

Energy Efficiency of Modernization of Translucent Building Envelope Structures

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Abstract

The article focuses on determining the energy efficiency of the translucent structures of building envelope (TSBE) use with different lighting and thermal parameters. The expediency of replacing TSBE with more modern ones with higher thermal resistance and lower solar radiations relative penetration coefficient (SRRPC) is considered. The comparison was made taking into account the influence of TSBE parameters on electricity consumption in the office premises on the compensation of heat energy losses, as well as its savings due to the receipt of solar radiation during the heating period, the removal of excess heat during the cooling period and energy savings through the use of daylight during a year. It was found that despite the smaller glazing area and light-transmitting characteristics of configuration No. 3 (profile Veka Softline 82 with triple-glazed window 4Solar-16Ar-4-12Ar-4i), electricity savings when changing the configuration of TSBE No. 1 to No. 3 leads to energy savings of 31.7 kWh/yr with the TSBE area of 0.5 m² to 419.5 kWh/yr at 6 m², and when replacing configuration No2 by No3 – from 24.7 ($S_{TSBE} = 0.5 \text{ m}^2$) up to 397.2 ($S_{TSBE} = 6 \text{ m}^2$). This makes it possible to determine the energy and economic feasibility of TSBE modernization by installing metal-plastic structures with different lighting and thermal parameters.

Keywords: TSBE; windows energy efficiency; composite index of glazing rooms; energy efficiency of daylighting.

1. Introduction

The lighting industry consumes about 2650 TWh of electricity per year ($\approx 19\%$ of global production) exclusively for lighting, exceeding its total production by all nuclear power plants in the world [1]. According to the State Inspectorate for Energy Supervision of Ukraine, the cost of electricity for artificial lighting in the integrated energy system of Ukraine is about 2.4 million kWh (10-12% of total electricity consumption) [2]. At the same time, it is possible to almost half electricity costs without deteriorating lighting conditions by improving the means and methods of lighting, reconstruction of existing lighting installations and the organization of its proper operation [3].

Despite the significant improvement in the energy consumption characteristics of devices and energy saving of buildings, an important aspect of energy efficiency is the use of renewable energy sources. In the case of the lighting industry, it is the use of daylight. The simplest design for daylighting is TSBE. Despite its important functional role, in terms of daylight, the parameters that affect its effectiveness are insufficiently studied.

2. Formulation of the problem

Despite a significant amount of research in the daylighting field, the issue of energy efficiency of TSBE replacement with modern ones, taking into account not only thermal parameters, but also lighting parameters, is not sufficiently disclosed. This determines the study relevance of changes in the total energy balance of the room depending on the type of profile and TSBE glazing.

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The study purpose is to determine the impact on the energy balance of the premises of different types of translucent external enclosing structures and to establish the energy efficiency of their replacement with modern ones.

3. Analysis of recent research and publications

Research on TSBE energy efficiency was conducted not only by Ukrainian researchers, such as: Martynov V.L. [3], [4], Halinska T.A. [5]-[8], Kolesnyk Y.S. [9], [10], Sopilniak A.M. [11], as well as foreign: Jennifer L. [12], Ghisi E. and Tinker J. [13], [14] etc.

In particular, Martinov V.L. in [3], [4] described a computerized way to optimize the orientation of energy-efficient face-shaped buildings (taking into account the geometric shape of the building, area and location of windows) by minimizing the thermal balance of building envelopes with the environment during the heating period with observance of norms of illumination and insolation.

The studies of Mason M et al. [15], [16] described a methodology of estimations for more precise calculation of heat flow through the windows and provide visual comfort to the occupants. They obtained the appropriate formulas based on data used by industry in glass manufacturing technologies. As a result, some empirical adjustment factors have been introduced and are publicly available at the Center of Glass.

Regulatory and legal framework analysis, existing buildings, approaches to the energy efficiency of buildings during the design, construction, reconstruction and operation, developed recommendations for improving the quality and resource efficiency of buildings by ensuring their energy efficiency conducted in [17]. In particular, the authors point out that houses can be designed to capture the low-altitude rays of the winter sun to heat and use window protection to block high altitudes in the summer sun. The aim is not to get the maximum possible amount of solar energy at any cost, but to keep the minimum energy demand for heating to a minimum [18].

