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Methodology for calculating heat loss through triple-layer transparent building enclosures

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Abstract: *This article presents an analysis of heat loss and heat gain through a triple-layer energy-efficient window system in various climatic zones of Uzbekistan. The study uses long-term data from 2000 to 2023, focusing on both January and July to account for the contrasting winter and summer conditions. The results highlight the significant role that energy-efficient windows play in reducing heat loss during the cold period (October to March), especially in regions with extreme winter temperatures, such as the mountainous areas in the east of Uzbekistan. During the warm period (April to September), the triple-layer window system effectively minimizes heat penetration into buildings, particularly in the central and southern regions, where summer temperatures can exceed 45°C. This reduces the energy demand for cooling. The study uses maps to visualize heat loss and heat gain across different regions, helping to illustrate the window system's efficiency in both winter and summer months. The findings underscore the energy-saving potential of triple-layer windows, demonstrating their ability to improve energy efficiency in buildings by reducing both heating costs in winter and cooling costs in summer. The practical significance of these results lies in their application to energy-efficient building design, material selection, and the planning of energy-saving measures. The use of such window systems can contribute to the overall reduction of energy consumption in both residential and*

INTRODUCTION

In recent years, the development and implementation of energy-efficient building materials have become a key focus in the construction industry. Among the most innovative solutions is the use of triple-glazed window units with specialized coatings, which have been extensively studied for their energy-saving potential. These windows incorporate low-emissivity (low-E) coatings, which significantly reduce the radiative heat transfer by lowering the emissivity of the glass surface. This, in turn, enhances the thermal insulation properties of the glass units, making them highly effective at reducing heat losses in both residential and commercial buildings [1-3].

Recent advancements in triple-glazed window technology have broadened the range of options available for modulating solar energy transmission, reflection, and absorption. Careful selection of glazing materials allows for precise control over the window's thermal performance, which plays a critical role in optimizing thermal comfort and energy efficiency in buildings [4, 5]. The ability of these windows to reduce heat transfer has significant implications for designing systems for comfortable air conditioning, particularly in climates with extreme temperature variations, such as Uzbekistan.

However, while low-E coatings effectively reduce heat loss, they can also decrease natural light transmission, which may impact the indoor environment. Studies have shown that this reduction in light transmission can influence natural daylighting, potentially requiring additional lighting during daylight hours [6, 7]. Nevertheless, by carefully balancing the optical and thermal properties of the glazing, it is possible to minimize these effects while still reaping the benefits of improved thermal insulation [8].

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In regions with harsh climatic conditions, such as the extreme summer heat and cold winters in Central Asia, triple-glazed units can be particularly beneficial. Research on these energy-saving windows has demonstrated their potential not only in reducing heat loss but also in limiting solar heat gains, which can contribute to overheating in summer months [9, 10]. Consequently, the adoption of triple-glazed windows with optimized coatings presents an opportunity to significantly reduce heating and cooling demands, thereby enhancing the overall energy efficiency of buildings.

The heat transfer through window glazing systems is typically modeled using thermal resistance and thermal transmittance (U-values), which quantify the rate of heat flow through the window material [11]. Computational models based on computational fluid dynamics (CFD) or finite element analysis (FEA) have been widely employed to simulate the thermal behavior of glazing units, including the effects of convection, conduction, and radiation [12].

To ensure accurate performance assessments, researchers often utilize climate data, such as those provided by the ERA5-Land dataset used in this study, which offers long-term hourly weather data with high spatial resolution. This dataset has proven reliable for modeling the energy performance of building components, and its use in this study ensures that the calculated heat gains and losses are based on real-world climatic conditions, reflecting the diverse weather patterns across Uzbekistan's regions. Additionally, the integration of localized climate data enhances the precision of energy modeling, which is particularly important in a country where climatic extremes, such as harsh winters and hot summers, vary significantly by region [13].

R.R. Avezov and his team conducted extensive research aimed at enhancing the efficiency of passive solar heating systems using triple-glazed transparent energy-active enclosures. Special attention in their work was paid to the effect of a partially radiation-absorbing film applied to the inner surface of such enclosures on heat losses and the thermal regime of the premises. Several models of both stationary and non-stationary thermal regimes in rooms heated by these solar insolation systems were developed. These studies demonstrated that a properly designed triple-glazed system can significantly reduce heat losses and improve the energy efficiency of buildings, especially considering the climatic features of Uzbekistan [14-25].

