EURASIAN PHYSICAL TECHNICAL JOURNAL

2026, Volume 23, No. 2 (56)

https://doi.org/10.31489/2026N2/57-66

Received: 21/01/2026 Revised: 26/05/2026 Accepted: 26/06/2026 Published online: 30/06/2026

Original Research Article

**UDC 53.538.9; 629.7.064.56**

# MODELING OUTPUT PERFORMANCE OF BIFACIAL SOLAR CELLS BASED ON SINGLE DIODE MODEL

Rustemov A., Ibraimov M., Almen D. *, Svanbayev Ye., Saymbetov A., Nurgaliyev M.,
Kapparova A., Orynbassar S.

Al-Farabi Kazakh National University, Almaty, Kazakhstan
**Corresponding author:* dinara.almen@gmail.com

***Abstract.*** *Bifacial photovoltaic cells represent a promising solution for increasing the energy efficiency of solar modules by utilizing the rear surface. In this study, the bifacial solar cell was modeled based on the single-diode model. Current-voltage (I-V) and power-voltage (P-V) characteristics were constructed for various bifacial factor values, allowing us to consider both typical operating conditions and configurations with increased reflectivity of the rear surface. Calculations showed that a 36-cell module provides a 3.5% increase in efficiency compared to a monofacial module. The annual energy output of the bifacial module was 910 Wh versus 517 Wh for the monofacial module, representing a 76% increase. Daily and monthly energy production profiles confirmed the significant contribution of the rear side and the consideration of seasonal fluctuations in solar radiation. These results demonstrate the high potential of bifacial modules to improve power generation and overall energy efficiency of photovoltaic systems.*

**Keywords:** Bifacial photovoltaic cells, Monofacial photovoltaic cells, Single-diode model, Bifacial factor, Bifacial energy effect.

## 1. Introduction

With the increasing demand for renewable energy sources, the cost-effective and efficient fabrication of photovoltaic (PV) cells has been developing in recent decades. One of the most promising technologies in the PV field in recent years is bifacial solar cells (BSC). Bifacial solar cells are already accounting for a significant portion of the PV market and demand for these cells is increasing. Solar cell manufacturers such as Panasonic, Prism Solar, LG, Solar World, Centrotherm are increasing their share of BSC production.

BSC panels have been produced and experimentally investigated since the 1980s and they were found to be able to generate up to 50% more energy than flat monofacial solar cells (MSCs) [1]. Currently, new BSC technologies such as PERC, PERT, and HIT are rapidly developing, and the price of such solar cells is becoming cheaper every year. The use of BSC technology reduces the levelized cost of energy (LCOE), because it collects light from both sides and expands the energy yield. Accordingly, costs such as land, cabling, and installation structure are reduced than MSCs [2]. That is, BSC modules capture sunlight from both the front and rear sides, thereby increasing the output power. This advantage not only increases energy efficiency, but also reduces the area occupied by the module, thereby increasing the power density. MSC albedo radiation utilization does not exceed 2%, while BSC has a much higher figure. Thus, this system is also more economical as the presence of both front and rear sides allows for a greater amount of electricity to be captured from the same area than MSC [3].

The disadvantage of BSC over MSC is its higher cost because the material is bifacial and requires more expenses. However, the advantage of BSC is that the warping effect is reduced due to the small difference in the thermal expansion coefficients of silicon and aluminum, and this reduces electrical losses. BSC also has a lower operating temperature and a better temperature coefficient [4].

Vertically mounted BSCs have higher yields at noon because they receive light from both sides. Another advantage of this configuration is that snow and dust do not accumulate on the surface of the solar cell, which reduces soiling. Currently, issues such as optimal installation of BSCs, installation at a certain angle or on sun trackers are being addressed. In the work [5], three configurations of south-facing monofacial, south-facing tilted bifacial, and ground-sculpted vertical bifacial modules were compared, and the south-facing tilted bifacial configuration was 73.3% better than the vertically mounted bifacial panel. And the south-facing tilted BSCs yield 21.3% better than the south-facing tilted MSC.

To extract maximum energy from BSCs panels, the problem is to maximize the light incident on both sides. One solution to this problem is to study the bifacial irradiance using a BSC model. For this, a precise model of BSCs is required. A precise model of BSCs also solves the problem of predicting its output energy under different environmental conditions [6]. Since the element has two sides, the illumination incident on it varies nonlinearly depending on the efficiency of the front and rear solar cells. Therefore, it is important to accurately characterize the total BSC current-voltage (I-V) and its parameters, taking into account the received irradiance of both sides [7]. The electrical characteristics of BSCs are more complex than those of MSCs, and traditional models may not fully describe the bifacial properties of the solar cell.