The research [19] highlights the problem of improving energy efficiency in the construction industry. The comparison of heat transfer indices for building envelope (BE) of Ukraine and those close to the climatic conditions of Finland was carried out. In the study [20] authors cite the main trends in improving the design of modern windows. The regulatory requirements for the production of modern energy efficient windows have been studied. Prospects for the introduction of innovative energy efficient window systems are revealed.

In [21]-[25] the results of experimental research into a heat transfer of various double-glazed windows and window profiles are given. For this purpose, an experimental measuring complex was created to study the thermal insulation properties of the building's TSBE. The authors first experimentally discovered the thermophysical effect, which is to reverse the direction of heat flow on the outer surface of the glass and window profile, which is associated with the non-stationary heat transfer process and the influence of daytime scattered solar radiation. As a result, the optimal type of double-glazed windows and the distance between the panes, which can be recommended for installation in a window opening and for use in passive type houses, have been determined.

The article [26] analyzed the influence of the installation of different types of windows on the thermal energy condition of a mass building for different window to wall ratios (WWR) using dynamic grid models created on the basis of the software product EnergyPlus. For northern and southern orientations, energy consumption was determined and analyzed when heating a building with energy-saving windows with selective spraying and/or filling the chambers with inert gas, the transmission characteristics of solar heat supply which meet and expand the limits of current standards in Ukraine. The influence of changes in environmental parameters during the heating period on the indicators of thermal comfort and the average radiation temperature for different TSBE glazing configurations was studied. The range of changes in the average radiation temperature and room temperature for the heating period is estimated. Recommendations were given for regulating changes in indoor air temperature to ensure the appropriate category of the building for comfortable conditions.

4. Methodology

The amount of saved electricity due to the TSBE use was determined by equation (1)

$$W_{\text{TSBE}} = S_{\text{R}} \times p_{\text{AL}} \times DA_{300} - (\omega_{\text{H}} - Q_{\text{H}}) / COP - Q_{\text{C}}^{\text{MAX}} / ERR, \text{ kWh/yr}, \quad (1)$$

where S_{R} is room's floor area, m^2 ; p_{AL} is specific power of artificial lighting, kWh/m^2 ; DA_{300} is daylight autonomy (at illumination in 300 lx), h/yr; ω_{H} is thermal energy losses in the heating period, kWh/yr ; Q_{H} is solar radiation gaining

through the TSBE during the heating period kWh/yr; COP is coefficient of performance (kW/kW); Q_C^{MAX} is the highest value of heat solar radiation gaining into the working space through the TSBE glazing during the cooling period kWh/yr; EER is energy efficiency ratio (kW/kW).

Since the daylight factor (DF) is influenced by the location of window openings in the BE in order to compare window openings of different shapes and areas, their centers must be at one point W (Fig. 1).



Fig.1. Appearance of a fencing structure with a rectangular TSBE area a) 1 m²; b) 6 m².

The thickness of foaming (l_{FF}) was determined by the algorithm presented in [27].

Daylight autonomy (DA) can be defined in specialized software Relux, for any location. According to [28], for arbitrary sizes of premises and the TSBE area, in Ternopil, DA_{300} was determined by equation (2) with a standard deviation of 82.6 and a determination coefficient of 0.979

$$DA_{300} = -0.227 \cdot I_{GLR}^2 + 45.854 \cdot I_{GLR} - 420.953, \text{ h/yr}, \quad (2)$$

where I_{GLR} is composite room glazing index (CRGI) [29], %.

According to [28], [29] the composite room glazing index (CRGI) is defined by the equation

$$I_{GLR} = S_{GL} / S_{WS} \cdot \sqrt{2 \cdot l_{WP} / d_{WP}} \cdot 100, \% \quad (3)$$

where S_{GL} is TSBE glazing area, m² [28]; S_{WS} is working surface area ($S_{WS} = 2 \times l_{WP} \times d_{WP}$), m²; d_{WP} , l_{WP} are the coordinates of the working point (WP) location in the room (Fig. 2), m.

Based on these data, as well as the dependence of the CRGI on DF (3), according to [29] it is possible to determine the required TSBE glazing area.