Furthermore, the analysis of solar heat gain coefficients (SHGC) and the effect of optical coatings on solar energy transmission are critical for understanding how these windows perform in different environmental contexts. In this study, the proposed triple-glazed transparent enclosure, designed by R.R. Avezov and his team, utilizes advanced low-emissivity coatings that not only reduce heat losses but also optimize solar energy control. By combining detailed thermal modeling with hourly climatic data for key months like January and July, the study provides a comprehensive approach to evaluating the annual energy performance of triple-glazed windows across various climatic zones in Uzbekistan. The inclusion of ERA5 data for the period from 2000 to 2023 ensures that these models are grounded in long-term trends, allowing for accurate predictions of energy consumption and heat losses.

Moreover, presenting the calculation results in the form of heat loss distribution maps across Uzbekistan further enhances the study's applicability. These maps allow for a visual and spatial understanding of how the proposed energy-efficient enclosure performs in different regions, providing valuable insights for future energy-saving measures and enabling the optimization of window design based on specific regional needs. This approach supports more efficient energy consumption, particularly in regions where extreme temperature fluctuations have the greatest impact on building energy demands.

METHODS AND MATERIALS

To conduct this study on the thermal efficiency of multilayer transparent enclosures under the conditions of Uzbekistan for both heating and cooling periods, climate data covering the period from 2000 to 2023 were used, sourced from the ERA5-Land hourly dataset. ERA5-Land is a global reanalysis dataset with a regular latitude-longitude grid projection. It provides gridded data at a high horizontal resolution of 0.1° x 0.1° (native resolution is 9 km). The dataset covers the period from January 1950 to the present and offers data with an hourly temporal resolution. The data are available in GRIB format and are updated monthly with a delay of approximately three months from the current date [26]. According to the literature [27, 28], ERA5-Land temperature data are well-aligned with ground observation data in Uzbekistan. The following analyses were conducted as part of this study:

2.1. Maximum monthly temperatures: An analysis of maximum outdoor air temperatures by month from 2000 to 2023 was conducted, based on which maps showing the spatial distribution of maximum temperatures across the regions of the republic for each month of the year were created. These maps allow for the assessment of the most extreme temperature conditions, which must be considered when designing transparent enclosures for effectively reducing thermal loads in buildings.

2.2. Minimum monthly temperatures: An analysis of minimum outdoor air temperatures by month from 2000 to 2023 was also performed, resulting in maps illustrating the distribution of minimum temperatures across different regions of the republic for each month of the year. These data are essential for understanding seasonal temperature fluctuations and for designing window systems that provide effective insulation and minimize heat loss during cold periods.

2.3. Calculation of heat losses (and heat gains): To determine heat losses through transparent building enclosures, calculations were carried out using key input data such as indoor air temperature, outdoor temperature, wind speed, and the structural parameters of the window systems. These parameters are fundamental to analyzing heat gains and losses, as they affect the energy efficiency of buildings during both the heating and cooling periods. The calculations allow for the quantitative assessment of heat loss through window structures and the identification of the main factors influencing these losses. Based on the obtained data, methods for optimizing heat gains can be proposed, which in turn contribute to improving the energy efficiency of buildings and reducing the costs of heating and cooling.

Calculation Steps:

1. *Thermal resistance of the air layer* (R_{AL}):

The equivalent thermal conductivity coefficient:

$$\lambda_{EC} = \varepsilon_C \cdot \lambda_A \tag{1}$$

where: λ_A– thermal conductivity coefficient of air; ε_C – convection coefficient, depending on the product of the Grashof number (Gr) and the Prandtl number (Pr).

Grashof number (Gr):

$$Gr = \frac{\beta_A \delta^3 g \Delta t}{v_A^2}, \tag{2}$$

where: β_B – coefficient of thermal expansion of air $\left(\beta_A = \frac{1}{t_{av}+273}\right)$; δ – thickness of the air layer; g– acceleration due to gravity (9.81 m/s²); Δt – temperature difference between the inside and outside; ν_B – kinematic viscosity of air.

Convection coefficient (ε_C):

$$\varepsilon_C = 0{,}18(Gr \cdot Pr)^{0{,}25}. \tag{3}$$

Thermal resistance of the air layer:

$$R_{AL} = \frac{\delta}{\lambda_{EC}}. \tag{4}$$

2. Thermal resistance of the inner surface (R_{IS})

Heat transfer through the inner surface of the window is caused by natural convection within the room:

Heat transfer coefficient of the inner surface:

$$\alpha_{C.IS} = \frac{\lambda_A}{l} \cdot 0{,}15 \cdot (Gr \cdot Pr)^{0{,}33}, \tag{5}$$

where *l* – the height of the window.

