| Ventilated wall | Mineral wool | 0.035 | 2.3 | 1.0 | 3.8 |
| Wooden framework wall | Mineral wool | 0.037 | 1.6 + 1.64 * | 1.1 | 4.9 |
| Floors on the ground | EPS | 0.038 | 2.8 | 0.51 | 3.8 |
| | Mineral wool | 0.036 | 3.2 | 0.51 | 4.3 |

* The price of 1 m$^2$ timber frame.

The initial investment for windows is the price of 1 m$^2$ of window of particular type. Windows with a plastic frame (thickness of 60, 70, and 80 mm), glass units of 2 and 3 panes, and 1 or 2 glass panes with low emissivity coatings were selected for this study. The prices of 1 m$^2$ of windows range from 75 to 111 EUR at Almaty trading companies. The cost of window installation does not depend on its thermal insulation properties. The initial investment of windows is shown in Table 4.

**Table 4.** Structures, characteristics, and energy transmission of windows.

| Description of the Window | Frame Thickness, mm | Glazing, Number of Glasses/Low E Coatings | Heat Transfer U, W/m$^2$·K | Solar Energy Transmission of Glass, $g_{gl}$ | Price of 1 m$^2$ of Window, EUR | Heat Losses through the Window, kWh/m$^2$ | | Solar Heat Gains, Heating Season, kWh/m$^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $t_{if}$ = +10 °C | $t_{if}$ = +12 °C | |
| F602gl1LowE | 60 | 2/1 | 1.6 | 0.67 | 75 | 152 | 173 | 260 |
| F702gl1LowE | 70 | 2/1 | 1.4 | 0.67 | 81 | 133 | 151 | 260 |
| F703gl1LowE | 70 | 3/1 | 1.2 | 0.54 | 97 | 114 | 129 | 209 |
| F803gl2LowE | 80 | 3/2 | 1.0 | 0.5 | 111 | 95 | 108 | 194 |

### 2.2.6. Scenario of Heating Energy Prices and Their Variation

The official prices of thermal energy of Almaty region heating networks and natural gas supplied to household customers were used to calculate the optimal thermal insulation level of building structures. After analysis of the forecasts of the EU energy price changes in different sectors in 2016 [32] and comparing these with the thermal energy and natural gas prices of the Almaty region during the last 5 years, we used a growth rate of the annual energy price of 2%.

For calculation of the optimal minimal thermal insulation levels, the actual discount rate that reflects the change in the value of money over the calculation period was also applied. Two actual discount rate values of 2% and 4% were used in the calculations. The first implies a very stable, state-controlled economic situation (where the rise in energy prices is offset by inflation); the second is more in line with global economic developments in the absence of major crises. The prices of thermal energy used for heating the buildings and their forecast for the next 30 years are presented in Table 5.

**Table 5.** Scenarios of prices of thermal energy from heat networks and natural gas.

| Type of Fuel or Energy Source | Year | Energy Price, Taking into Account the Increase in Energy Prices, 0.01·EUR/kWh | The Price of Fuel, Taking into Account the Depreciation of Money, 0.01·EUR/kWh | |
|---|---|---|---|---|
| | | | r = 2 | r = 4 |
| Thermal energy of heat networks | 2019 | 1.33 | 1.33 | 1.33 |
| | 2029 | 1.60 | 1.31 | 1.09 |
| | 2039 | 1.86 | 1.25 | 0.84 |
| | 2049 | 2.10 | 1.17 | 0.64 |
| Natural gas | 2019 | 0.83 | 0.83 | 0.83 |
| | 2029 | 1.00 | 0.81 | 0.68 |
| | 2039 | 1.16 | 0.78 | 0.53 |
| | 2049 | 1.31 | 0.73 | 0.40 |

