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Analysis and research of solar heating in the design of residential buildings

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Abstract. The aim of the study was to develop a mathematical model for improving the energy efficiency of residential buildings through the seasonal use of solar heating. A method for the theoretical calculation of energy-efficient houses was proposed, taking into account the geometric parameters of windows and the design features of the window roof. The conditions for the optimal placement of windows for effective capture of solar radiation during the heating season were identified. The study paid particular attention to the climatic characteristics of Kyrgyzstan, such as the duration of the heating season, the level of solar radiation and the potential for reducing the consumption of traditional energy sources. A climate analysis of the cities of Osh and Bishkek showed that even on the shortest winter days, it is possible to obtain a significant amount of solar energy, sufficient for partial or complete heating of premises. A mathematical model of heat loss has been developed, taking into account the temperature difference between the indoor and outdoor environments, as well as the heat transfer coefficient of the building envelope. This allows for an assessment of the duration of effective use of solar energy for heating. Key design parameters have been formalised, including the angle of incidence of sunlight, the length of the roof overhang, the height of the window and the geometry of the facade. Formulas for calculating the length and height of the canopy, taking into account seasonal changes in the position of the sun, have also been proposed. The article presents a roof and window layout that provides protection from overheating in summer and maximum solar energy inflow in winter. The study confirms that well-designed solar heating systems can significantly reduce the load on central heating and increase the efficiency of renewable energy use. The presented methods are applicable in the design of modern energy-efficient buildings, especially in regions with mountainous terrain and a long heating season. Thus, this study is of great importance for the practical implementation of solar heating systems capable of ensuring the sustainable and efficient use of solar energy, taking into account local climatic characteristics

Keywords: renewable energy sources; thermal efficiency; architectural solutions; thermal insulation of buildings; climatic characteristics; optimisation of building elements; seasonal adaptation of structures

Introduction

Heating residential buildings is a pressing issue, as the constant rise in the cost of coal and other traditional energy sources, as well as the environmental problems associated with their use, require ways to reduce consumption. One way to solve this problem is to expand the use of solar energy, including its application in heating systems. Solar energy is a renewable resource that can significantly reduce dependence on

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centralised energy sources and reduce the load on heating infrastructure. Given the climatic characteristics of Kyrgyzstan and the potential for using solar heating in mountainous areas, research in this field is important for improving the energy efficiency of residential buildings.

When using solar energy in passive heating systems, it is necessary to study the location of windows, which is an important element of a residential building. Analysing the impact of the geometric parameters of windows and roofs on solar energy capture, as well as developing mathematical models to optimise these parameters, will help create effective solutions that can be applied in real-world conditions, especially in regions such as Osh and Bishkek.

In their study, scientists R.A. Akparaliev *et al*. [1] analysed the climatic conditions of Kyrgyzstan in detail, creating a resource map that includes geographical coordinates, administrative divisions, as well as solar radiation parameters and surface inclination angles. Their work made it possible to take into account the characteristics of the local climate when designing solar heating systems, but issues of seasonal adaptation of structures and integration of geometric characteristics of buildings remained insufficiently addressed. According to reports from international energy organisations, heating buildings accounts for 20% to 30% of total final energy consumption, and in countries with cold climates, this figure can reach 40% or more [2]. The book by N.R. Avezova *et al.* [3] examined the energy efficiency of residential buildings with an emphasis on the use of the Trombe wall passive solar system. However, the authors do not conduct a detailed analysis of architectural solutions in a broader context, such as building shape, orientation, planning features, and other parameters that affect energy consumption reduction.

The study by S.I. Khamraev [4] noted the importance of improving the energy efficiency of residential heating systems through the use of renewable energy sources, in particular solar energy. The author proposed a combined heating scheme that allows up to 70% of the heat load to be covered during the winter period through the effective use of solar collectors. The work was based on experimental research conducted in real conditions in the south of Uzbekistan, in the city of Karshi, from November 2020 to February 2021, which gives the results practical reliability and relevance. The proposed system takes into account the climatic characteristics of the region, which is characterised by high levels of solar radiation and a continental climate, and demonstrates the technical feasibility of solar heating in domestic conditions.