Thermal resistance of the inner surface:

$$R_{IS} = \frac{1}{\alpha_{C.IS}} \tag{6}$$

3. Thermal resistance of the outer surface (R_{US})

On the outer surface of the window, heat is transferred via convection and radiation.

Heat transfer coefficient (convection):

$$\alpha_{C.US} = \frac{\lambda_A}{l} \cdot 0{,}032(Re)^{0{,}8} \tag{7}$$

where, $Re = \frac{\omega \cdot l}{\upsilon_A}$ – Reynolds number, depending on wind speed, ω - is the wind speed, and υ_A – is the kinematic viscosity of air.

Heat transfer coefficient (radiation):

$$\alpha_{R.US} = \sigma \cdot \varepsilon \cdot \frac{\left(\frac{273+t_{IN}}{100}\right)^4 - \left(\frac{273+t_{OUT}}{100}\right)^4}{t_{IN} - t_{OUT}} \tag{8}$$

where, σ – is the Stefan-Boltzmann constant, and ε – is the emissivity coefficient.

Thermal resistance of the outer surface:

$$R_{US} = \frac{1}{\alpha_{US}} \tag{9}$$

where, $\alpha_{US} = \alpha_{C,US} + \alpha_{R,US}$.

4. Total thermal resistance (R)

The total thermal resistance is: $R = R_{IS} + R_{AL} + R_{US}$

5. Calculation of heat loss through the window (Q_W)

Heat loss through the window is calculated by the following formula [13]:

$$Q_W = F_W \cdot \frac{t_{\text{IN}} - t_{OUT}}{R} \cdot n \cdot (1 + \beta) \tag{10}$$

where: F_W – window area (1 m²), t_{IN} – indoor temperature (22°C), t_{OUT}– outdoor temperature, R – total thermal resistance, N – utilization coefficient (1), β – correction factor (0.1).

6. Estimation of total heat loss for January (July):

After calculating the average values of heat loss Q_W for each hour of January (or July), the total heat loss for the month can be estimated:

$$Q_{AV} = Q_W \times n \tag{11}$$

where n – the total number of hours in January and July (744 hours).

Initial parameters for the calculation: Indoor temperature (t_{IN} – 20°C, Outdoor temperature (t_{OUT}) – average temperature for January (or July) according to ERA5 data, Air layer thickness (δ) – 0.08 m, window height (l) – 1.2 m, wind speed (ω) – average wind speed for January (or July) based on ERA5-lend data, Emissivity coefficient (ε) – 0.93, Window area (F_W) – 1 m², Utilization coefficient (N) – 1, Correction coefficient (β) – 0.1.

RESULTS AND DISCUSSION

Considering that one of the dominant factors in determining the thermal efficiency of transparent enclosures is the outdoor air temperature, the authors have studied the dynamics of changes in the monthly maximum and minimum temperatures across the regions of Uzbekistan for the period from 2000 to 2023 (Fig. 1, Fig.2).