#### 2.2.7. The Calculation of Annual Costs of the Thermal Insulation Improvement Measures

The thickness of the thermal insulation layer of building envelope elements increases in steps of 0.05 m from the uninsulated structure to 0.25 m thickness for the roof, wall, and floor. Increasing the thickness of the thermal insulation layer of the envelope, the corresponding heat transfer coefficients of the envelope were calculated according to EN ISO 6946:2017 [33], and the heat losses through the roofs, ceilings, walls, and floors were calculated for the heating season of different duration according to EN ISO 13790:2008 [34]. The heat transfer coefficients of windows were taken from the window manufacturer's declarations that match the window descriptions. The heat losses through 1 $m^2$ of the windows were calculated as difference between heat transfer and solar heat gains through them for each month of the heating season. Thereafter, the monthly heat losses were summed for the entire heating season. Additionally, the heat loss and solar heat gains through the windows were calculated for each month of the heating season, and the calculation results were used for complementary evaluation of optimal thermal properties of windows. The solar heat gains for each month were calculated according to the equation:

$$E_{sol} = q_{sol} \cdot g_{gl} \cdot 0.9 \cdot A_{gl}; \quad (4)$$

where: $E_{sol}$—solar heat gains for month, for 1 $m^2$ of window, kWh/$m^2$; $q_{sol}$—average monthly amount of solar radiation, kWh/$m^2$, see Table 2; $g_{gl}$—coefficient of total solar energy transmission of the glazed part of the window when the solar radiation is perpendicular to the glazed part of the window (parts of units); 0.9—coefficient of correction for the indistinctness of the solar radiation to glazed part of the window; $A_{gl}$—glazed area of 1 $m^2$ of window, $m^2$.

The annual energy consumption was calculated as heat losses through 1 square meter of the enclosure element during each heating season of different duration. The annual energy cost was calculated for each year taking into account different heating energy sources and scenarios of increase in energy prices (see Table 5). The total energy cost during period of 30 year is a sum of annual energy cost.

For each step of the insulation, the initial investment, the annual cost, and the total cost were calculated. The heat loss through 1 $m^2$ of envelope during the heating season was calculated in 2 cases: temperatures of the beginning and the end of the heating season—$t_{if}$ = +10 °C and $t_{if}$ = +12 °C, respectively, the duration of the season is 182 and 212 days, and the average outside air temperature, respectively is −0.8 °C and −0.2 °C.

The annual costs of the thermal insulation improvement measures were the annual cost of thermal energy, in addition to part of the cost with taxes of using, maintaining, and element substitution of the entire building. When calculating the annual cost related to the insulation of walls, roofs, and floors, only the cost of thermal energy was taken into account, because no other costs appeared during the calculation period. When calculating the annual cost related to windows, 2% of the initial investment value was added to the cost of thermal energy, thus taking into account the cost of window maintenance (see Table 6).

**Table 6.** Structures, energy consumption ant total cost of elements of building envelope.

| Construction Description | Insulation Thickness, m | Heat Transfer U, W/m$^2$·K | Initial Investment 1st Year Cost, KZT/m$^2$ | Annual Energy Consumption kWh/m$^2$ | | Total Cost, KZT/m$^2$ District Heating $t_{if}$ = +10 °C | |
|---|---|---|---|---|---|---|---|
| | | | | $t_{if}$ = +10 °C | $t_{if}$ = +12 °C | r = 2 | r = 4 |
| Wooden framework ceiling to ventilated attic | 0.05 | 0.79 | 1868 | 75 | 85 | 13,189 | 10,203 |
| | 0.10 | 0.43 | 3736 | 41 | 46 | 8431 | 6801 |
| | 0.15 | 0.29 | 5604 | 28 | 32 | 7132 | 6019 |
| | 0.20 | 0.22 | 7474 | 21 | 24 | 6820 | 5986 |
| Concrete ceiling to ventilated attic | 0.05 | 0.44 | 1060 | 56 | 63 | 9697 | 7471 |
| | 0.10 | 0.28 | 2120 | 31 | 35 | 6058 | 4825 |
| | 0.15 | 0.20 | 3180 | 21 | 24 | 4888 | 4054 |
| | 0.20 | 0.16 | 4240 | 16 | 18 | 4542 | 3906 |

The results of the calculation are presented in the results and discussion section with graphs of the dependence of the total costs on the level of thermal insulation.