Typically, two methods are used to describe the electrical characteristics of BSCs: the single-diode model and the double-diode model [8]. The single-diode model is simple and easy to use, has low computational cost, and consists of five parameters. However, it cannot fully describe the recombination under low illumination and different temperatures [9]. For this reason, the double-diode model is used and consists of seven parameters. Although the double-diode model can describe solar cells more accurately, it is considered more complex, especially for BSC cells, because the two-sided asymmetric irradiance distribution makes the model even more complicated. In the work [10], a method for characterizing the electrical characteristics of BSCs was proposed, and this method was based on the standard MSC model of BSCs. By studying the two sides of the solar cell separately, new bifacial parameters of BPV, such as short-circuit current, open-circuit voltage, fill factor and efficiency, were introduced for the one-diode model of PV. Thus, the BSC characteristics for different illumination conditions were compared with the experimental results and found a deviation of 1%. In addition, many works have tried to describe the BSC more precisely. For example, in the work [11], a dataset-based five-parameter analytical model of the MSC was developed based on the single-diode model, and it was tested with commercial panels under different irradiance and temperature conditions, and it showed good performance.

In the study [12], the generalized MSC model for BSC was able to describe the effect of the back side of the solar cell by adding an additional parameter. The next work [13] described the BSC using a single double-diode model by including alpha and beta parameters. Here, α refers to the error and precision of the measurements, and β is a parameter that describes the interaction of the illumination of the rear and front parts. The authors of [14] proposed a method for characterizing BSC and tested their model under standard test conditions (STC). The proposed model considers the radiation from the rear and front surfaces simultaneously, rather than separately. Two new parameters are introduced: the bifacial effective efficiency and the gain-efficiency product. The article [15] is also based on the single-diode model, but they consider each parameter as a function of the individual side's parameter. The next study [16] proposed a method for reducing the error of the single-diode model for BSC by accurately determining the saturation current. The work [12] also proposes a new parameter to adjust the series resistance of BSC using traditional MSC and compared with conventional single-diode and double-diode models, the proposed method can provide an accurate model for the whole operating range of BSC. Another work [17] also models the BSC using a single-diode model and describes the series resistance and shunt resistance values using two physical equations. The study [18] evaluated the performance of the BSC using the single-side illumination method instead of double-side illumination and showed that the short-circuit current and the open-circuit voltage parameters were not significantly different from those when double-side illumination was considered. Most of the parameter extraction methods are based on numerical optimization and provide limited insight into the mathematical role and sensitivity, so the work [19] proposed a new method that combines analytical formulation, hybrid optimization, and parametric sensitivity analysis and does not require single-diode modification. As a result, the model was tested for different environments and showed an error of 1.1%. Obtaining an accurate model of

BSC and extracting its parameters is very important and fundamental. The work [20] demonstrated a method for estimating the output power of vertically mounted bifacial solar panels using an optical and electrical model.

Thus, an accurate BSC description allows for a more accurate prediction of the energy production of the panel under different environmental conditions. This plays an important role in assessing the panel performance in advance when installing BSC panels in different locations. This is because the data in the datasheets of bifacial solar panels is often measured under standard test conditions (STC) and is not sufficient for accurate analysis and planning of the installation, since it is exposed to different environmental conditions in real-world applications. An accurate model of the panel can not only increase the efficiency of its installation but also reduce economic costs. In addition, a model that describes its operation is also needed to obtain the maximum output power from the panel during operation [21].

Many works proposed methods to accurately describe the BSC behavior and the problem of improving these models and using them correctly in energy forecasting is still a problem [12, 22]. Many works have validated their models with experimental results or performed simulations, but there is still a lack of work that has performed an in-depth analysis of the IV curve. In-depth analysis of the IV curve and each parameter is needed. In particular, since the combination of the rear-side irradiance and the front-side irradiance increases the nonlinearity of the BSC, it is important to accurately describe the bifacial illumination. In real-world conditions, part of the other side of the BSC may be shaded and the nonlinearity of the model increases. At this point, simple single-diode and double-diode models reduce accuracy. Therefore, the nonlinearity characteristics of the BSC should be considered and the different combinations of the front- and rear-side illuminations should be considered when performing their models.

In this paper, a method for obtaining a bifacial silicon solar cell model, taking into account the two-sided illumination parameter, is presented using a five-parameter single-diode equivalent model. The output power of the bifacial solar module at different coefficients x is determined. The obtained bifacial solar module output power is compared with that of the monofacial solar module. As a result of the proposed modeling, it is found that the bifacial solar module produces more energy in the same area than the monofacial solar module.