However, despite the high practical value of the study, the work lacks an in-depth analysis of architectural solutions for buildings, such as orientation, thermal insulation, insolation, building envelope materials, etc., which have a significant impact on reducing the overall heat load. Failure to take these factors into account narrows the overall systemic assessment of energy efficiency and limits the adaptability of the proposed model to a wider range of architectural contexts.

Sh. Wang *et al*. [5] noted that energy-active houses provide significant savings in energy costs by using solar energy for heating and lighting. The authors emphasised that such houses contribute to reducing the carbon footprint, as they do not depend on fossil fuels, and reduce dependence on external electricity supplies, providing greater autonomy. The Sunny Inside project, presented at the Solar Decathlon China 2013 competition [5], developed and analysed key design elements such as an eco-friendly atrium, shading systems, natural ventilation, a heat storage system and thermal insulation. However, the project does not take into account the specific climatic conditions of Kyrgyzstan, which limits its applicability in this region. This article proposes an adaptation of the Sunny Inside design elements to take into account the climatic characteristics of Kyrgyzstan, which is an important step towards improving the energy efficiency of residential buildings in the country.

Given that previous studies and implemented projects in the field of solar heating did not fully take into account the specific features of the region and the architectural parameters of buildings, this study set out to develop a mathematical model that would improve the energy efficiency of residential buildings through the rational seasonal use of solar energy. The proposed theoretical approach is based on adapting existing technologies to the specific conditions of Kyrgyzstan and includes taking into account the geometry of the glazing, the design features of the roof and other factors affecting heat loss.

Materials and Methods

This study examined the optimisation of structural elements of glazing and roofing for more efficient use of solar energy throughout the year. A mathematical approach based on geometric and climatic parameters was used as a basis, allowing for a quantitative assessment of insolation through window openings. To refine the insolation parameters under clear sky conditions, this study used a simplified model of direct and diffuse solar radiation proposed by R.E. Bird & R.L. Hulstrom [6]. This model made it possible to quantitatively assess the amount of solar energy reaching horizontal and vertical surfaces at different times of the year, taking into account the sun's altitude, atmospheric transparency, and climatic conditions in the region. This approach made it possible to analyse light transmission and the formation of conditions conducive to improving the thermal efficiency of building envelopes in different seasons. Key factors were taken into account: the angle of incidence of sunlight, the geometry of the building, the size of the windows, the angle of the canopy and the duration of solar radiation [7]. One of the most important parameters of solar radiation is the angle of incidence of sunlight on the surface, which determines the proportion of direct solar radiation passing through the windows of an energy-efficient house [8]. During the heating season, sunlight may not fall directly into the window, encountering obstacles such as trees, rocks or hills that temporarily block direct solar radiation.

Determining the optimal angle of incidence of sunlight is the initial stage of design. This angle changes throughout the year and is determined by the ratio of the sun's height above the horizon to the distance from the Earth to the Sun. Formally, the angle of incidence θ_s is expressed as [9]:

$$\theta_s = arcsin\left(\frac{h_s}{l_r}\right), \quad (1)$$

where h_s – height the sun above the horizon, l_r – the distance from the Sun to the Earth. Let the height of the window be h. In order for the sun's rays to hit the window in winter, the horizontal projection of the rays must cross the upper edge of the window. In summer, the roof must be long enough to cover the upper part of the window and prevent overheating. The length of the roof L is calculated using the formula:

$$L = h \cdot tg(\theta_s), \quad (2)$$

where L is the length of the visor blocking sunlight. The distance from the upper edge of the window to the lower edge of the roof (h_k) depends on the length of the visor and the angle of incidence of the rays:

$$h_k = L \cdot sin(\theta_s). \quad (3)$$

These formulas made it possible to calculate the optimal sizes and angles for windows and roofs, ensuring efficient use of solar energy in different seasons. For climate analysis, data on the duration of the heating season and total solar radiation were used, obtained using specialised Delphi 7.0 software. The Python programming language was used to implement the mathematical model and perform numerical calculations, including modelling indoor temperature dynamics and constructing graphs, which ensured flexibility and accuracy of calculations and allowed for the automation of the results visualisation process. The indoor heat exchange model was described by a differential equation:

$$\frac{d_t}{d_\tau} = -k(t - t_c), \quad (4)$$

where t is the indoor temperature at time τ, t_c is the outdoor air temperature, and k is the heat transfer coefficient of the walls. The solution to the equation with initial conditions $\tau = 0$, $t = t_0$ is:

$$t(\tau) = t_c + (t_o - t_c) \cdot e^{-k\tau}. \quad (5)$$

This made it possible to model the temperature dynamics inside the room in the absence of additional heating, taking into account heat loss through the walls.