## 3. Results and Discussion

The analysis of total costs of pitched insulated roofs showed that the optimal insulation thickness for the use of district and gas heating is 15 cm. This is, on average, 0.29 W/(m$^2$·K) (Figure 2). A more detailed analysis of the total costs showed that in the case of district heating use, the total costs increase slightly when the thickness of the thermal insulation layer reaches up to 20 cm, and in the case of gas, this difference is larger. In the case of a longer heating season, the minimum values of total costs approach a thinner insulation layer. Summarizing the calculation results, under the given conditions and future energy use, the optimal value of the heat transfer coefficient of the insulated pitched roof proposed is 0.25 W/m$^2$·K.

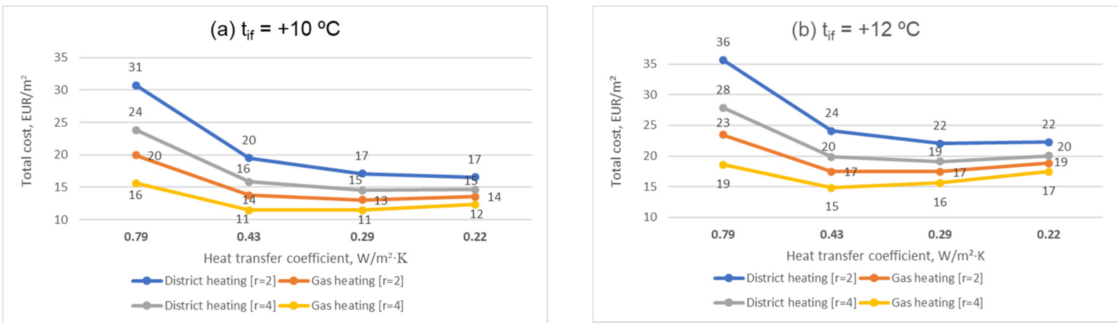


**Figure 2.** Dependence of the total cost of pitched roofs on the heat transfer coefficient for (**a**) shorter ($t_{if}$ = +10 °C) and (**b**) longer ($t_{if}$ = +12 °C) heating seasons.

The minimum total costs of flat roofs are obtained by a thickness of 15 cm thermal insulation, but the optimal heat transfer coefficient of this structure is less than that of pitched insulated roofs, because there is no influence of the timber that crosses the thermal insulation layer (Figure 3). The choice of lower thermal conductivity materials would make it economically optimal to achieve the heat transfer coefficient of the flat roofs not more than 0.22 W/m$^2$·K.

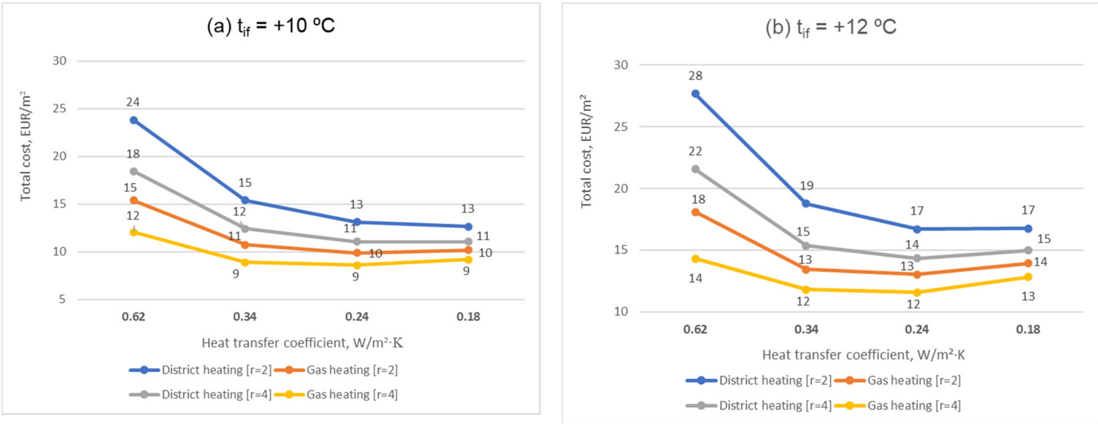


**Figure 3.** Dependence of the total cost of flat roofs on the heat transfer coefficient for (**a**) shorter ($t_{if}$ = +10 °C) and (**b**) longer ($t_{if}$ = +12 °C) heating seasons.

