UDC 662.997+697.7 https://doi.org/10.20998/2074-272X.2021.3.10

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INVESTIGATION OF ORIENTATION IMPACT ON ELECTRICAL POWER OF BIFACIAL SOLAR ELEMENTS

Purpose. *To develop the integrated mathematical model for definition of bifacial solar element rational power operation in the various operation conditions caused by orientation of solar panels and power influence.* ***Methodology.*** *We have proposed the method of definition of bifacial solar elements irradiation and temperature mode and also electric power production at various orientation of panels.* ***Results****. We have made analytical investigations of temperature operation conditions of solar elements and their influence on electrical power for various panels orientation in space. Features of irradiation of the forward and back parts of solar panels, conditions of a temperature operating mode and its influence on electric power production are shown. Possibilities of rational conditions of spatial panels orientation are considered.* ***Originality****. We have suggested and proved the model of definition bifacial irradiation solar panels and thermal conditions of electric power production and also rational conditions of spatial orientation of panels.* ***Practical value****. The developed by us methodology as well as results of its application, allows to choose rational architecture of a solar power station with high efficiency.* References 13, figures 5.
Key words: **bifacial solar photo panels, irradiation of solar panels, orientation of solar cells, power generation.**

Розроблений метод аналітичного визначення опромінення, температурного режиму, а також вироблення електроенергії двосторонніх сонячних елементів при різній орієнтації панелей. Створено інтегральну математичну модель для оцінки енергетичного режиму роботи сонячних елементів при змінних кліматичних умовах і просторових настановних характеристик. Проведені аналітичні дослідження роботи сонячних елементів. Показані особливості опромінення передньої й тильної сторін сонячних панелей, умови формування температурного режиму роботи і його впливу на вироблення електроенергії. Розглянуто можливості формування раціональних умов просторової орієнтації панелей за фактором електричної продуктивності. Використання запропонованої методики й результатів аналізу, проведених на її основі, дозволяє вибрати раціональну архітектуру сонячної електростанції високої ефективності. Бібл. 13, рис. 5.
Ключові слова: **двосторонні сонячні фотопанелі, опромінення сонячних панелей, орієнтація сонячних елементів, виробництво електроенергії**.

Разработан метод аналитического определения облучения, температурного режима, а также выработки электроэнергии двухсторонних солнечных элементов при различной ориентации панелей. Создана интегральная математическая модель для оценки энергетического режима работы солнечных элементов при переменных климатических условиях и пространственных установочных характеристиках. Проведены аналитические исследования работы солнечных элементов. Показаны особенности облучения передней и тыльной сторон солнечных панелей, условия формирования температурного режима работы и его влияния на выработку электроэнергии. Рассмотрены возможности формирования рациональных условий пространственной ориентации панелей по фактору электрической производительности. Использование предложенной методики и результатов анализа, проведенных на ее основе, позволяет выбрать рациональную архитектуру солнечной электростанции высокой эффективности. Библ. 13, рис. 5.
Ключевые слова: **двухсторонние солнечные фотопанели, облучение солнечных панелей, ориентация солнечных элементов, производство электроэнергии**.

Introduction. Bifacial solar cells (SEs) have emerged as a result of the search for methods for the most efficient use of a valuable semiconductor layer that absorbs solar radiation for power generation [1-4]. Their advantage is the additional irradiation of the absorber from the back of the SE, which is not carried out in conventional one-acial devices. Obviously, the radiation is related to the orientation of the SE relative to its radiation source. Bifacial irradiation affects the energy balance by changing the operating parameters of SE: operating temperature and power generation, which are known to be interdependent [4, 5].

Stimulation of radiation intensity leads to a change in energy balance – not always in the direction of increasing efficiency. This fact imposes restrictions on the applicability of such devices, causing the need for additional measures to change the way the organization of the SE operation.

Analysis of recent research and publications. Considerable attention is paid to the study of temperature conditions of solar elements [3-7]. Existing models for determining the energy performance of solar elements are based on the idea of one-facial frontal irradiation of the device. However, the back side, perceiving the radiant energy, has a corresponding effect on the overall energy balance [3, 4]. Among the various factors influencing the radiation, from the point of view of operating mode control, the geometric, i.e. the spatial location of the solar elements is important. Different options are offered to choose the orientation of bifacial solar panels [8, 9], but they do not have sufficient justification, in particular, the impact of the radiation component on the back of the panel is not taken into account. Therefore, the analysis of the real operating conditions of the solar elements requires a model that describes the features of the absorber irradiation and the influence of the orientation of the SE on energy processes.