Results and Discussion

Ordinary window glass transmits about 3-4% of ultra-shortwave radiation (280-315 nm) and almost completely blocks harmful ultraviolet radiation in the range of 100-280 nm. At the same time, it transmits up to 75% of less dangerous ultraviolet radiation (315-400 nm), which not only contributes to the accumulation of heat in the room, but also has an antiseptic effect, destroying harmful microbes [10].

Since windows are key elements through which solar heat enters energy-efficient buildings, an important stage in the design process is determining their optimal location [11]. The main principle here is the rational use of sunlight, taking into account seasonal changes in the position of the sun on the horizon [12]. Accordingly, the height of window openings and the structural placement of the roof must be adapted to maximise the intake of solar energy during the heating season – autumn, winter and spring [13].

For the effective use of solar radiation, it is necessary to take into account the dynamics of the angle of incidence of sunlight in different seasons. At the beginning of the heating season, the angle of incidence is between 27° and 40°, and in the winter months, the sun's rays are almost parallel to the horizon, which makes south-facing windows particularly effective for natural heating of rooms. However, during the transition periods before the start of the heating season, there may be an excessive amount of solar radiation, which can lead to overheating of interior spaces. This requires careful design of architectural elements, in particular the placement of windows, overhangs and canopies, as described by T. Muneer *et al*. [14].

Calculations obtained using a simplified model of direct and diffuse solar radiation were used to determine the rational geometry of windows and canopies, aimed at limiting solar overheating in summer and maximising heat gain in winter. For example, if the width of the window is 1.5 m and the height is 1.7 m, the optimal length of the canopy should be about 1.4 m, and the distance from the upper edge of the window to the lower plane of the canopy should be about 1.06 m. With these parameters, summer sunlight will be completely blocked, preventing overheating, while in winter, solar radiation will freely enter the room, providing natural heating. To visualise the geometric layout of the windows and roof, the authors developed the diagram shown in Figure 1.

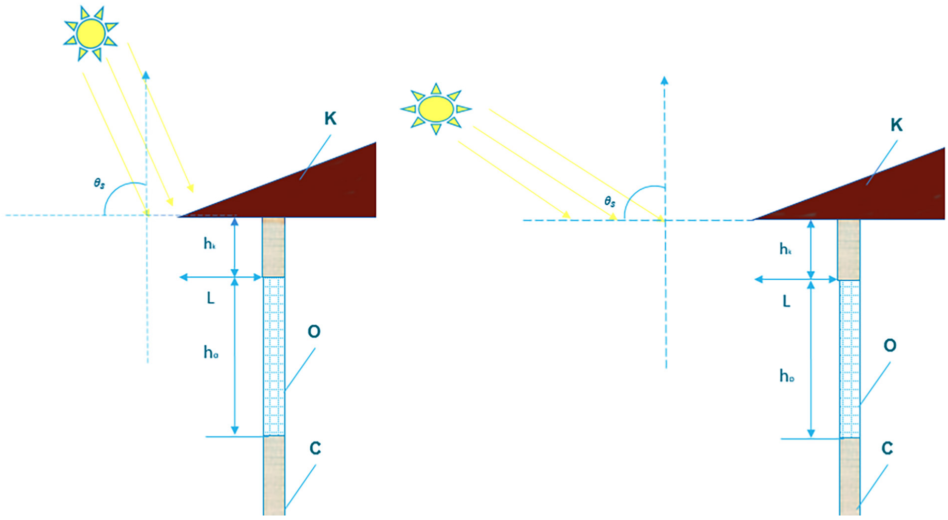

Figure 1. Scheme of the optimal arrangement of the roof and windows of the building
Notes: O – windows oriented towards the sun; K – roof optimised for the heating season; C – building walls
Source: developed by the authors

As a result of the modelling, a geometric diagram of the optimal location of windows and the roof of the building was developed (Fig. 1), taking into account the seasonal characteristics of solar radiation. Based on this diagram, an analysis of insolation for the summer and winter periods was carried out. In summer (Fig. 1a), the roof is designed to shade the windows and prevent overheating of the rooms, while in winter (Fig. 1b), the design allows maximum use of solar heat for natural heating of the interior spaces. This approach ensures effective management of solar energy throughout the year and helps to reduce energy costs for air conditioning and heating.