Thermal energy losses were defined as the difference between losses due to TSBE and losses due to the same area of BE. Heat losses due to TSBE, kWh/yr with the option of regular heating during non-working hours, according to SNiP II-4-79, are determined by the equation (4)

$$\omega_H = \left(10^{-3} \cdot 1.1 \cdot (1.3 + \eta) \cdot (1/R_{TSBE} - 1/R_R) \cdot z_H \cdot S_{TSBE} \times \right. \\ \left. \times [(t - t_{AV.OUTD}) \cdot T + (t_{ST} - t_{AV.OUTD}) \cdot (8760 - T)] \right) / 365, \text{ kWh/yr}, \quad (4)$$

where 1.1 is the coefficient, which takes into account heat losses in heating systems [30], rel. units.; 1.3 is the coefficient which takes into account heat losses on heating the external air entering through TSBE [30], rel. units; η is the coefficient which takes into account the additional heat losses through the BE [31, Append. 5, Table 2] (Table 1), rel. units; R_{TSBE} is thermal resistance of TSBE, (m²×°C)/W; R_R is prescribed by the regulations BE thermal resistance value [32], (m²×°C)/W; $t_{AV.OUTD}$ is average outdoor temperature for the heating period (DSTU B EN 15251), °C; t is the estimated winter air temperature indoors during working hours [31], °C; T is annual working hours, taken in 2150 hours when working in one shift, 4300 hours when working in two shifts, 6500 hours when working in three shifts, h/year; S_{TSBE} is TSBE area in ceiling or BE, m²; z_{HP} is the duration of the heating period for residential premises (DSTU-N B V.1.1-27 2010), days; t_{ST} is the temperature inside the room, in standby heating mode [33], °C.

For calculation of the thermal insulation of TSBE properties and radiation heat inputs through their transparent part, it is necessary to know what TSBE part is taken up by glazing (glass), profile and foaming. These results were obtained as a result of the calculation performed by the algorithm described in [27].

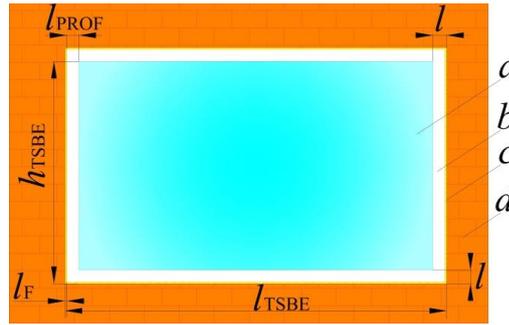


Fig. 2. Schematic representation of a rectangular TSBE: a) glazing b) profile; c) foaming; d) building envelope [34].

Three TSBE configurations were chosen for calculations: No. 1 – wooden profile with double glazing (Fig. 3a) [35]; No. 2 – profile Veka PROLINE [36] with double-glazed window 4-16-4 (Fig. 3b) [37]; No. 3 – profile Veka Softline 82 [38] with triple-glazed window 4Solar-16Ar-4-12Ar-4i (Fig. 3c) [39].



Fig. 3. Selected window profiles.

The parameters of the selected profile, double-glazed windows and foaming (foam) are given in Table 1.

Table 1. Selected profiles, glazing and foaming parameters [35]-[39].

Name	Thermal resistance, (m ² ×C)/W
Paired wooden profile	0.44
Profile glass	0.31
Profile Veka PROLINE	0.8
Profile Veka Softline 82	1.06
Double-glazed window 4-16-4	0.32
Triple-glazed window 4Solar-16Ar-4-12Ar-4i	1.14
Foam Ceresit TS 62	2.73

The inflow of solar radiation through the TSBE during the heating period (Q_H), for the facades of the house, oriented in four directions – south (S), north (N), west (W) and east (E), were determined, according to [36], by the equation (5)

$$Q_H = \varepsilon_{GL} \cdot (S_{GL,S} \cdot I_S + S_{GL,N} \cdot I_N + S_{GL,W} \cdot I_W + S_{GL,E} \cdot I_E), \text{ kWh/yr}, \quad (5)$$

where $S_{GL,S}$, $S_{GL,N}$, $S_{GL,W}$, $S_{GL,E}$ are the area of glazing in the facade of the building, oriented to the south, north, west and east, respectively, m²; I_S , I_N , I_W , I_E are the average value of solar radiation during the heating period, directed to the vertical surface under cloudy conditions, oriented to the south, north, west and east, respectively [36, Table 2], kWh/m².