Mathematical models used for research include radiation [3, 4, 7, 10, 11] and convective components as external conditions. The latter is usually associated with wind interaction [5, 8]. Both components depend on the orientation of the panel. The description of the influence of the radiation component on the frontal surface can be based on sufficiently reliable model representations [6-8, 11-13].

For the back side, in [4] studies of the effect of reflectivity of different surfaces were conducted. In [3], a dynamic three-layer model of the solar element is proposed, which includes the radiation component of the interaction with the back side. The results showed an increase in temperature in the bifacial panels, taking into account the radiation. But the effect of irradiation in the dynamics of diurnal and seasonal changes in orientation relative to the source is not shown.

The method [10] developed for the conditions of Ukraine can be used for the analytical description of surface irradiation. According to it, the intensity of the radiation flux is determined for the horizontal surface as a function of geographical parameters, seasonality and time of day. Correction R, which specifies the slope and orientation of the surface, which is represented as the ratio of the flux of direct solar radiation, which flows normally on the inclined surface, to the radiation flux on the horizontal surface, is defined as:

$$R=\left(1-\frac{H_d}{H}\right)R_b+\frac{H_d}{H}\cdot\frac{1+\cos\beta}{2}+\frac{1-\cos\beta}{2}\cdot\rho\,, \quad (1)$$

where H_d is the arrival of diffusion radiation on the horizontal surface as part of the integrated radiation on the horizontal surface H; R_b is the ratio of direct solar radiation on the inclined and horizontal surface; β is the angle of inclination of the surface; ρ is the reflectivity of the soil.

This dependence can be applied to the surface on the south side. It takes into account the direct solar radiation (the first term), scattered in the atmosphere one (the second term, which shows which part of the sky is visible from the surface), and reflected from the earth's surface (the third term, which shows the proportion of reflected total radiation). There are no similar methodological provisions for the back side of the surface.

The goal of the work is to develop a method for determining the radiation and energy performance of bifacial solar elements; creation on its basis of the integrated mathematical model concerning studying of an energy mode of operation of SE in various climatic and installation conditions of operation; study of energy modes of SE operation.

A mathematical model. The following terminology is used to formalize the problem of the location of the solar panel. Orientation along the «south-north» (S-N) is realized when the normal to the front (obverse) surface of the solar panel is directed to the south with an azimuth of 0 degrees. Orientation «east-west» (E-W) determines the direction of the normal of the obverse surface to the east.

For the back side of the receiver oriented on the S-N axis, the direct component is absent, respectively, the component of the reflected radiation for the reverse side should not include direct radiation. Thus, for the back side of the surface oriented along the S-N axis, the ratio of radiation fluxes R_r is determined as

$$R_r=\frac{H_d}{H}\left(\frac{1-\cos\beta}{2}+\frac{1+\cos\beta}{2}\rho\right). \quad (2)$$

For surfaces oriented along the E-W axis, the calculation method is the same, but for the surface «east» orientation the azimuth angle γ = + 90°, for «west» γ = –90°. The straight component for the back side appears after noon at the zenith angle $\theta_Z \geq 90-\beta$.

The energy balance of the bifacial SE has its own peculiarities. Irradiation of external surfaces is the same as for a one-facial battery. Radiant energy is absorbed by both the front and back sides of the SE. However, in one-facial SE, the active beam-absorbing surface (absorber) is irradiated only on one side – the front one. The energy supplied to the back side is not involved in the process of electricity production – it is spent on heating the device, including the absorber. In the bifacial SE, the absorber is irradiated on two sides. But the irradiation of the absorber from the back side is characterized by the fact that this side has a special translucent coating to reduce electron-hole recombination of charge carriers. Therefore, the radiation transmission from the back side is less than from the front side. Accordingly, the optical characteristics ($\tau\alpha$), which determine the transmission of the transparent coating and the absorption of the absorber, for the front and back sides are different.

The energy balance equation for bifacial SE can be represented as

$$\begin{aligned}&[H\cdot R\cdot(\tau\alpha)\cdot(1-\eta_{ph})]_a+[H\cdot R\cdot(\tau\alpha)\cdot(1-\eta_{ph})]_r=\\&=U\cdot(T_{ab}-T_a),\end{aligned} \quad (3)$$

where η_{ph} is the coefficient of efficiency of conversion of solar energy into electricity (efficiency); U is the heat loss coefficient; T_{ab} is the absorber temperature; T_a is the outside air temperature; indices: a – the obverse side of the SE; r – the reverse side of the CE.