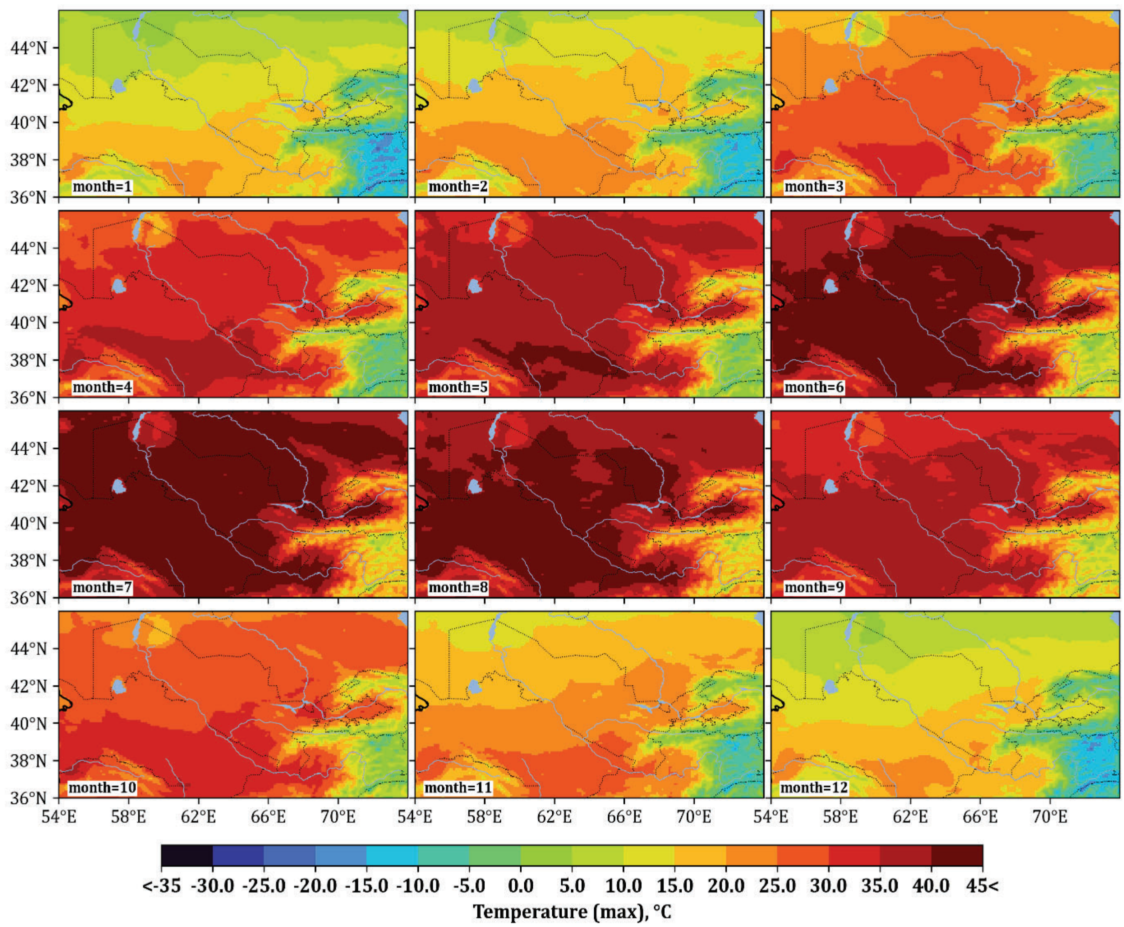

FIGURE 1. Map of the distribution of average monthly maximum temperatures by regions of Uzbekistan for the period from 2000 to 2023.

As seen in Figure 1, during the summer months (from May to September), the maximum temperatures in most regions of Uzbekistan and neighboring territories exceed 35°C. In the spring and autumn months (March, April, October, November), a gradual decrease in maximum temperatures is observed, while in the winter months (December, January, February), they reach their lowest values. This trend indicates that extreme high temperatures are recorded in the southern and central regions of the republic during the summer, increasing the need for cooling systems and highlighting the necessity of improving the energy efficiency of buildings.