This method is particularly relevant for mountainous regions such as Kyrgyzstan, where the long heating season and high solar energy potential create favourable conditions for improving the energy efficiency of residential buildings and reducing the consumption of traditional energy sources. In such conditions, it is particularly important to accurately assess the duration of the heating period and the characteristics of solar radiation, which allows for the optimisation of heating system design using passive and active solar technologies. Figure 2 shows the dynamics of the duration of the heating season (in days) in the city of Bishkek over the last 15 years.

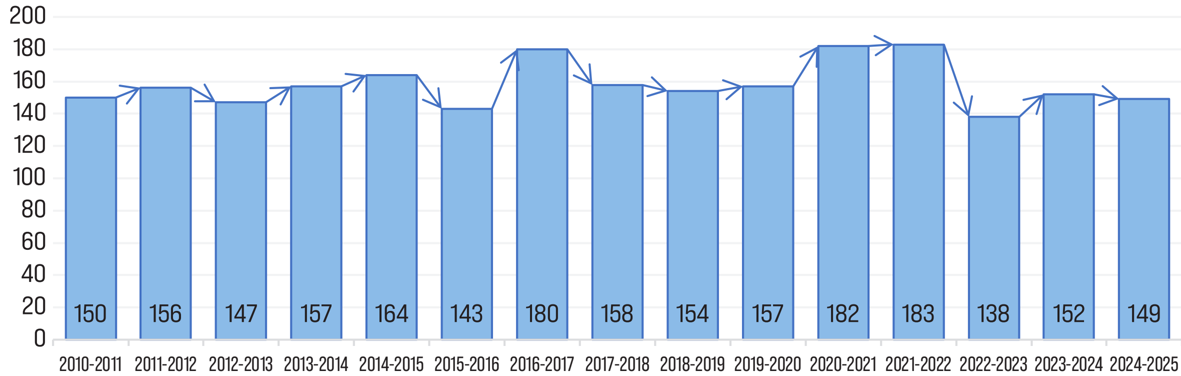

Figure 2. Duration of the heating season (days) in Bishkek
Source: compiled by the authors based on [15]

The analysis shows that the duration of the heating season in Bishkek ranges from 138 to 183 days, with an average of about 158 days. Such significant seasonal fluctuations directly affect the choice and configuration of heating systems, as well as the calculation of thermal insulation and solar collector parameters. The duration of the heating season in other large cities of Kyrgyzstan, such as Osh, is close to that of Bishkek, as confirmed by a comparative analysis of data for several years [15]. This indicates the need to develop universal solutions that are adaptable to local conditions and take into account regional climate and terrain specifics.

To gain a more complete understanding of the region's solar potential, an assessment of daylight hours and total solar radiation was carried out using specialised software. For example, the shortest day of the heating season – 22 December – in the city of Osh lasts only 6 hours and 10 minutes, with total solar radiation of about 388.73 W·h/m^2 (Fig. 3). These data highlight the need to integrate seasonal changes in sunlight into energy consumption models and the design of energy-efficient heating systems.

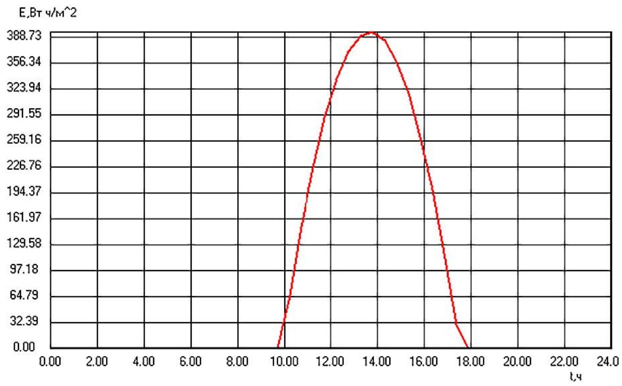

Figure 3. Forecast of total solar radiation for 22 December – the shortest day of the heating season (Osh)
Source: developed by the authors using Delphi 7.0

According to calculations, even on the shortest winter day, a significant amount of solar energy enters through a 4 m^2 window – approximately 9,573.24 W·h. This highlights the potential of solar energy as an important source of heat for energy-efficient buildings in cold climates. Using a mathematical model that takes into account an outside temperature of -5 °C and no additional heating, the dynamics of indoor temperature changes were simulated (Fig. 4).