Usually they try by adjusting to maintain the value of the efficiency η_{ph} on the maximum level of η_{ph} = $\eta_{ph.\max}$. The coefficient $\eta_{ph.\max}$ depends on various factors and, in particular, on temperature. The dependence of $\eta_{ph.\max}$ on the temperature in the region of positive temperatures can be described as follows [12]

$$\eta_{ph.\max}=\eta_{\max ST}\cdot[1+\alpha_p\cdot(T_{ab}-T_{ST})]\,, \quad (4)$$

where $\eta_{\max ST}$ is the efficiency of the solar element at the point of maximum power under standard conditions; α_p is the temperature power factor of the SE, K^{-1}; T_{ST} is the temperature of the solar element under standard conditions.

Under standard conditions they understand the following: the flux density of solar radiation H_{ST} = 1 kW/m^2, the surface temperature of the SE T_{ST} = 25 °C.

For the bifacial element, the efficiency is determined for each of the sides under the same irradiation conditions. At one-facial irradiation of the absorber the equation of energy balance will differ by the absence for the reverse side of the factor of conversion of solar energy into electric energy: $(1-\eta_{ph})_r$.

The solution of the energy equation taking into account the presented dependencies on the temperature of the absorber of bifacial radiation has the form

$$T_{ab} = \frac{[H\cdot R\cdot(\tau\alpha)]_a + [H\cdot R\cdot(\tau\alpha)]_r - (1-\alpha_p T_{ST})\cdot\{K\} + U\cdot T_a}{U+\alpha_p\cdot\{K\}}, \quad (5)$$

where $\{K\} = \sum_{a,r}[H\cdot R\cdot(\tau\alpha)\cdot\eta_{\max ST}]_i$.

The electric power of the SE should be found taking into account its temperature [12]

$$P = P_{rat}\cdot k_{r.e}\frac{H}{H_{ST}}[1+\alpha_p\cdot(T_{ab}-T_{ST})], \quad (6)$$

where P_{rat} is the rated power of the SE under standard conditions; $k_{r.e}$ is the coefficient of reduction of efficiency of the SE.

At one-facial irradiation of the absorber $H = H_a$. At bifacial irradiation, electricity generation is not a linear function of the joint irradiation of the front and rear sides [13]. This factor is taken into account by the coefficient of bifacial efficiency η_e. Therefore, effective irradiation can be represented as

$$H = H_a + H_r\cdot\eta_e = H\cdot R_a + H\cdot R_r\cdot\eta_e. \quad (7)$$

Analysis of the energy mode in different ways of orientation. The research was conducted for the conditions of Ukraine at latitude 46°.

Features of electricity production are due to two factors. The first one is the radiation intensity of the panel. Intensity correlates well with electricity production. Therefore, such a factor can be considered the main one. The second factor is the heating temperature of the absorber, the growth of which reduces the efficiency of the battery and reduces its service life.

Heating of the absorber is characterized by a significantly variable nature of the temperature versus time of day (Fig. 1). With the S-N orientation, the temperature rises smoothly in the morning and decreases in the afternoon. The view of the dependence curves throughout the year and for different angles of inclination is symmetrical with respect to noon time. The temperature of the absorber in summer, as well as performance, largely depends on the angle of inclination, and in winter there is almost no such effect.