The maximum value of solar radiation heat input to the working area during the cooling period is determined by the maximum value of the total solar radiation that enters the TSBE surface during the day and is calculated, according to [30], by equation

$$Q_C^{\text{MAX}} = (Q_{\text{DIR,R.VII}}^{\text{MAX}} + Q_{\text{DIF,R.VII}}^{\text{MAX}}) \cdot \varepsilon_{GL} \cdot \tau_2 \cdot \tau_3 \cdot \tau_4 \cdot \bar{s}_{GL} \cdot S_{\text{TSBE}} \cdot T_C \cdot 10^{-3}, \text{ kWh/yr}, \quad (6)$$

where $Q_{\text{DIR,R.VII}}^{\text{MAX}}$ is the highest value of direct solar radiation in July at the time of a cloudless sky on a vertical surface by a certain orientation [32], W/m²; $Q_{\text{DIF,R.VII}}^{\text{MAX}}$ is the highest value of diffuse solar radiation in July in the cloudless sky

on the vertical surface of a certain orientation (DSTU-N B V.1.1-27 2010), W/m^2 ; τ_2 is coefficient that takes into account the light loss in the opaque covers (window profile) TSBE [41], rel. un.; τ_3 is coefficient that takes into account the decreasing of heat gains due to a glass pollution [31, Append. 12, Table 5], rel. un.; τ_4 is coefficient of heat transmission of shading devices, rel. un. [41]; T_C is duration of the cooling system work during cooling period [40], h/yr.

According to [43], the average COP value for modern ducted air conditioners is 3.41, and the EER is 2.73. Thermal resistance for the first temperature zone of Ukraine is $R_R=3.3 \text{ m}^2 \times \text{C}/\text{W}$. Equations for determining the energy savings by using of the TSBE, for the Ternopil city, according to [42]:

– South orientation

$$W_{TSBE} = S_R \cdot p_{AL} \cdot DA_{300} - S_{TSBE.S} \cdot ((34.097 / R_{TSBE} - 10.333) - 19.74 \cdot \bar{s}_{GL} \cdot \varepsilon_{GL}), \text{ kWh/yr} \quad (7)$$

– North orientation

$$W_{TSBE} = S_R \cdot p_{AL} \cdot DA_{300} - S_{TSBE.S} \cdot ((36.720 / R_{TSBE} - 11.127) - 12.18 \cdot \bar{s}_{GL} \cdot \varepsilon_{GL}), \text{ kWh/yr}; \quad (8)$$

– West orientation

$$W_{TSBE} = S_R \cdot p_{AR} \cdot DA_{300} - S_{TSBE.W} \cdot ((35.409 / R_{TSBE} - 10.730) + 26.12 \cdot \bar{s}_{GL} \cdot \varepsilon_{GL}), \text{ kWh/yr}; \quad (9)$$

– East orientation

$$W_{TSBE} = S_E \cdot p_{AL} \cdot DA_{300} - S_{TSBE.E} \cdot ((36.720 / R_{TSBE} - 11.127) + 27.12 \cdot \bar{s}_{GL} \cdot \varepsilon_{GL}), \text{ kWh/yr}. \quad (10)$$

5. Results of the research

The dependence of heat loss on the value TSBE thermal resistance was carried out according to the method presented in [44]. Premises whose parameters meet the requirements of current regulations of Ukraine were analyzed [32], [44], [45].

Currently, a large number of free, high-precision programs for daylighting calculating have been developed. Calculations of the daylight autonomy (DA) were performed in the Relux program, the reliability of which was tested experimentally in [46], [47]. The calculations were performed according to the algorithm given in [28]. Calculations were performed for a room with dimensions (width×depth×height) 6×5×3 m.

As a result, the dependence of the annual DA_{300} (for prescribed by regulators illumination of 300 lx) for the Ternopil city was obtained (Fig. 4).