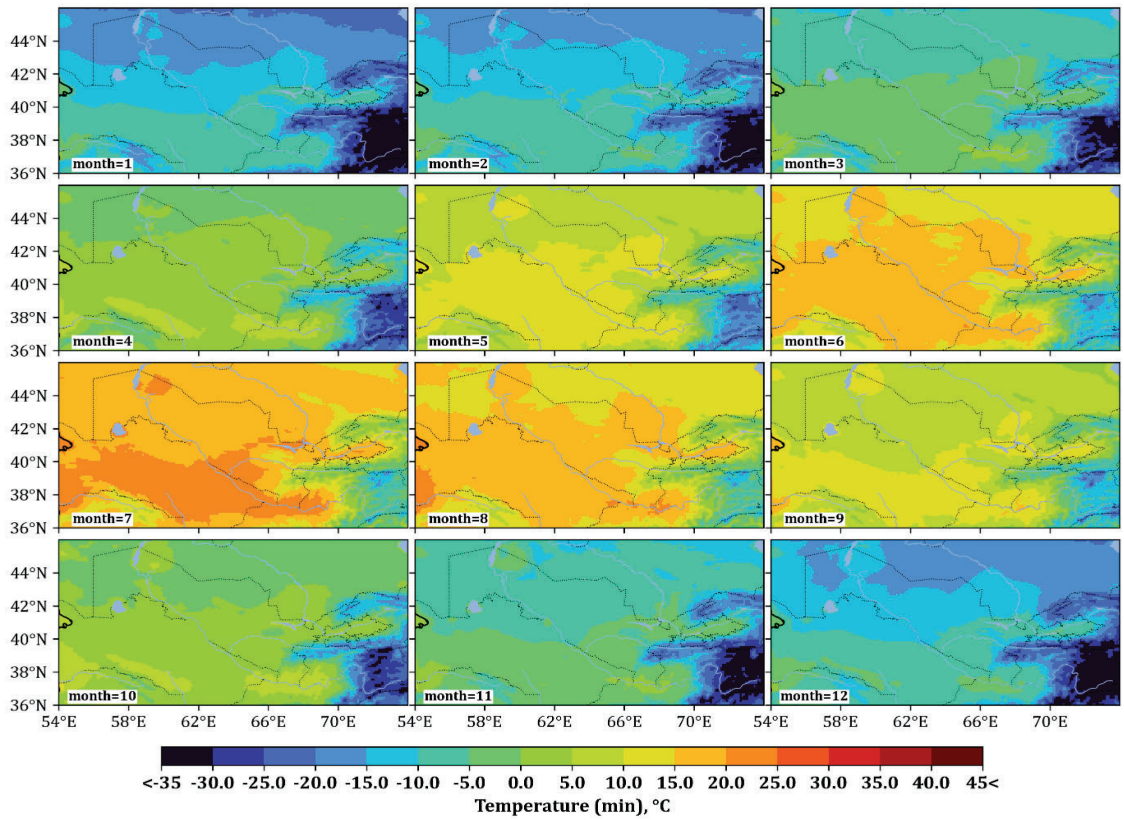

FIGURE 2. Map of the distribution of average monthly minimum temperatures by regions of Uzbekistan for the period from 2000 to 2023

As seen in Figure 2, the values of minimum temperatures across the months vary significantly between the regions of Uzbekistan and neighboring territories. In the winter months (December, January, February), temperatures drop to their lowest levels, especially in the northern and eastern regions, where extreme lows of below -25°C are observed. In spring and autumn (March, April, October, November), the minimum temperatures gradually rise, and during the summer months (June, July, August), they reach their peak, typically ranging from 15°C to 25°C. These data emphasize the importance of considering seasonal temperature fluctuations when designing buildings, particularly to ensure adequate thermal insulation during the cold season.

In Figure 3, the map illustrates heat loss through a 1 m² window in various regions of Uzbekistan in January, calculated based on average minimum temperatures for the period from 2000 to 2023. The calculations used the long-term average wind speed for January.

Climatic Features: In eastern Uzbekistan, where mountainous areas dominate, higher heat losses can be observed due to colder winters in these regions. Central and southern areas generally lose less heat, as winter temperatures are less severe here.

Practical Application: The map helps assess which regions of Uzbekistan require more effective thermal insulation for windows to minimize heat loss during the winter period. This information can be used for planning energy-saving measures and selecting the most suitable building materials for different climatic zones.

Figure 4 illustrates the potential heat flows through the proposed triple-layer energy-efficient window design in various regions of Uzbekistan in July, based on data for average long-term maximum temperatures and wind speeds from 2000 to 2023. The thermal properties of the window play a key role in regulating these flows.

Heat loss and heat gain through the window: Negative values (ranging from yellow-green to purple shades) on the map indicate the amount of heat that can enter the room through the energy-saving window while maintaining an indoor temperature of 22°C. These values reflect the window's efficiency in conditions where the outdoor temperature significantly exceeds the indoor temperature. Thanks to the proposed design, the window will prevent excess heat from entering the room, which reduces the load on cooling systems and decreases energy consumption for air conditioning.