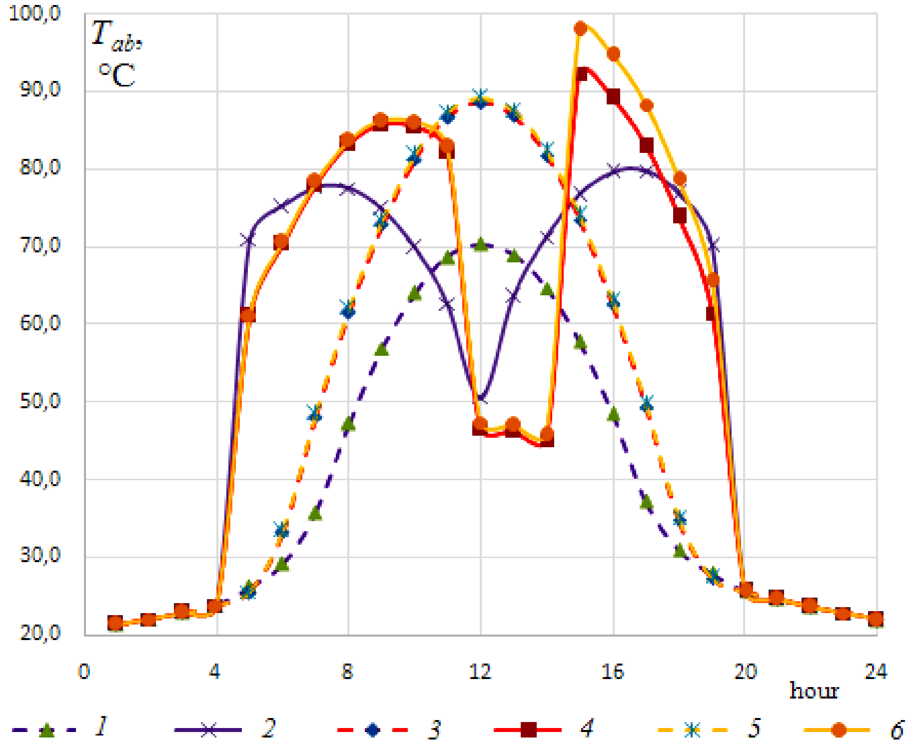

Fig. 1. Daytime thermogram of the absorber in the summer for various orientations, angles of inclination and types of the SE (one-facial – 1s, bifacial – 2s):
1 – S-N,90°,2s; 2 – E-W,90°,2s; 3 – S-N,45°,2s; 4 – E-W,45°,2s; 5 – S-N, 45°,1s; 6 – E-W,45°,1s

At E-W orientation change of temperature during the day is more difficult. Symmetry relative to noon is observed only in summer – for the vertical location of the panel. The type of temperature curves differs by a much larger integral filling of the graphical field in the morning and evening periods and the presence of a failure at noon, compared with the S-N orientation. This is due to the features of the panel irradiation.

The general trend determined by the analysis results is an increase in temperature with decreasing angle of inclination. In summer, when the temperature of the absorber is highest, its level exceeds that normally recommended for the SE (45-50 °C), and reaches a high value (in our example 94 °C).

Comparison of temperature modes of bifacial and one-acial panels shows (Fig. 1) that the heating levels of the absorber in the most heat-stressed period (summer) in both versions are almost the same. However, with the E-W orientation in the afternoon, the one-facial SE heats up more. This is due to the presence of excess heat with limited use of solar energy to generate electricity.

The similar heating temperatures of the absorber in the considered variants are explained by a small share of irradiation of the side of the SE, which is in the shade

(Fig. 2). Therefore, the front surface is decisive in the formation of the temperature of the absorber, both for one-facial and bifacial panels. The patterns of irradiation change are similar for angles of 90° and 45°, but the maximum value in the latter case is greater, although the irradiation intensity of the back panel is less.

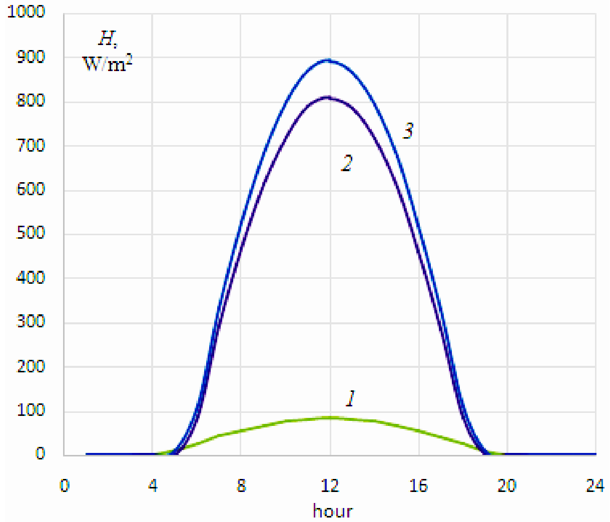

Fig. 2. Radiation flux density on the SE at S-N orientation and angle of inclination 45°
(direction of the sides: *1* – north; *2* – south; *3* – total)

Irradiation of the eastern side at the E-W orientation at the beginning of the day, from 4am to 12am, changes dramatically: there is an increase and subsequent decline with a significant rate (Fig. 3). After noon, the rate of decline decreases. In this part of the day, the irradiation of the reverse side is much less. The picture of the change in the irradiation of the sides at the E-W orientation is a mirror image of the noon time. In the afternoon, for some time the solar radiation does not fall on the back side of the inclined panel, so its total exposure during this period is less. When the zenith angle reaches the value $\theta_Z \geq 90 - \beta$, a straight component appears. For the vertical panel $\theta_Z = 0$ and this transition is almost imperceptible.