A similar situation was found in the analysis of the insulation of ceilings to a ventilated shelter (Figure 4). In the case of a wooden ceilings, the lowest total costs correspond to 15 cm insulation thickness, but in the case of a reinforced concrete ceiling, these were even greater than 20 cm in thickness when the heat transfer coefficient is less than 0.20 W/m$^2$·K. Therefore, it is recommended that this value of the transfer coefficient be considered as the optimal value of the heat transfer coefficient of the ceilings to ventilated shelters. More efficient thermal insulation materials should be used in wooden frame ceilings or part of the insulation layer should be installed on top of this ceiling to minimize the initial investment (excluding the price of the wooden framework).

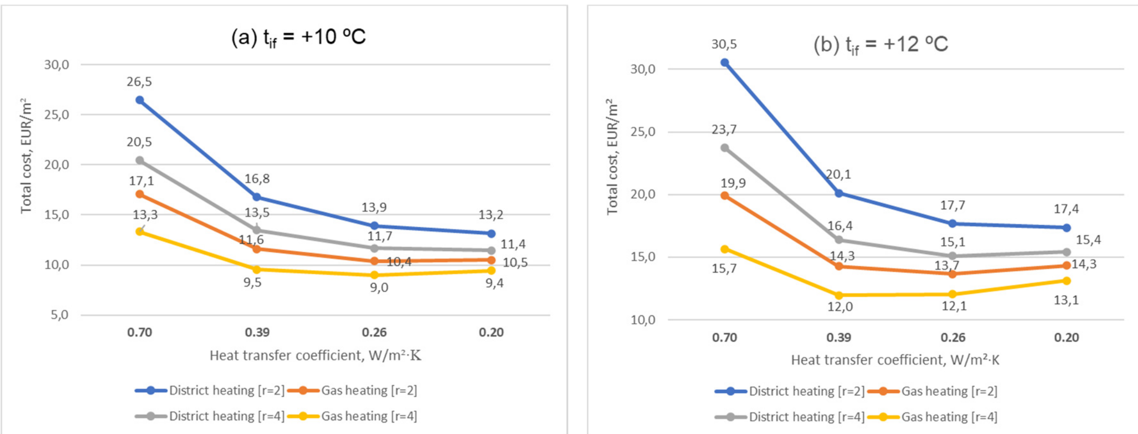


**Figure 4.** Dependence of the total cost of ceilings of a ventilated shelter on the heat transfer coefficient for (**a**) shorter ($t_{if}$ = +10 °C) and (**b**) longer ($t_{if}$ = +12 °C) heating seasons.

The results of the total costs calculation of the walls show that most of the analyzed cases fall within the area of the lowest total costs corresponding to 15 cm thick insulation (Figure 5). The lowest costs reflect a 10 cm insulation area with cheaper gas heating and longer heating season. Due to the variety of wall construction and insulation, the heat transfer coefficients of the walls corresponding to the minimum total cost are from 0.21 to 0.29 W/m$^2$·K. After summing the results, 0.25 W/m$^2$·K is the recommended optimal wall heat transfer coefficient.