## 2. Methodology

In this study, a single-diode equivalent model, which is widely used to analyze the current-voltage characteristics of solar cells, is used to describe the electrical characteristics of a bifacial silicon solar cell. This model accounts for the key physical processes that determine cell operation, including photogeneration of charge carriers, recombination losses, and the influence of internal resistances:

$$I = I_{ph} - I_0\left[exp\left(\frac{q(V+R_sI)}{nkT}\right)-1\right] - \frac{V+R_sI}{R_{sh}}, \tag{1}$$

where $I$ denotes the output current of the solar cell, $V$ is the terminal voltage, $k$ represents the Boltzmann constant, and $T$ is the absolute temperature.

The five-parameter solar cell model is formulated based on the open-circuit voltage $V_{OC}$ , the voltage at the maximum power point $V_{mp}$ , the short-circuit current $I_{sc}$ , and the current at the maximum power point $I_{mp}$. These parameters are either specified by the manufacturer or obtained through experimental measurements. The remaining solar cell model parameters are subsequently evaluated using Equations (2)-(6) [23].

$$I_0 = \left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right)exp\left(-\frac{qV_{oc}}{nkT}\right) \tag{2}$$

$$I_{ph} = I_{sc}\left(1+\frac{R_s}{R_{sh}}\right) + I_0\left[exp\left(1+\frac{qI_{sc}R_s}{nkT}\right)-1\right] \tag{3}$$

$$R_s = R_{s0} - \left[\frac{nkT}{qI_0}exp\left(-\frac{qV_{oc}}{nkT}\right)\right] \tag{4}$$

$$R_{sh} = R_{sh0} \tag{5}$$

$$n = \frac{V_m+I_{mpp}R_{OC}-V_{OC}}{[\ln(I_{sc}-I_{mpp})-\ln(I_{sc})]V_T}, \tag{6}$$

where $R_{sc}$ and $R_{oc}$ denote the short-circuit and open-circuit resistances, respectively.

The parameters $\mathrm{I_{sc}}$ and $\mathrm{V_{oc}}$ correspond to the short-circuit current and open-circuit voltage, while $\mathrm{I_{mpp}}$ and $\mathrm{V_m}$ represent the current and voltage at the maximum power point. The thermal voltage is defined as $V_T = kT$, where $k$ is the Boltzmann constant and $T$ is the absolute temperature. Below is the equivalent circuit diagram of a bifacial solar cell, in which the total output current is defined as the algebraic sum of the currents generated by the front and rear sides of the cell [24]. This model allows for the contribution of radiation incident on both sides of the cell, as well as the influence of internal electrical parameters described within the single-diode approximation (Figure 1).

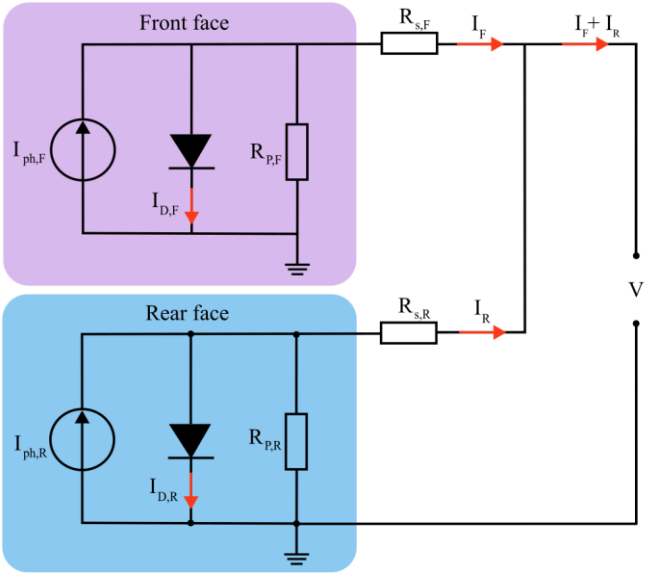


**Fig.1.** Equivalent circuit for a bifacial solar cell.

When determining the energy performance of bifacial photovoltaic cells, it's important to consider the characteristics of incident solar radiation, as the output power is directly determined by the irradiance of the active surface. Unlike monofacial photovoltaic cells, bifacial cells receive solar radiation from both the front and rear sides (Figure 2).