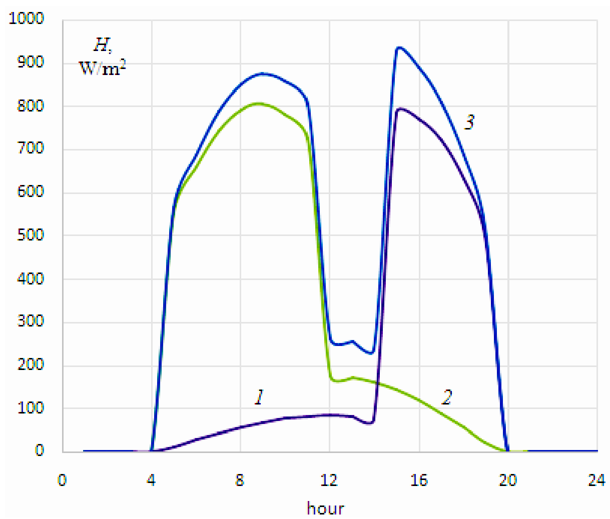

Fig. 3. Radiation flux density on the SE at E-W orientation and angle of inclination 45°
(direction of the sides: *1* – east; *2* – west; *3* – total)

Thus, in the first half of the day the intensity of radiation prevails on the obverse side, in the second one – on the reverse one, which determines the predominant influence of one of the sides on the heating. The total radiation, in contrast to that which falls on each side, is more smoothed, although with a decline in the afternoon.

Figure 4 presents data on the daily development of panel performance in the two considered orientations in the summer. At the direction along the S-N axis, the main time of electricity production is the middle of the day, for E-W – the beginning and end of the day. The same dependencies are characteristic of other periods of the year. The integrated amount of power generation that can be produced in daylight at the S-N orientation is less than at the E-W. Regarding the data in Fig. 4, then in July its level is 1534 W·h/m^2 and 1864 W·h/m^2, respectively.

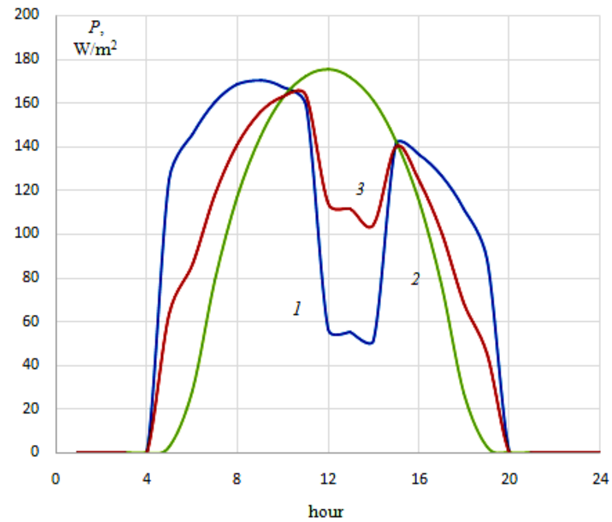

Fig. 4. Power of electric generation of the SE in the development of the day for the summer period at an angle of 45° and orientation:
1 – S-N; *2* – E-W; *3* – (S-N) + (E-W)

The nature of the curves of power change of electric generation of the SE during daylight hours correlates with the irradiation and temperature of the panel (Fig. 2-4).

These features can be opportunistically attractive in practice, and for some consumers this situation may be favorable. However, presented in Fig. 4 data allow to draw an important conclusion for practical application. The alignment of curves 1 and 2 shows that the simultaneous operation of panels with different orientations equalizes the performance of the station during daylight. The total production of electricity by panels of different orientation (curve 3) is characterized by increased uniformity and controlled integrated filling of the daily schedule. For example, the amount of daily total electricity production at the same ratio of the sizes of multidirectional panels for the data in Fig. 4 is 1699 W·h/m^2. Changing the ratio of the number of panels with different orientations allows to increase or decrease daily productivity in the range of levels of components of orientation and manage the noon decline in production. In this way, it is possible to adjust the schedules of production and consumption of energy.