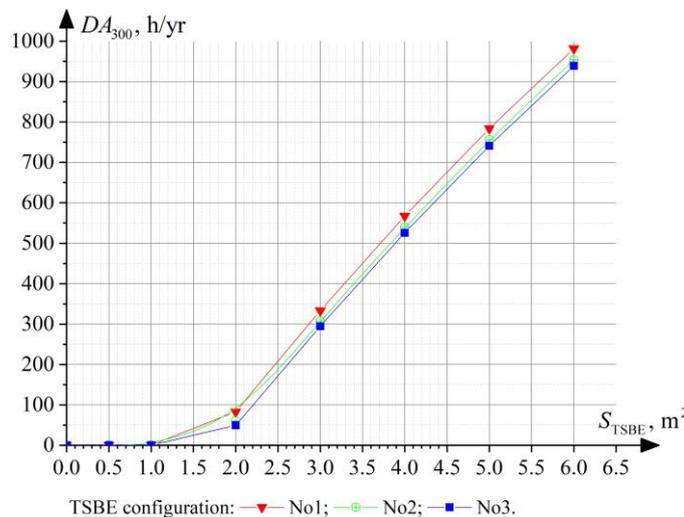


Fig. 4. Total annual DA_{300} at the reference point, h/yr.

As can be seen from Fig. 4, the largest DA_{300} value is provided by TSBE with the largest SRRPC (configuration No.1). For the TSBE configuration No.2, with the TSBE area of 6 m², the DA_{300} value is 1.6% higher than in the configuration No.3. For the TSBE configuration No.1, with the TSBE area of 6 m², the DA_{300} value is 2.9% higher than in the configuration No.2 and 5% higher than in the configuration No.3.

The integrated thermal resistance calculation results for the rectangular metal-plastic windows mounted in the slot of the main bearing opaque TSBE of different area, at the coordination index equal to 1, are given in Table 4.

Table 4. Integral thermal resistance (R_{TSBE}) of different area TSBE with different types of windows glazing, profiles, ($m^2 \times C$)/W.

TSBE option	TSBE area, m^2						
	0.5	1	2	3	4	5	6
No.1	0.355	0.341	0.332	0.329	0.327	0.325	0.325
No.2	0.424	0.384	0.365	0.357	0.352	0.349	0.347
No.3	1.147	1.145	1.144	1.145	1.145	1.146	1.146

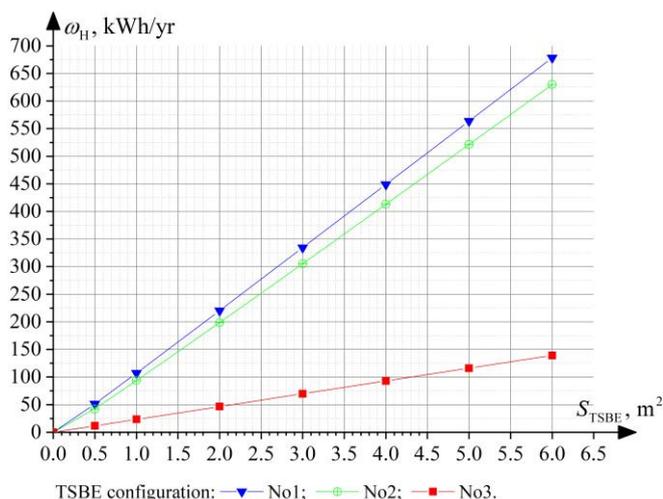


Fig. 5. Heat losses during the heating period (ω_H) for the climatic zone I (Ternopil city), kWh/yr

The heating system operating temperature, according to [31], is 20°C . The cooling system operating temperature is 26°C . All calculations were performed for the Ternopil city ($49^\circ 34' \text{N}$ $25^\circ 36' \text{E}$). The results of electricity consumption for heating calculations are shown in Fig. 5.

As can be seen from Fig. 5, the largest losses of thermal energy are observed in the TSBE configuration No.1. For the TSBE configuration No.2, with the TSBE area of 6 m^2 , heat losses during the heating period are lower by 7.2%, than with the configuration No.1. For the TSBE configuration No.3, with the TSBE area of 6 m^2 , heat losses during the heating period are lower by 77.9%, than with the configuration No.2 and by 79.5% than with No.2.

The results of the solar radiation receipts calculation through the TSBE during the heating period, when changing the TSBE area for its various configurations, are shown in Fig. 6.