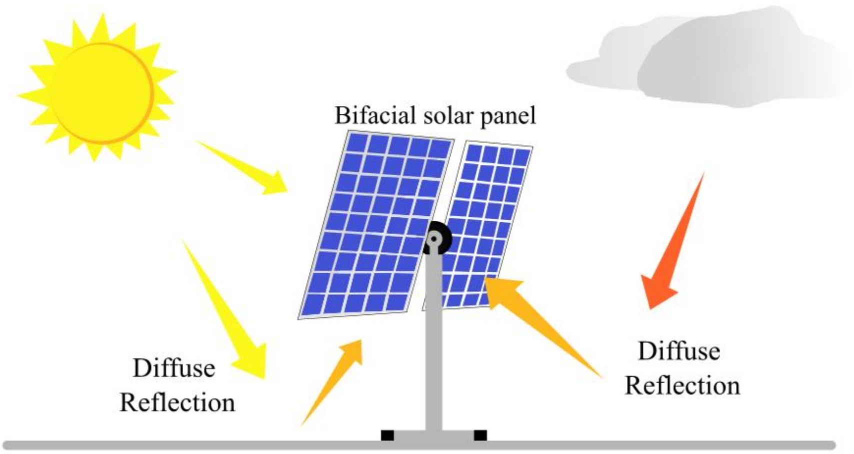


**Fig. 2.** Bifacial solar panel.

To quantify the contribution of insolation from the rear side, a dimensionless coefficient $x$ is introduced, called the bifacial impact factor. This coefficient is defined as the ratio of the radiation incident on the rear surface of the cell to the radiation incident on its front surface:

$$x = \frac{G_r}{G_f} \tag{7}$$

where $G_f$ is the solar radiation falling on the front side of the module (W/m²), $G_r$ is the solar radiation arriving on the rear side (W/m²) [14].

The value of the coefficient $x$ is determined depending on the reflectivity of the lower surface, the installation geometry and the operating conditions. This allows one to determine the energy of a bifacial solar cell taking into account the additional contribution of radiation from the rear side. Typically, the x-factor ranges from 0.05 to 0.5 for simple practical installations and can reach 0.8 in optimized or experimental configurations with surrounding highly reflective surfaces [25].

The efficiency of converting solar energy into electrical energy is characterized by the efficiency factor, which is defined as the ratio of the maximum output electrical power of a photovoltaic cell to the total power of solar radiation incident on it. For a bifacial solar cell, the efficiency is written as:

$$\eta = \frac{P_{max}}{A(G_f + G_r)}, \tag{9}$$

where A is the active area of the bifacial solar cell (m$^2$), $P_{max}$ is the maximum output electrical power of the solar cell (W).

The active area is determined by the geometric dimensions of the bifacial cell and is independent of the cell's operating mode. The contribution of the rear side is taken into account solely through the magnitude of incident radiation, not through changes in area. Therefore, when comparing monofacial and bifacial photovoltaic cells, the active area is assumed to be the same [8]:

$$A = A_{mono} = A_{bif}. \tag{10}$$

Taking into account the introduced coefficient $x$, the expression for the output power of a bifacial photovoltaic cell can be represented as follows:

$$P_{out} = \eta(1 + x)GA. \tag{11}$$

This allows one to clearly see the effect of rear insulation on increasing output power at a constant active area and front illumination.

To estimate the daily energy output of a photovoltaic cell, the instantaneous output power is integrated over time. Daily electrical energy output is determined by the expression:

$$E = \int_{t_{sr}}^{t_{ss}} P(t)dt\ , \tag{12}$$

where $t_{sr}$ is the sunrise time, $t_{ss}$ is the sunset time.

To determine the temporal dependence of solar radiation during daylight hours, a sinusoidal model is used, approximating the characteristic distribution of solar radiation depending on the time of day. This model is widely used in modeling insolation and hourly radiation distribution:

$$G(t) = G_{max} \cdot \sin\left(\frac{\pi(t - t_{sr})}{t_{ss} - t_{sr}}\right),\ \ t_{sr} \le t \le t_{ss}, \tag{13}$$

where $G_{max}$ is the peak value of solar radiation corresponding to midday and the maximum angle of incidence of solar rays.

When performing calculations over long periods of time, such as a month or a year, using peak solar radiation does not accurately account for temporal variability in insolation. Annual energy calculations use the average daily solar radiation value $G_{avg}$, which is determined by integrating the daily radiation profile over time. Using this value allows for seasonal fluctuations in insolation to be taken into account.

The energy efficiency of a bifacial module is the difference in energy production between bifacial and monofacial systems with the same active area:

$$\Delta E = \frac{E_{bif} - E_{mono}}{E_{mono}}, \quad (14)$$

where $E_{bif}$ is the energy generated by a bifacial solar cell, $E_{mono}$ is the energy generated by a monofacial solar cell.