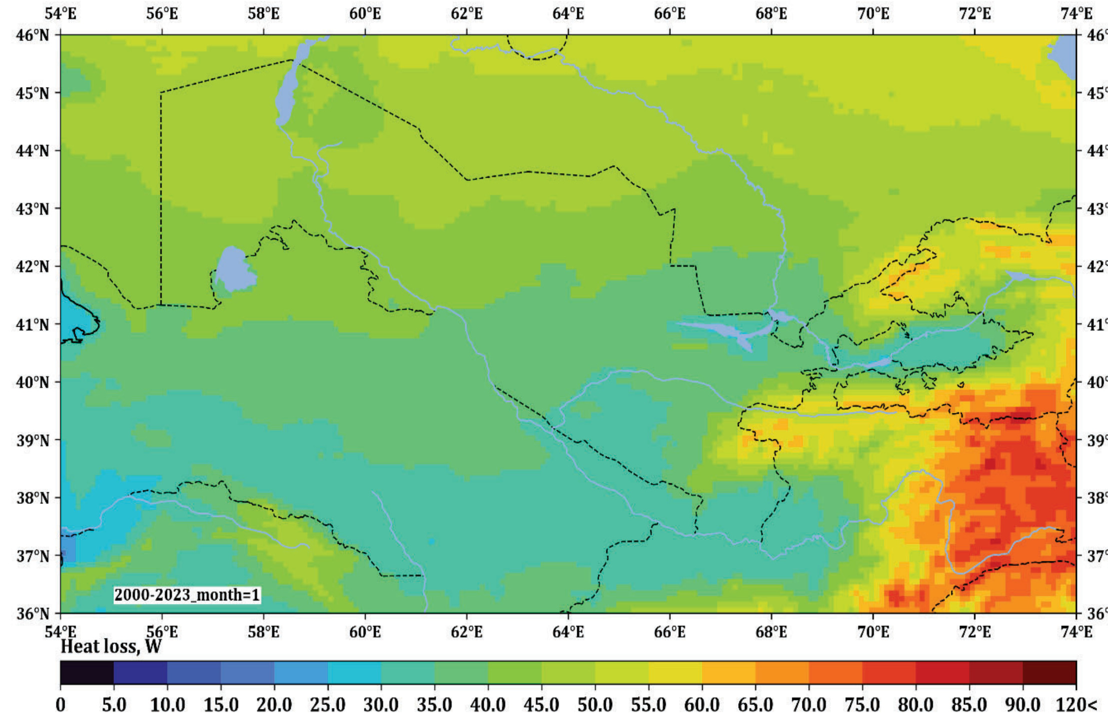

FIGURE 3. Heat loss through a 1 m² window in January based on the average minimum temperatures for the period 2000–2023

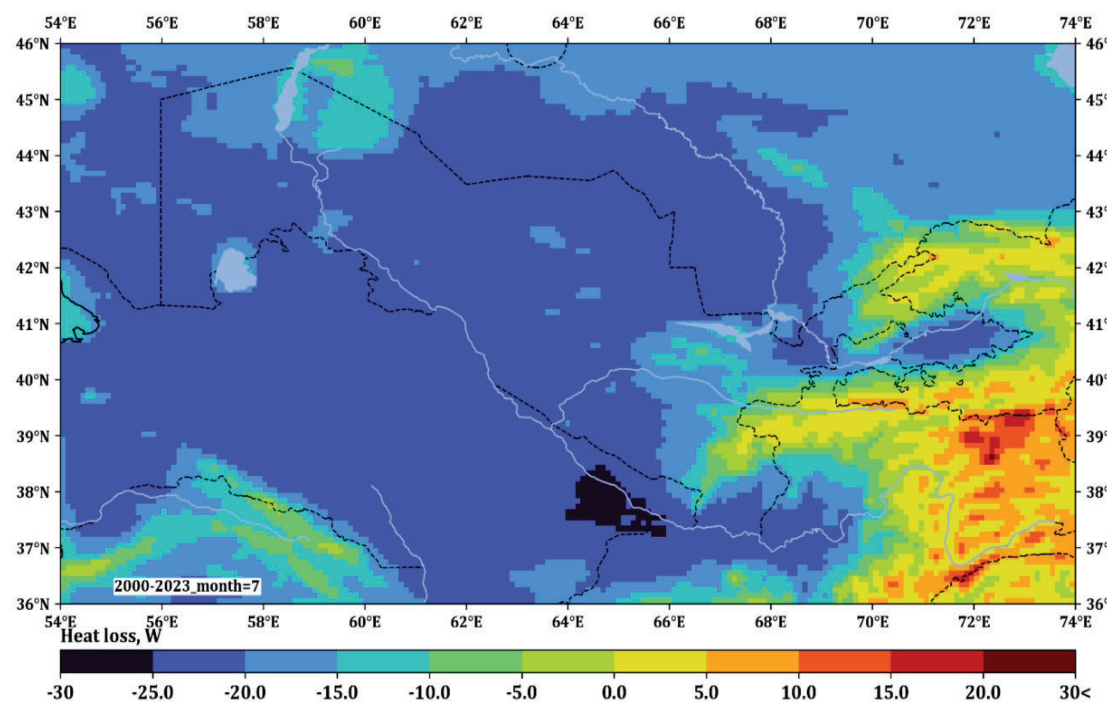

FIGURE 4. Distribution of potential heat flows through a triple-layer energy-saving window in July at maximum temperatures (based on data from 2000–2023)