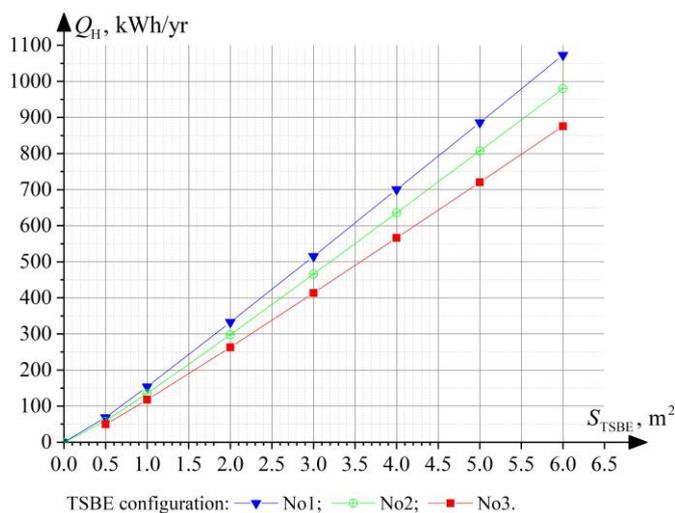


Fig. 6. The solar radiation flow through TSBE during the heating period dependence on the TSBE area for different TSBE configurations, for Ternopil city.

As can be seen from Fig. 6, the largest inflows of thermal energy during the heating period are observed at TSBE with the configuration No.1. For the TSBE configuration No.2, with the TSBE area of 6 m², the heat input during the heating period is greater by 9.5%, than with the configuration No.2. For the TSBE configuration No.1, with 6 m² area, the value is greater by 11.9% than with the configuration No.2 and by 22.5% than with No.3.

The maximum value of radiation heat input to the working area during the cooling period results of calculating for the Ternopil city are shown in Fig. 7.

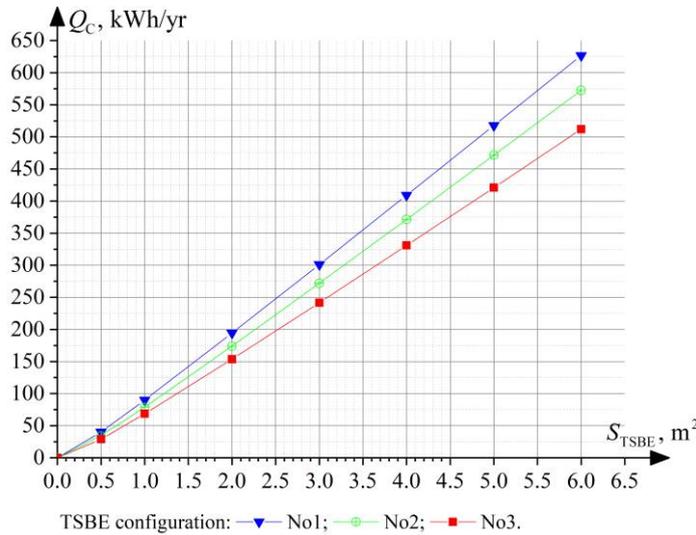


Fig. 7. The maximum value of radiation heat inputs through TSBE during the cooling period dependence on the TSBE area for the Ternopil city.

In terms of penetration of solar thermal energy TSBE configurations differ in the SRRPC values and the glazing area. That's why, in percentage terms, the difference in excess heat during the cooling period between them is the same as the heat during the heating. However, in absolute units, the values differ. Thus, when using TSBE with configuration No.2, excess heat is less than in No.1 by 54.274 kWh/yr, with No.3 by 60.662 kWh/yr than in No.2 and by 114.936 kWh/yr than in No.1. Revenues during the heating period with configuration No.2 are lower by 92.880 kWh/yr, and in No.3 are lower by 103.811 than with No.2 and by 196.691 less in No.1. That is, as we see from Fig. 6 and Fig. 7 receipts during the heating period are greater than excess heat receipts during the cooling period.