## 3. Results and discussion

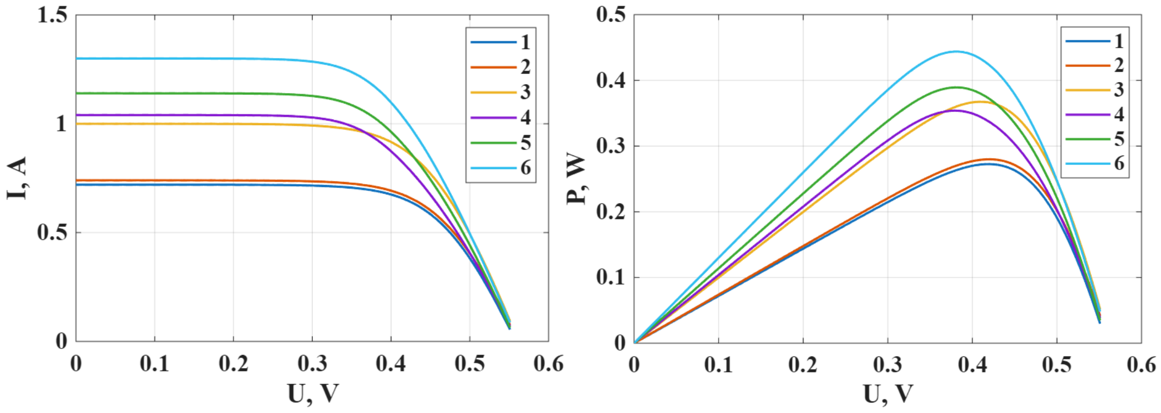
To construct the current-voltage characteristic of a bifacial photovoltaic cell, the current equation according to formula (1), which is used to describe monofacial solar cells, was used. This approach is based on the equivalent electrical circuit of a bifacial solar cell, shown in Figure 1. To analyze the effect of different illumination levels on the electrical characteristics of the module, several values of the coefficient *x*, listed in Table 1, were considered.

**Table 1.** Calculated characteristics of a bifacial solar cell.

| № | Coefficient *x* | $G_f$, W/m² | $G_r$, W/m² | $P_{max}$, W |
|---|---|---|---|---|
| 1. | 0.5 | 600 | 300 | 0.27 |
| 2. | 0.66 | 600 | 400 | 0.28 |
| 3. | 0.75 | 800 | 600 | 0.37 |
| 4. | 0.4 | 1000 | 400 | 0.35 |
| 5. | 0.6 | 1000 | 600 | 0.39 |
| 6. | 0.8 | 1000 | 800 | 0.44 |

As the table shows, this allows us to cover both typical practical operating conditions for bifacial modules and configurations that optimize the reflectivity of the lower surface.

The I-V and P-V characteristics are shown in Figure 3, a and b. The curve designations in the graphs correspond to the numbering of the variants in Table 1, and each characteristic is plotted based on the corresponding solar radiation values.

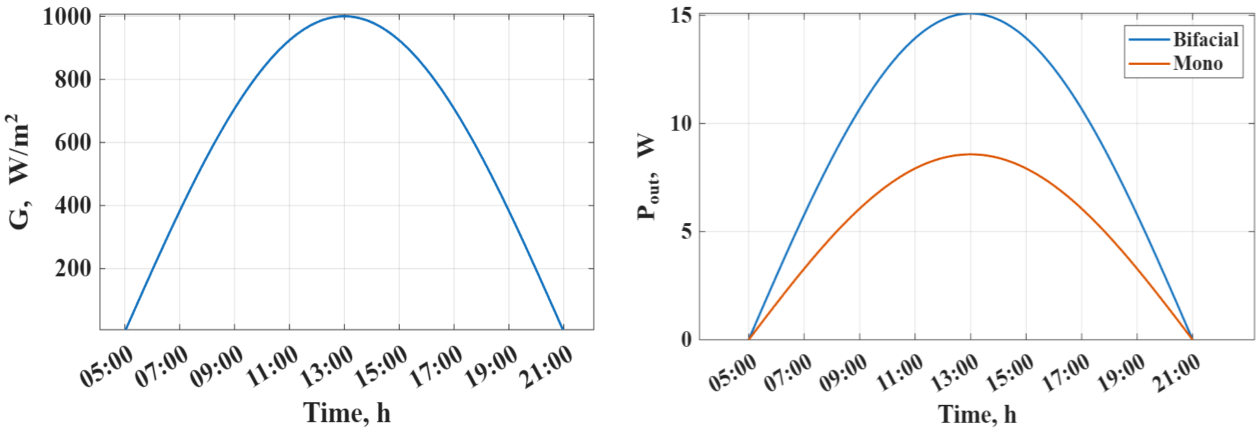


a b

**Fig. 3.** I-V and P-V characteristics of a bifacial photovoltaic cell.

As can be seen from the obtained results, with an increase in the coefficient *x* and an increase in solar radiation on the surface, the corresponding current-voltage characteristics show an expected increase in the output current and power. After constructing the current-voltage and power-voltage characteristics of the bifacial PV cells, the efficiency of a module consisting of 36 bifacial cells was calculated based on the obtained results.