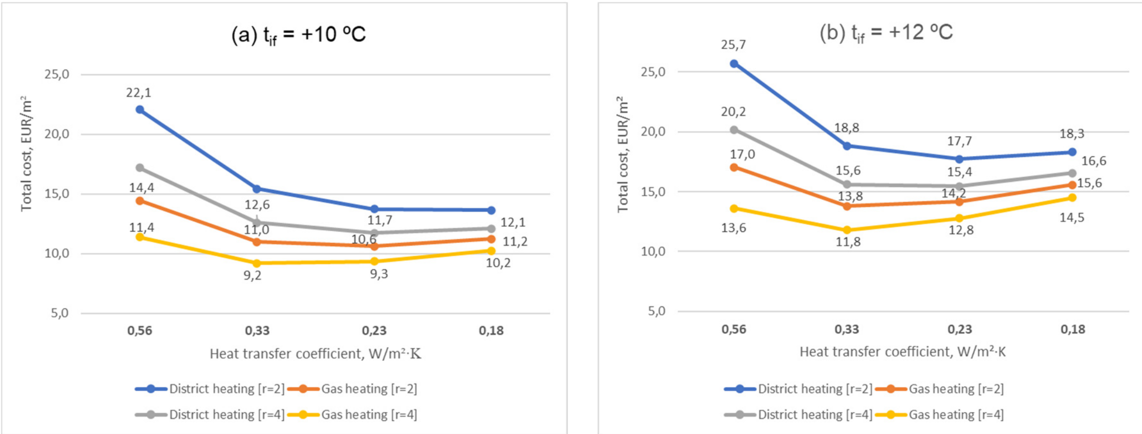


**Figure 5.** Dependence of the total cost of walls on the heat transfer coefficient for (**a**) shorter ($t_{if}$ = +10 °C) and (**b**) longer ($t_{if}$ = +12 °C) heating seasons.

Floor calculations clearly show the lowest total cost for the 10 cm thick floor insulation, but in the case of more expensive heating networks and a shorter heating season, the total cost increases slightly with a 15 cm thick thermal insulation layer (Figure 6). This corresponds to a range from 0.22 to 0.30 W/m$^2$·K of the floor to ground heat transfer coefficient. Considering that increasing the floor insulation thickness is one of the cheapest ways to install thermal insulation, the value of the heat transfer coefficient depends on the size of the building, and that increased floor on the ground insulation further reduces the energy consumption of the building when installing floor heating, an optimal floor for the ground heat transfer coefficient could be 0.23 W/m$^2$·K.

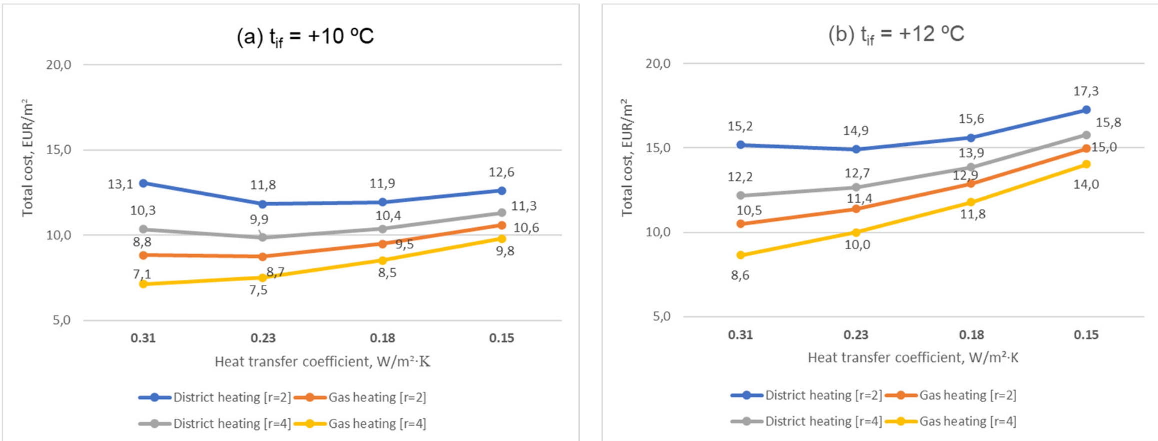


**Figure 6.** Dependence of the total cost of floors on the heat transfer coefficient for (**a**) shorter ($t_{if}$ = +10 °C) and (**b**) longer ($t_{if}$ = +12 °C) heating seasons.