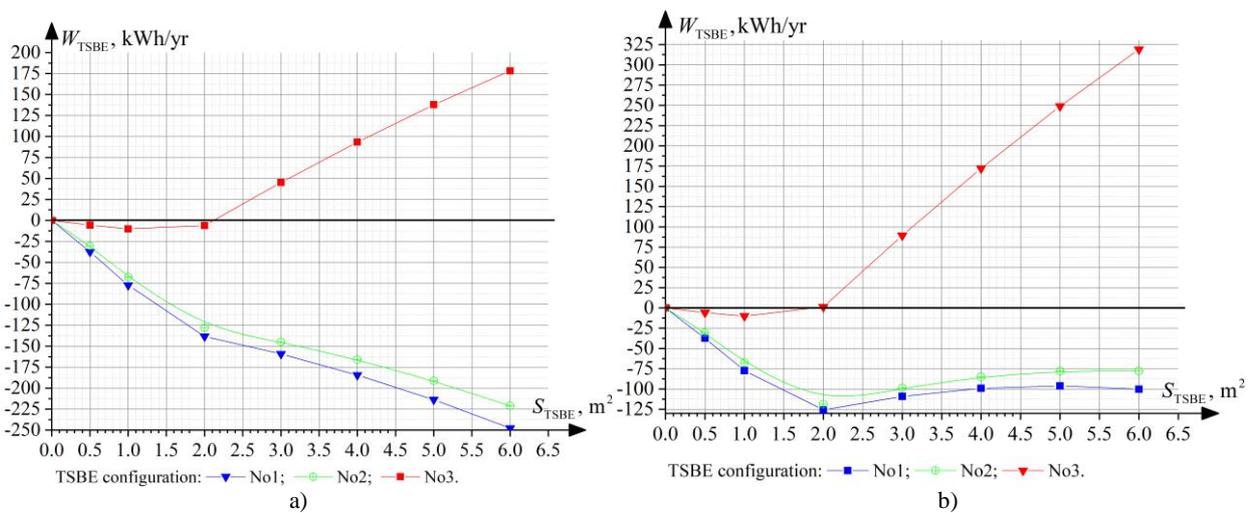


Fig. 8. Energy savings due to the TSBE use at the specific power of the artificial lighting: a) 8 W/m²; b) 13 W/m².

Modern HVAC cooling devices use two parameters to assess energy efficiency: coefficient of performance (*COP*) and energy efficiency ratio (*EER*). *COP* is the ratio of the declared power for heating the air to the nominal

power input for space heating, which provides heating under standard test conditions. *EER* is the ratio of the cooling capacity to the power input under standard test conditions. These two parameters are not the same. According to [43], the average *COP* value for Neoclima duct air conditioners [48] is 3.41 kW/kW, and the average *EER* value is 2.73 kW/kW. That is, the electricity consumed to remove 1 kWh of heat energy during the cooling period is by 25% greater than to compensate of 1 kWh of heat loss during the heating period.

According to [41, p. 22], the maximum specific power of artificial lighting to provide illumination of 300 lx, depending on the index of the room ranges from 8 to 13 W/m². Therefore, we consider options with these two values of the specific power of the artificial lighting system to compare the energy efficiency of TSBE replacement (Fig. 8).

As can be seen from Fig. 8, the use of modern TSBE (No.3) with an area of more than 2 m² allows reducing the total electricity consumption in the room to ensure prescribed by regulators climatic requirements. While the use of TSBE with configurations No.1 and No.2 leads to an increase in total electricity consumption.

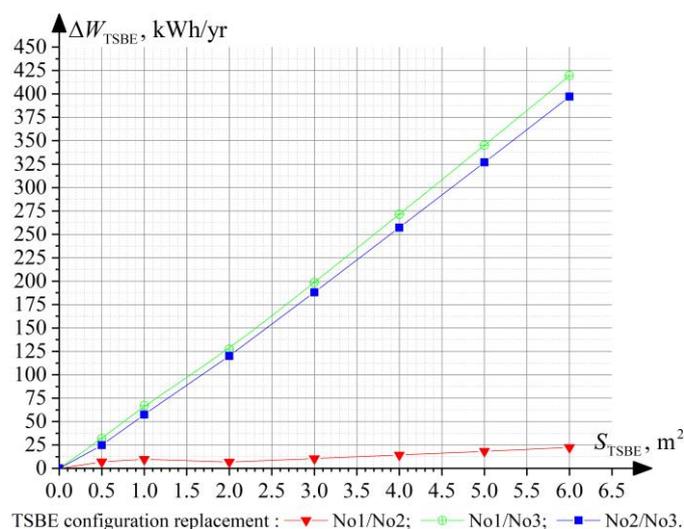


Fig. 9. Dependence of electricity savings due to the TSBE configuration replacement No.1 by No.2, No.1 by No.3 and No.2 by No.3 on the TSBE area.