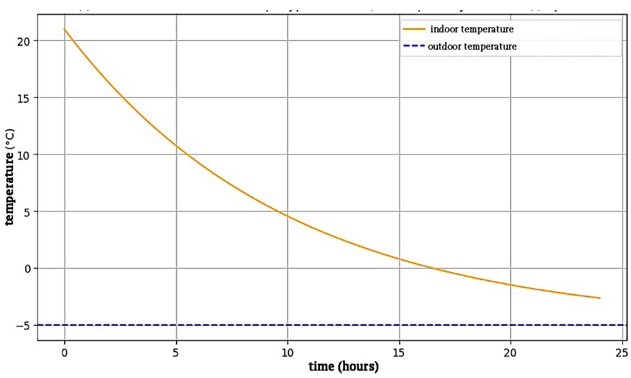

Figure 4. Temperature dynamics in a room without heating
Source: the authors' own calculations using Python

As can be seen from the results, a comfortable indoor temperature can be maintained for approximately 5 hours thanks to accumulated solar heat. After that, the temperature begins to gradually decrease, indicating the need to connect additional heating systems to maintain comfortable conditions. At the same time, the indoor temperature does not drop to the outdoor level (below 0 °C) for 15 hours, which significantly extends the time period during which energy costs for heating are reduced. Considering that the average time until sunrise in winter is about 16 hours, the use of solar energy in combination with properly designed architectural elements (windows, canopies, etc.) can reduce the consumption of traditional energy sources for heating by approximately 40%.

These results are consistent with preliminary calculations of insolation, modelling of the angles of incidence of sunlight and analysis of the duration of the heating season, which confirms the complexity and integrity of the proposed approach. Taken together, this demonstrates the high effectiveness of the proposed model for improving the energy efficiency of buildings in mountainous regions with long heating seasons, such as Kyrgyzstan. It should be noted that the proposed approach is consistent in a number of cases with the research of other scientists in the field of energy-efficient building design. For example, in an article on solar architecture, authors L. Zhong *et al.* [16] emphasised the importance of correct window orientation and the use of solar energy for heating in winter.

Nevertheless, there are a number of differences between the proposed model and other approaches. For example, the article considers a specific geographical area – Kyrgyzstan – and takes into account the natural features of this region, such as the duration of the heating season and the level of solar radiation. The research by K. Mehta *et al.* [17] specifically takes into account the climatic characteristics and conditions of different regions, which is particularly important as climate significantly affects the efficiency of solar heating systems. At the same time, many studies conducted in other countries focus on their own climatic conditions, which can lead to differences in the results of calculations. For example, studies conducted in regions with higher levels of solar radiation often use increased values of solar radiation and climatic parameters in their calculations, which leads to differences in recommendations for the design of solar heating systems. As noted by W. Mo *et al.* [18], climatic conditions, especially the level of solar radiation, significantly affect the design and efficiency of passive solar systems, requiring the adaptation of technical solutions to a specific region.

However, despite these differences, the conclusions of this article are conceptually very close to the results of other studies proposing the use of mathematical models to optimise solar architectures. In particular, the International Energy Agency (IEA) report [2] considered the use of energy for heating in conditions of short daylight hours, including the shortest days of the year. The document emphasises that the amount of solar energy available in the winter months depends significantly on geographical location and local climatic conditions. This is confirmed by the calculations made in the article, where on 22 December, the shortest day of the heating season, 388.73 W·h/m^2 of solar energy is available. Other studies, for example, those conducted in the United Kingdom and Scandinavian countries, note that the results may vary significantly due to lower levels of solar radiation associated with longer winters and a low angle of incidence of sunlight. As pointed out by R. Renaldi & D. Friedrich [19] and M. Herrando & C.N. Markides [20], climatic conditions significantly affect the efficiency of solar heating systems and require design solutions to be adapted to low levels of insolation.