Based on this simulation, the efficiency values for monofacial and bifacial cells were determined using the standard formula and formula (9), respectively. The calculation results showed that the bifacial module provides a 3.5% efficiency increase compared to a monofacial module with the same active area and the same lighting conditions. This result indicates a positive impact of the rear side on the energy efficiency of the bifacial PV cell. To determine the module's daily output power, the solar radiation-time dependence G(t) was used using formula 13 described above (Figure 4, a). Based on this data and the corresponding formula for calculating output power with formula (11), a graph of the module's power change over the course of the day was constructed, reflecting the dynamics of energy production (Figure 4, b).



a) b)

**Fig.4.** Time-dependent solar irradiance and output power

Using formula (14), the increase in energy generated by a bifacial solar cell compared to a monofacial one was calculated to be 76%, demonstrating a significant increase in energy efficiency when using the rear side of the module. Figure 5 shows a histogram of monthly energy production for a monofacial and bifacial PV module. The calculations were based on average solar radiation values $G_{avg}$ for each month, accounting for seasonal variations in solar radiation.

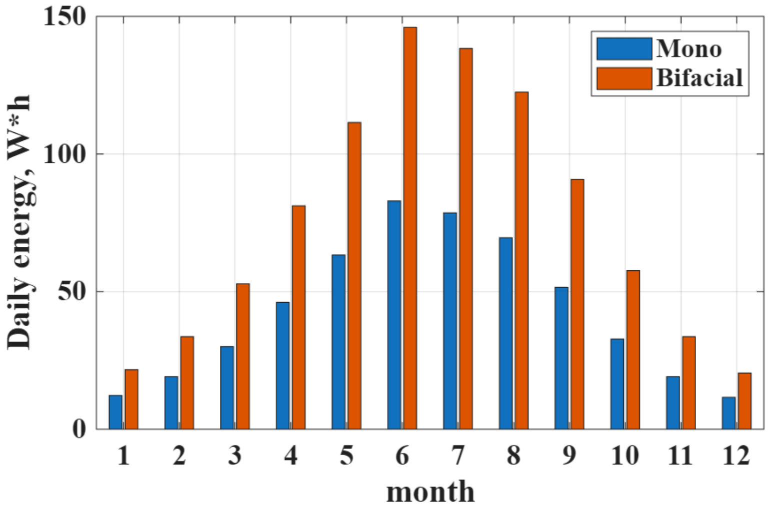


**Fig.5.** Monthly distribution of energy production

As the histogram shows, the bifacial cell exhibits higher energy yield than the monofacial module in all months of the year. Annual energy yield was 517.0 Wh for the monofacial module and 910.0 Wh for the bifacial module, confirming the significant contribution of the rear side to the overall energy output of the module. The maximum increase is observed during periods of high insolation. These results allow us not only to estimate the annual energy efficiency but also to determine the efficiency of bifacial cells compared to monofacial cells.

## 4. Conclusion

The conducted modeling of bifacial photovoltaic cells was based on a single-diode model previously used for monofacial cells. This allowed for a comprehensive assessment of their electrical efficiency and comparison with single-sided cells. The constructed current-voltage and power-voltage characteristics for various values of the bifacial factor demonstrated that using the rear side of the module significantly increases output current and power. Based on the characteristics of individual cells, the efficiency of a 36-cell module was calculated: the bifacial module demonstrated a 3.5% efficiency increase compared to the monofacial module under the same area and illumination conditions. Daily power calculations confirmed the positive impact of the rear side on energy production dynamics throughout the day, and the monthly and annual integrated values showed a significant increase in total energy: 910 Wh versus 517 Wh, corresponding to an increase of 76%. An analysis of monthly generation profiles also allowed us to account for seasonal fluctuations in solar radiation and determine the periods of peak performance for bifacial modules. Overall, the study's results demonstrate that the use of bifacial modules significantly improves the energy efficiency of photovoltaic systems, which is particularly important for optimizing solar power plant operation in various climatic and operating conditions.

**Conflict of interest statement**

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

**CRediT author statement**

**Rustemov A.**: Investigation, Writing – original draft; **Ibraimov M.**: Conceptualization, Methodology; **Almen D.**: Data curation, Writing – review & editing; **Svanbayev Ye.**: Methodology, Supervision; **Saymbetov A.**: Funding acquisition, Project administration; **Nurgaliyev M.:** Validation, Funding acquisition; **Kapparova A.**: Formal analysis, Writing – review & editing; **Orynbassar S.**: Visualization, Writing – original draft. The final manuscript was read and approved by all authors.

**Statement on the use of Artificial Intelligence.**

The authors declare that no artificial intelligence tools were used to generate scientific content, results, or conclusions of this article.