Since daylight is a mandatory factor in terms of compliance with regulatory requirements and ensuring standardized sanitary and hygienic indicators, TSBE must be available in the premises for various purposes.

To determine the feasibility of modernizing TSBE by replacing them with more modern ones, consider the energy efficiency of TSBE replacement (ΔW_{TSBE}) with the configuration No.1 by No.2 and No.3 and, No.2 by No.3, which is defined as the difference between energy consumption at the corresponding TSBE configurations (Fig. 9).

As can be seen from Fig. 9, the TSBE modernization with configurations No1 and No2 by No3 allows reducing electricity consumption by 2.898 times and 2.604 times, respectively. While changing the TSBE configuration No1 to No2 leads to a decrease in electricity consumption only by 1.103 times.

6. Conclusion

Despite the slight improvement of the thermal insulation characteristics of the Veka PROLINE profile with double glazing 4-16-4 in comparison with the paired wooden profile with double glazing, their energy efficiency is almost the same. From the energy saving point of view, there is no sense in replacing the TSBE configuration No.1 by No.2, as the reduction in electricity consumption is 1.103 times with the TSBE area of 6 m², and when the area is reduced it will be reducing as well.

Although the TSBE configuration No.3 has a smaller relative glazing area and worse light transmission characteristics than the configuration No.1, replacing the latter with No.3 leads to energy savings, from 31.699 kWh/yr at the TSBE area of 0.5 m² to 419.508 kWh/yr at 6 m². Replacement of the configuration No.2 by No.3 leads to energy savings, from 24.731 at 0.5 m² to 397.146 at the TSBE area of 6 m². According to the presented data, TSBE modernization with the use of modern profile and triple-glazed windows allows not only reducing electricity consumption, but also eliminating heat loss during the heating period and its excess during the cooling period by reducing the duration of artificial lighting and heat gains during the heating period.

The replacement of obsolete TSBE with both wooden and metal-plastic profile with low thermal resistance to modern leads to significant energy savings and the larger TSBE area leads to the greater energy savings, which is why research in this area is relevant and requires more detailed study of the parameters that affect the TSBE energy-saving properties.

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Енергоефективність модернізації світлопрозорих зовнішніх огорожувальних конструкцій

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Анотація

Стаття присвячена визначенню енергоефективності використання світлопрозорих зовнішніх огорожувальних конструкцій (СЗОК) з різними світлотехнічними та теплотехнічними параметрами. Також розглянуто доцільність заміни СЗОК на сучасніші з більшим термічним опором та меншим коефіцієнтом відносного проникнення сонячної радіації (КВПСР). Порівняння проведено при врахуванні впливу параметрів СЗОК на споживання електроенергії в офісному приміщенні на компенсацію втрат теплової енергії, а також її економію за рахунок надходження сонячного випромінювання протягом опалювального періоду, видаленням надлишкового тепла протягом охолоджувального періоду та економію електроенергії за рахунок використання денного світла. Встановлено, що попри меншу площу застосування і світлопропускаючі характеристики варіанту №3 (профіль Veka Softline 82 з склопакетом 4Solar-16Ar-4-12Ar-4i), економія при заміні конфігурації СЗОК №1 на №3 призводить до економії енергії від 31,7 (кВт×год)/рік при площі СЗОК 0,5 м² до 419,5 (кВт×год)/рік при 6 м², а при заміні варіанту №2 на №3 – від 24,7 при 0,5 м² до 397,2 при площі СЗОК 6 м². Це дає можливість визначити енергетичну та економічну доцільність модернізації СЗОК шляхом встановлення металопластикових конструкцій з різними світлотехнічними та теплотехнічними параметрами.

Ключові слова: СЗОК; енергоефективність вікон; зведений індекс застосування приміщення; енергоефективність природного освітлення.