It is more difficult to optimize windows than other building elements as windows perform other functions in addition to saving thermal energy (Figure 7).

However, in terms of heat loss estimation, less energy-saving windows are currently optimal due to the low energy price, although windows of 60 mm thickness with double-glazed insulated glass units and one low emissivity glass pane with a heat transfer coefficient of 1.6 W/m$^2$·K are eligible for indoor microclimate conditions. The total cost is only slightly increased by using a window frame with better thermal properties when the value of the heat transfer coefficient of the window decreases up to 1.4 W/m$^2$·K. The use of triple glazing is not optimal under the investigated conditions, not only due to rising total costs, but also due to the decreasing amount of solar energy entering the building through the windows. A window with a triple-glazed unit, on average, has lower solar heat gains than it saves thermal energy compared to a double-glazed insulated glass unit (Table 7). Therefore, it is suggested to set the optimal heat transfer coefficient of the windows at 1.4 W/m²·K, which can be achieved using a frame of better thermal performance and a double-glazed glass unit.

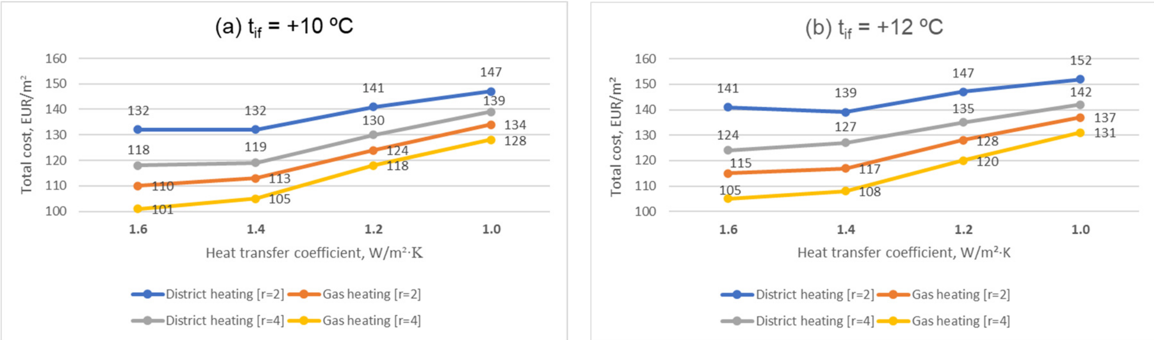


**Figure 7.** Dependence of the total cost of windows on the heat transfer coefficient for (**a**) shorter ($t_{if}$ = +10 °C) and (**b**) longer ($t_{if}$ = +12 °C) heating seasons.

**Table 7.** Recommended minimum optimal values for the heat transfer coefficient of the building envelope.

| Construction, Element | Pitched Roof | Flat Roof | Ceiling to Ventilated Attic | Walls | Floor | Windows |
|---|---|---|---|---|---|---|
| Heat transfer U, W/m²·K (KZ) | 0.25 | 0.22 | 0.20 | 0.25 | 0.23 | 1.4 |
| Heat transfer U, W/m²·K (LT) | 0.15 | 0.15 | 0.15 | 0.165 | 0.18 | 1.0 |

The analysis of the dependence of total costs and the scenarios of changes in energy prices and the value of money was also performed. For all partitions, the trends of change in total cost differ slightly, it was found that the total costs are 7–10% higher at a lower actual discount rate (r = 2). This means that with more intensive changes in energy prices and value for money, the optimal level of insulation would be even higher. This analysis has shown that in order to significantly change the situation of increasing the energy efficiency of residential buildings in the region, the artificial regulation of low thermal energy prices needs to be stopped as soon as possible. Therefore, it is recommended for the management of the construction sector of the region to set the heating energy prices as close as possible to the market conditions, and allocate the additional funds to subsidize the implementation of energy efficiency measures in new residential buildings. The results of the analysis show that a gradual increase in thermal energy prices will not produce tangible results of energy efficiency in the long perspective.