A. Olgyay & V. Olgyay [21] used a method for calculating solar insolation, which facilitated their adaptation to different types of buildings and climatic conditions. This is particularly relevant for architects and designers who need to consider not only the geographical orientation of the building but also seasonal changes in the angle of incidence of sunlight. In particular, the equations proposed by the authors allow determining the optimal parameters of architectural elements: the length of the canopy blocking direct solar radiation in summer and the height of the glazing ensuring the penetration of sunlight in winter. Such calculations serve as a practical guide for the design of energy-efficient buildings.

At the same time, there are several aspects that could be further explored. For example, the influence of different types of window glass on the efficiency of solar heating could be considered. The article mentions that glass transmits up to 75% of ultraviolet radiation in the 315-400 nm range, but does not consider other materials that could increase the efficiency of solar radiation. Thus, in a classic work by B.Y.H. Liu & R.C. Jordan [22], empirical relationships were proposed for calculating scattered solar radiation on a horizontal surface based on total radiation data. These relationships allow determining both instantaneous and average daily values of scattered radiation for various weather conditions, including clear and cloudy days, and are widely used in modelling solar heat exchange in buildings.

The proposed model is useful for practical application, especially in countries with variable climates, such as Kyrgyzstan. It provides clear recommendations for the design of roofs and windows for optimal use of solar energy, which can significantly improve the energy efficiency of buildings and reduce the need for artificial heating. The work confirms the importance of competent solar architecture design, which is supported by other studies, and opens up prospects for the application of such methods in real conditions, including their adaptation to specific climatic conditions.

Conclusions

Even on the shortest winter days, the amount of solar radiation can provide a significant amount of solar energy, sufficient to heat rooms through windows. This allows for a significant reduction in dependence on traditional energy sources such as coal and gas. To assess the efficiency of solar energy use in heating, it is important to consider heat transfer through the walls of the building and the temperature difference between the interior and exterior environments. Mathematical modelling of these processes allows for accurate calculation of the time required for solar energy to provide the necessary heating for a room.

The results confirmed that even on the shortest winter days, a significant amount of solar energy can be obtained through correctly oriented and well-designed windows. The heat loss model made it possible to estimate the duration of effective solar energy use and its impact on the internal temperature of rooms. The study showed that competent design of solar heating systems (taking into account the angle of the roof, the orientation of the windows and the length of the eaves) can significantly reduce heat loss and reduce the load on traditional energy sources. This is particularly relevant for regions with long heating seasons and high solar insolation, such as Kyrgyzstan.

Thus, the results of the study confirm the importance of using solar heating to improve the energy efficiency of residential buildings in Kyrgyzstan. The theoretical and computational approaches developed provide a solid foundation for the further development and implementation of solar technologies in architectural design in the region. The use of solar energy in heating systems is a promising and effective way to solve energy shortages and environmental problems, especially in Kyrgyzstan with its natural characteristics and long heating seasons.

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Conflict of Interest

None.

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Турак жай имараттарын долбоорлоодо күн жылытуусун анализдөө жана изилдөө