**Data Availability Statement**

The data are available upon reasonable request from the authors.

## Funding

This work has received funding from the research project AP26197983 of Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

## References

1 Diao, A., Thiaw, B., Boiro, M., Mbodji, S., Sissoko, G. (2021). A junction electric field determination of a bifacial silicon solar cell under a constant magnetic field effect by using the photoconductivity method. *Journal of Modern Physics*, 12(5), 635-645. https://doi.org/10.4236/jmp.2021.125041

2 Patel, M. T., Khan, M. R., Sun, X., & Alam, M. A. (2019). A worldwide cost-based design and optimization of tilted bifacial solar farms. *Applied Energy*, 247, 467 – 479. https://doi.org/10.1016/j.apenergy.2019.03.150

3 Matarneh, G. A., Al-Rawajfeh, M. A., & Gomaa, M. R. (2022). Comparison review between monofacial and bifacial solar modules. *Technology audit and production reserves*, 6(1/68), 24 – 29. https://doi.org/10.15587/2706-5448.2022.268955

4 Guerrero-Lemus, R., Vega, R., Kim, T., Kimm, A., & Shephard, L. E. (2016). Bifacial solar photovoltaics–A technology review. *Renewable and sustainable energy reviews*, 60, 1533-1549. https://doi.org/10.1016/j.rser.2016.03.041

5 Jahangir, J. B., Al-Mahmud, M., Shakir, M. S. S., Haque, A., Alam, M. A., & Khan, M. R. (2022). A critical analysis of bifacial solar farm configurations: Theory and experiments. *IEEE Access*, 10, 47726-47740. https://doi.org/10.1109/ACCESS.2022.3170044

6 Joseph, K. V., Rosana, N. M., Kumar, J. A., & Samrot, A. V. (2025). Commercial bifacial silicon solar cells-Characteristics, module topology and passivation techniques for high electrical output: An overview. *Results in Engineering*, 26, 104971. https://doi.org/10.1016/j.rineng.2025.104971

7 Ohtsuka, H., Sakamoto, M., Koyama, M., Tsutsui, K., Uematsu, T., & Yazawa, Y. (2001). Characteristics of bifacial solar cells under bifacial illumination with various intensity levels. *Progress in Photovoltaics: Research and Applications*, 9(1), 1-13. https://doi.org/10.1002/pip.336

8 Silvestre, S., Boronat, A., & Chouder, A. (2009). Study of bypass diodes configuration on PV modules. *Applied energy*, 86(9), 1632-1640. https://doi.org/10.1016/j.apenergy.2009.01.020

9 Ko, S. W., Ju, Y. C., Hwang, H. M., So, J. H., Jung, Y. S., Song, H. J., & Kang, G. H. (2017). Electric and thermal characteristics of photovoltaic modules under partial shading and with a damaged bypass diode. *Energy*, 128, 232-243. https://doi.org/10.1016/j.energy.2017.04.030

10 Singh, J. P., Aberle, A. G., & Walsh, T. M. (2014). Electrical characterization method for bifacial photovoltaic modules. *Solar energy materials and solar cells*, 127, 136-142. https://doi.org/10.1016/j.solmat.2014.04.017

11 Brano, V. L., & Ciulla, G. (2013). An efficient analytical approach for obtaining a five parameters model of photovoltaic modules using only reference data. *Applied Energy*, 111, 894-903. https://doi.org/10.1016/j.apenergy.2013.06.046

12 Ahmed, E. M., Aly, M., Mostafa, M., Rezk, H., Alnuman, H., & Alhosaini, W. (2022). An accurate model for bifacial photovoltaic panels. *Sustainability*, 15(1), 509. https://doi.org/10.3390/su15010509

13 Hong, D., Ma, J., Man, K. L., Wen, H., & Wong, P. (2022). Prediction of IV characteristics for Bifacial PV Modules via an alpha-beta single double-diode model. In *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, 1-5. IEEE. https://doi.org/10.1109/ECCE50734.2022.9948042

14 Singh, J. P., Walsh, T. M., & Aberle, A. G. (2014). A new method to characterize bifacial solar cells. *Progress in Photovoltaics: Research and Applications*, 22(8), 903-909. https://doi.org/10.1002/pip.2341

15 Sahu, P. K., Batzelis, E. I., Chakraborty, C., & Roy, J. N. (2024). Electrical modeling of bifacial PV modules. *IEEE Journal of Photovoltaics*. https://doi.org/10.1109/JPHOTOV.2024.3501403

16 Becerra, V. G., Valdivia-Lefort, P., Barraza, R., & García, J. G. (2024). Electrical model analysis for bifacial PV modules using real performance data in laboratory. *Energies*, 17(23), 5868. https://doi.org/10.3390/en17235868