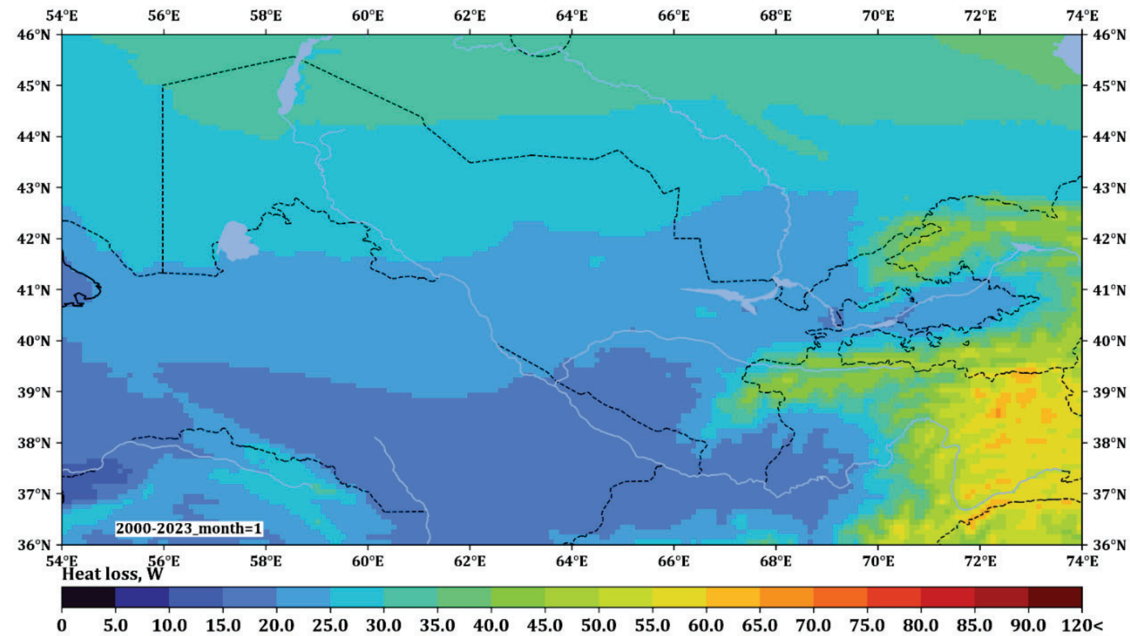

FIGURE 5. Average hourly values of heat loss in January per 1 m² of window in Uzbekistan based on average hourly temperature data for the period 2000–2023

As seen in Figure 5, the map shows the average heat loss through a 1 m² window in Uzbekistan in January, based on data from 2000 to 2023. The heat losses are expressed in watts and were calculated considering the long-term average hourly air temperatures and wind speeds in January.

January consists of 31 days, which totals 744 hours. By multiplying the average hourly heat loss by 744 hours, the total energy loss for January can be calculated.

Total heat loss for January in different zones:

1. Zone with heat loss of 20 W (blue shades): 14.88 kWh;
2. Zone with heat loss of 25 W (green shades): 18.6 kWh;
3. Zone with heat loss of 30 W (light green shades): 22.32 kWh.

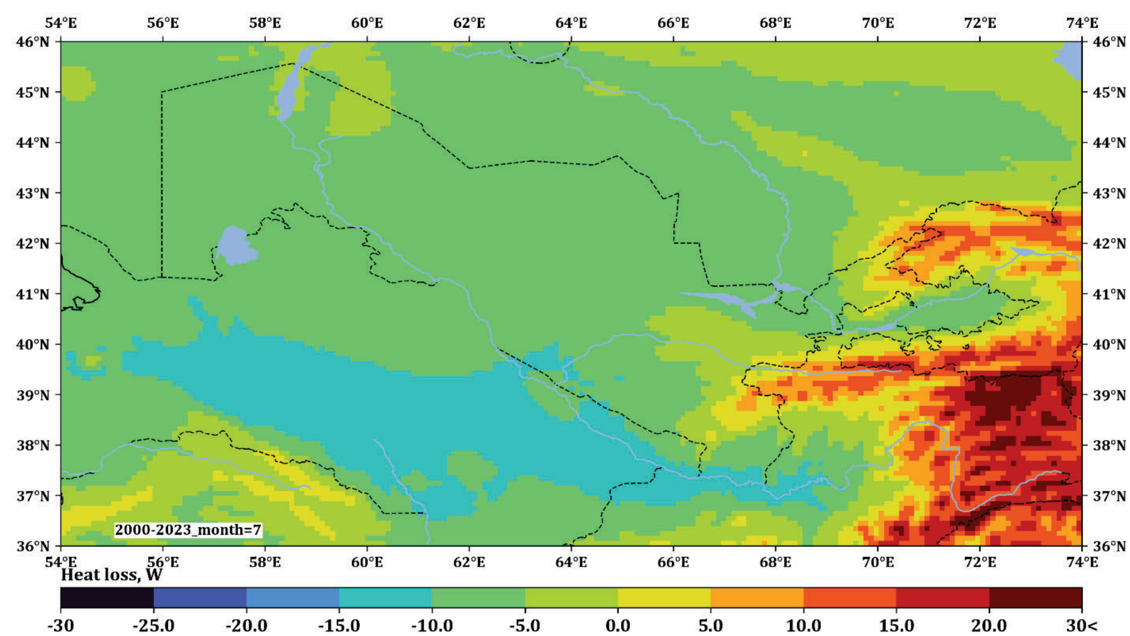

FIGURE 6. Average hourly values of heat gain in July through a 1 m² window in Uzbekistan based on average hourly temperature data for the period 2000–2023

As seen in Figure 6, the map shows the distribution of heat flows through 1 m² windows in Uzbekistan in July. The data are based on long-term average hourly temperature values and the average monthly wind speed.