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Аннотация. Изилдөөнүн максаты күн энергиясын сезондук колдонуу аркылуу турак жай имараттарынын энергия эффективдүүлүгүн жогорулатуунун математикалык моделин иштеп чыгуу болгон. Терезелердин геометриялык параметрлерин жана терезе чатырынын конструкциялык өзгөчөлүктөрүн эске алуу менен энергия-активдүү үйлөрдү долбоорлоо үчүн теориялык эсептөө методу сунушталат. Жылытуу мезгилинде күн радиациясын эффективдүү кармоо үчүн терезелерди оптималдуу жайгаштыруу шарттары аныкталган. Изилдөөдө Кыргызстандын климаттык өзгөчөлүктөрүнө өзгөчө көңүл бурулган, мисалы, жылытуу мезгилинин узактыгы, күн радиациясынын деңгээли жана салттуу энергия булактарын керектөөнү кыскартуу потенциалы. Ош жана Бишкек шаарларынын климаттык анализи кыштын эң кыска күндөрүндө да жайларды жарым-жартылай же толук жылытуу үчүн жетиштүү күн энергиясын алууга болоорун көрсөттү. Ички жана тышкы чөйрөнүн ортосундагы температуранын айырмасын, ошондой эле курчап турган конструкциялардын жылуулук өткөрүмдүүлүк коэффициентин эске алган жылуулук жоготуусунун математикалык модели иштелип чыккан. Бул жылытуу үчүн күн энергиясын натыйжалуу пайдалануу узактыгын баалоого мүмкүндүк берет. Дизайндын негизги параметрлери, анын ичинде күндүн түшүү бурчу, чатырдын ашкан узундугу, терезенин бийиктиги жана фасаддын геометриясы расмий түрдө бекитилген. Күндүн абалынын сезондук өзгөрүшүн эске алуу менен чатырдын узундугун жана бийиктигин эсептөө үчүн формулалар да сунушталган. Макалада жайкысын ысып кетүүдөн коргоону жана кышында күн энергиясын максималдуу тийүүсүн камсыз кылган чатырларды жана терезелерди жайгаштыруунун схемасы келтирилген. Изилдөө жакшы долбоорлонгон күн жылытуу системалары борборлоштурулган жылытууга болгон жүктү олуттуу түрдө азайтып, энергиянын кайра жаралуучу булактарынын натыйжалуулугун жогорулата аларын тастыктайт. Сунушталган ыкмалар заманбап энергияны үнөмдөөчү имараттарды долбоорлоодо, өзгөчө тоолуу аймактарда жана жылытуу мезгили узак болгон аймактарда колдонулат. Ошентип, бул изилдөө жергиликтүү климаттык өзгөчөлүктөрдү эске алуу менен күн энергиясын туруктуу жана натыйжалуу пайдаланууну камсыз кыла ала турган күн жылытуу системаларын практикалык ишке ашыруу үчүн чоң мааниге ээ

Негизги сөздөр: энергиянын кайра жаралуучу булактары; жылуулук эффективдүүлүгү; архитектуралык чечимдер; имараттарды жылуулуктан коргоо; климаттык өзгөчөлүктөр; курулуш элементтерин оптималдаштыруу; структуранын сезондук ыңгайлашуусу

Анализ и исследование солнечного отопления при проектировании жилых зданий

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Аннотация. Цель исследования заключалась в разработке математической модели для повышения энергоэффективности жилых зданий за счёт сезонного использования солнечного отопления. Предложено методику теоретического расчета к проектированию энергоактивных домов с учётом геометрических параметров окон и конструктивных особенностей оконной крыши. Выявлены условия оптимального размещения окон для эффективного улавливания солнечного излучения в течение отопительного сезона. Особое внимание в исследовании уделено климатическим особенностям Кыргызстана, таким как длительность отопительного сезона, уровень солнечной радиации и потенциал снижения потребления традиционных энергоносителей. Климатический анализ городов Ош и Бишкек показал, что даже в самые короткие зимние дни возможно получение значительного объёма солнечной энергии, достаточного для частичного или полного обогрева помещений. Разработана математическая модель теплопотерь, учитывающая разность температур между внутренней и наружной средой, а также коэффициент теплопередачи ограждающих конструкций. Это позволило оценить продолжительность эффективного использования солнечной энергии для отопления. Были формализованы ключевые параметры проектирования, включая угол падения солнечных лучей, длину свеса крыши, высоту окна и геометрию фасада. Также предложены формулы для расчёта длины и высоты козырька с учётом сезонных изменений положения солнца. В статье представлена схема размещения крыш и окон, обеспечивающая защиту от перегрева летом и максимальный приток солнечной энергии зимой. Исследование подтверждает, что грамотно спроектированные солнечные системы отопления могут значительно снизить нагрузку на центральное теплоснабжение и повысить эффективность использования возобновляемых источников энергии. Представленные методики применимы при проектировании современных энергоэффективных зданий, особенно в регионах с горным рельефом и длительным отопительным сезоном. Таким образом, данное исследование имеет большое значение для практической реализации систем солнечного отопления, способных обеспечить устойчивое и эффективное использование солнечной энергии с учётом местных климатических особенностей

Ключевые слова: возобновляемые источники энергии; тепловая эффективность; архитектурные решения; теплозащита зданий; климатические особенности; оптимизация строительных элементов; сезонная адаптация конструкции