From the analysis of the influence of the SE orientation on productivity it follows that the worst conditions of electricity generation are observed at the direction along the S-N axis and the angle of inclination of 90°. The E-W orientation is best at different angles. The effect of the slope on productivity in the summer is manifested to a large extent only for the installation of the SE on the S-N axis. Electrical performance increases with decreasing slope. In the period from September to April, the efficiency of the SE depends little on the installation angle. During this period, the main influence is the orientation of the SE.

Given the different degree of dependence of the SE productivity on the main parameters and the seasonality of the determinants, the most informative is the consideration of the SE productivity on the total annual indicator.

Figure 5 presents data on electricity generation during the year for the considered four options for installation of the SE. As it can be see, the best option is with the orientation on the E-W axis, the worst one – on the S-N axis. Variants with orientations on the E-W axis, an angle of inclination of 90°, and on the S-N axis, an angle of inclination of 45° are close in efficiency.

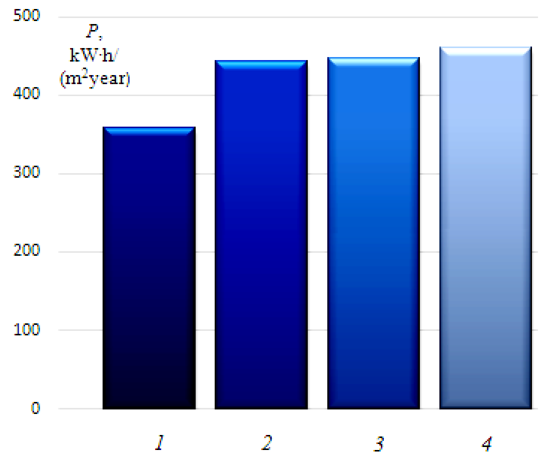

Fig. 5. Annual electricity production depending on the orientation and angle of inclination of the SE:
1 – S-N, 90°; *2* – E-W, 90°; *3* – S-N, 45°; *4* – E-W, 45°

Conclusions.

A method for determining the bifacial irradiation of solar elements has been developed, which has been used to create an integrated mathematical model of the energy mode of SE operation depending on its spatial location. The model allows to carry out more exact, in comparison with existing methods, the analysis of efficiency of operation of the SE at various ways of orientation and to create rational architecture of power plant.

According to the results of the analytical study it is shown that:

1. In summer, the temperature of the SE is almost twice that of the usually recommended (45-50 °C). The heating levels of the absorber of bifacial and one-facial panels are almost the same. However, at the E-W orientation in the afternoon, the one-facial SE heats up more. This is due to the presence of excess heat with limited use of solar energy to generate electricity.

2. The use of bifacial photo panel for all ways of orientation is positive for electrical performance. The greatest effect from the bifacial irradiation of the solar panel can be obtained by directing on the E-W axis. As the angle of inclination decreases beginning from the level of 90°, the total exposure of the panel increases. The dependence of the annual production of electricity on the angle of inclination is most pronounced for the S-N orientation, and for angles of 90° and 45° the difference reaches 26 %. The difference in annual production between the E-W and S-N orientations at the angle of inclination of 45° is small and is about 3 %.

At the angle of 90° and at the E-W direction, the annual production is 24 % higher than at the S-N orientation. Meanwhile, at the E-W orientation, the performance of the vertical panel is only 2.6 % worse compared to panels inclined at the angle of 45°. Therefore, such an arrangement is justified if used, for example, for fencing or facade cladding.

3. Combining photo panels with different methods of spatial placement allows to manage the level of electricity production during daylight hours, adjusting the schedules of production and energy consumption. Changing the ratio of the number of panels with different orientations allows to increase or decrease the daily productivity in the range of levels of components of orientation and to manage the level of the noon decline in electricity production.

Conflict of interest. The authors declare no conflict of interest.

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Received 03.04.2021
Accepted 12.05.2021
Published 25.06.2021

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How to cite this article:
Wysochin V.V., Nikulshin V.R., Denysova A.E. Investigation of orientation impact on electrical power of bifacial solar elements. *Electrical Engineering & Electromechanics*, 2021, no. 3, pp. 62-67. doi: https://doi.org/10.20998/2074-272X.2021.3.10.