An additional analysis of subsidies for energy efficiency improvement measures has shown that the elimination of artificial price reductions alone is not enough to achieve long-term energy efficiency goals [35]. In many countries, subsidies for innovative energy performance measures, in particular those using renewable energy, are used to increase the energy efficiency of a building [36]. Other researchers suggest that most appropriate measures are demonstration projects and soft loans for energy efficiency measures [37]. However, other studies have found that subsidizing energy efficiency measures needs to be well thought out and systematically addressed, as otherwise most subsidies could go to corporate profits [38] or reductions in energy and construction taxes and would have a negative impact on public budgets [39].

The recommended minimum optimal values for the heat transfer coefficient of the building envelope elements for the Almaty region of Kazakhstan are given in Table 7, line 1.

In 2017, cost-optimal analysis according to the methodology used in this study, applying the same scenarios of energy price change and monetary value change, was performed in Lithuania using a district network price of 0.06 EUR/kWh and gas heating price of 0.04 EUR/kWh. These were about four times higher than the prices of Almaty in 2019. The calculated optimal values of heat transfer coefficients are presented in Table 6 (line 2). Comparative analysis showed that the optimal level of thermal insulation of building partitions in Lithuania is about 30% higher than that in Almaty. This difference is not large because a longer calculation period was chosen, and the prices of thermal insulation materials and construction work in Almaty are also lower.

Using recommended values of the heat transfer coefficients of the partitions, the energy efficiency characteristics of the reference building were calculated; results are presented in Table 8.

**Table 8.** Energy efficiency characteristics of the reference building.

| | Roof | Walls | Floors | Windows and Doors | Thermal Bridges | Ventilation | Heat Gains | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Solar | Internal |
| Heat losses/gains, $kWh/m^2 \cdot y$ | 23.82 | 32.66 | 19.91 | 21.92 | 20.34 | 22.96 | 34.92 | 17.80 |

The heat losses through the external envelope of the reference building are 118.7 $kWh/m^2 \cdot y$, ventilation heat losses are 23.0 $kWh/m^2 \cdot y$, and heat gains are 52.7 $kWh/m^2 \cdot y$. The approximate heating energy consumption of this reference building is 90 $kWh/m^2 \cdot y$. As an example for comparison purposes, the average heating energy consumption for 1–2 family buildings in Germany in 2017 was 122 $kWh/m^2 \cdot y$ [40]. The significant part of this difference is due to higher solar heat gains in Almaty.

## 4. Conclusions

The results of the study showed the level of insulation of residential buildings, at which investments in construction and cost of thermal energy in the long run in the Almaty region will be efficient. The tendencies have been identified:

- The low cost of thermal energy and a shorter heating season leads to lower annual costs for heating the building. This does not promote improvement of the energy performance of buildings or saving of energy resources.
- The analysis of the total energy costs associated with the windows, as an example, showed that the current relationship between energy prices and the cost of introducing energy-saving measures is holding back the introduction of innovative energy-saving measures in the Almaty region.
- Extending the heating season to improve indoor microclimate conditions leads to higher long-term energy consumption when the insulation level of buildings is low.
- To reduce long-term thermal energy consumption and improve thermal conditions in buildings, their energy efficiency must be higher than that calculated in this study. It is recommended to redistribute a portion of energy subsidies for the implementation of energy efficient measures in the residential building sector.
- The elimination of artificial price reductions alone is not enough to achieve long-term energy efficiency goals. Subsidies for innovative energy performance measures, could be used to increase the energy efficiency of a buildings;
- The validation of the building's optimized insulation levels according results of this study would slow down the increase in the demand for thermal energy in the region due to the intensive development of residential construction.

These conclusions can be applied to many countries that aim to raise people's living standards by lowering heating energy prices. Research has shown that this approach is not suitable for a longer period of time. A more appropriate strategy is to allow the market to regulate thermal energy prices and to subsidize innovative measures to increase the energy efficiency of buildings. The additional benefits of this approach are the overall reduction in energy consumption, the increase in independence from fossil energy and the reduction of environmental pollution.

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