17 Raya-Armenta, J. M., Ortega, P. R., Bazmohammadi, N., Spataru, S. V., Vasquez, J. C., & Guerrero, J. M. (2021). An accurate physical model for PV modules with improved approximations of series-shunt resistances. *IEEE Journal of Photovoltaics*, 11(3), 699-707. https://doi.org/10.1109/JPHOTOV.2021.3056668

18 Zhang, Y., Yu, Y., Meng, F., & Liu, Z. (2019). Experimental investigation of the shading and mismatch effects on the performance of bifacial photovoltaic modules. *IEEE Journal of Photovoltaics*, 10(1), 296-305. https://doi.org/10.1109/JPHOTOV.2019.2949766

19 Shahverdian, M. H., Sayyaadi, H., & Sohani, A. (2026). Integrated mathematical and hybrid optimization framework for parametric analysis of single diode bifacial photovoltaic panels. *Energy Conversion and Management*. X, 101516. https://doi.org/10.1016/j.ecmx.2025.101516

20 Becchi, L., Belloni, E., Bindi, M., Intravaia, M., Lozito, G. M., & Laudani, A. (2024). Optical and electrical model for vertical-mounted bifacial solar panels. In 2024 IEEE International Symposium on Systems Engineering (ISSE), 1-6. https://doi.org/10.1109/ISSE63315.2024.10741094

21 Nussbaumer, H., Klenk, M., Morf, M., & Keller, N. (2019). Energy yield prediction of a bifacial PV system with a miniaturized test array. *Solar Energy*, 179, 316-325. https://doi.org/10.1016/j.solener.2018.12.042

22 Bouchakour, S., Valencia-Caballero, D., Luna, A., Roman, E., Boudjelthia, E. A. K., & Rodríguez, P. (2021). Modelling and simulation of bifacial PV production using monofacial electrical models. *Energies*, 14(14), 4224. https://doi.org/10.3390/en14144224

23 Dosymbetova, G., Mekhilef, S., Saymbetov, A., Nurgaliyev, M., Kapparova, A., Manakov, S., & Koshkarbay, N. (2022). Modeling and simulation of silicon solar cells under low concentration conditions. *Energies*, 15(24), 9404. https://doi.org/10.3390/en15249404

24 Salilih, E. M., Leon-Salas, W. D., Gonzalez, L. G. R., Larico, P. F., Cornejo, M. V., Postigo-Málaga, M., & Gonzales, J. M. J. (2025). Energy output assessment and tilt angle optimization of north/south configured bifacial PV module using single diode model in mountainous region. *Energy Conversion and Management*: X, 101302. https://doi.org/10.1016/j.ecmx.2025.101302

25 Ghafiri, S., Darnon, M., Davigny, A., Trovão, J.P.F., & Abbes, D. (2024). A comprehensive performance evaluation of bifacial photovoltaic modules: insights from a year-long experimental study conducted in the Canadian climate. *EPJ Photovoltaics*, 15, 28. https://doi.org/10.1051/epjpv/2024025

## AUTHORS' INFORMATION

**Rustemov, Almas** – PhD student, Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan; https://orcid.org/0009-0009-6970-0746 rustemov_almas3@kaznu.edu.kz

**Ibraimov, Margulan** – PhD, Acting Professor, Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan; Scopus ID: 57189617696, https://orcid.org/0000-0002-8049-3911, Margulan.Ibraimov@kaznu.edu.kz

**Almen, Dinara –** PhD, Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan; Scopus ID: 58837948600, https://orcid.org/0009-0000-8527-4921; dinara.almen@gmail.com

**Svanbayev, Yeldos** – Candidate of Physical and Mathematical Sciences, Associate professor, Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan; Scopus ID: 54906220800, https://orcid.org/0000-0002-0093-7958, yeldos.svanbayev@kaznu.edu.kz

**Saymbetov, Ahmet** – PhD, Professor, Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan; Scopus ID:58529450500, https://orcid.org/0000-0003-3442-8550, Ahmet.Saymbetov@kaznu.edu.kz

**Nurgaliyev, Madiyar** – PhD, Associate Professor, Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan; Scopus ID: 57202335235, https://orcid.org/0000-0002-6795-5384, Madiyar.Nurgaliyev@kaznu.edu.kz

**Kapparova, Ainur** – PhD student, Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan; Scopus ID: 58028607300, https://orcid.org/0009-0008-8348-902X, Ainur.Kapparova@kaznu.edu.kz

**Orynbassar, Sayat** – PhD student, Department of Physics and Technology, Al-Farabi Kazakh National University, Almaty, Kazakhstan; Scopus ID: 58028274600, https://orcid.org/0009-0001-9124-2560, Sayat.Orynbassar@kaznu.edu.kz