July also consists of 31 days, which totals 744 hours. By multiplying the average hourly heat gains by 744 hours, the total energy cost to maintain the room temperature for July can be calculated.

Total heat gains for July in different zones:

1. Zone with heat gain of -15 W (blue shades): In these regions, windows lead to a heat gain of up to 11.16 kWh per square meter during July;
2. Zone with heat gain of -10 W (light blue shades): 7.44 kWh;
3. Zone with heat gain of -5 W (green shades): 3.72 kWh.

CONCLUSION

The conducted analysis of heat losses and heat gains through the triple-layer energy-efficient window in various climatic conditions of Uzbekistan for January and July, based on data from 2000 to 2023 and the long-term average maximum and minimum temperatures, provides important insights for assessing its efficiency throughout the year.

Window efficiency during the cold period (October – March): In January and February, when minimum temperatures in the eastern and mountainous regions of Uzbekistan can drop below -10°C, the relevance of energy-saving windows is particularly high. During these months, the outdoor temperature is significantly lower than the indoor temperature, and heat loss through the windows becomes a critical factor. The proposed triple-layer window, with its insulating properties, significantly reduces heat losses, allowing for comfortable indoor temperatures while reducing heating costs. The most pronounced effect is observed in regions with extremely low winter temperatures, such as the eastern regions and mountainous areas of Uzbekistan. During the winter period, the window provides substantial energy savings, which is especially important in regions with harsh climates.

Window efficiency during the warm period (April – September): In the summer months, particularly in July and August, maximum temperatures in Uzbekistan can exceed 45°C. During this time, the primary function of windows is to prevent excessive heat from entering the building to avoid overheating and to reduce the load on air conditioning systems. The triple-layer window design effectively blocks solar heat and hot outdoor air, thereby reducing energy consumption for cooling. This is especially important for the central and southern regions of the country, as well as for the Fergana Valley, where summer temperatures reach their peak. During the summer period, the window helps maintain a stable and comfortable indoor temperature, minimizing air conditioning expenses.

Heat losses in January (Figure 3 and Figure 5): In January, the most significant heat losses are observed in the eastern and mountainous regions of Uzbekistan, where winter temperatures are particularly low. These areas are characterized by substantial heat loss through windows, which increases the demand on heating systems.

In the central and southern parts of the country, where winter temperatures are more moderate, heat losses through windows are less significant, but the use of triple-layer windows still helps retain heat inside the buildings.

The scientific significance of these results lies in the confirmation that the triple-layer window effectively reduces heat losses in cold climatic conditions, minimizing energy costs for maintaining comfortable indoor temperatures during the winter.

Heat gains in July (Figure 4 and Figure 6): In July, when outdoor temperatures reach their maximum, the triple-layer energy-efficient window demonstrates high effectiveness in preventing indoor overheating. In zones with heat gain (negative values, especially in central and southeastern regions), the window blocks a significant amount of heat, reducing the load on air conditioning systems.

In some cases, even when the outdoor temperature may be lower than the indoor temperature (e.g., at night), the window effectively retains heat inside the building, which is particularly important for maintaining a stable indoor climate during nighttime.

These data demonstrate that, under the extreme high temperatures typical of Uzbekistan in the summer, the proposed window design contributes significantly to reducing energy consumption for cooling and maintaining a comfortable indoor environment.

Energy efficiency throughout the year: A combined analysis of maximum and minimum temperatures shows that in the summer, the windows protect indoor spaces from excessive heat, while in the winter, they prevent heat loss. This makes the proposed design especially effective in Uzbekistan's contrasting climate, where the difference between winter and summer temperatures can be significant.

Practical significance: The maps presented in *Figure 3, Figure 4, Figure 5, and Figure 6* can be used for planning energy-saving measures in construction, selecting optimal designs and materials for windows, as well as forecasting energy consumption in residential and commercial buildings. The implementation of such triple-layer window solutions will contribute to the overall reduction of energy costs, improve living comfort, and enhance the energy efficiency of buildings both in winter and summer. Additionally, its use could have a significant impact on energy savings in the construction and operation of buildings in various climatic conditions.

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