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Performance assessment of bifacial photovoltaic modules based on multivariant simulation and outdoor measurements

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ABSTRACT

Due to growing interest in the use of bifacial photovoltaic modules this paper analyzes the actual performance of an installation consisting of three types of modules, bifacial monocrystalline silicon among them. An analysis of the operation of the on-grid photovoltaic installation working in the warm summer continental climate of south-eastern Poland was carried out in 2021–2022. The roof-top installation with a rated power of 14.04 kWp, consisting of modules made of monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si) and monocrystalline silicon bifacial (bifacial-Si) delivered 936.76 kWh/kWp in 2021 year and 1070.94 kWh/kWp in 2022 year. In order to predict the optimal configuration of bifacial modules in the tested location, a simulation was performed in the PV-Syst v.7.4 program. Based on a comparison of numerous simulated variants, differing in the orientation of the modules and the reflectivity of the ground surface the best results were found for 1.5 m height above the roof level, 45° inclination angle and albedo coefficient of 0.8.

Keywords: albedo coefficient, bifacial modules, double-sided modules, photovoltaics, PV real conditions, PV simulation, PVSyst.

INTRODUCTION

The usage of solar and wind power is the most reliable alternative in the energy transformation, which aims to reduce the burning of fossil fuels due to their depletion and the negative health and environmental impact. Solar technologies in energetics are of particular interest mainly in locations with large potential in terms of insolation [Louwen et al., 2016]. However photovoltaics is also spreading over the countries characterized by temperate climate conditions, Poland among them [Zdyb and Szałas, 2021; Ameur et. Al, 2022]. The reported studies refer to the monofacial modules representing the first and second generation of photovoltaic technology e.g. monocrystalline and polycrystalline silicon as well as thin film CdTe and CIGS modules. Bifacial solar modules are studied and described much less often, however the history of bifacial solar cells dates back to 1961 when Hiroshi Mori invented the first bifacial solar cells, which he patented 5 years later [Mori, 1966]. In 1970, bifacial technology was used for the first time in the Russian Space Program during the Luna 16 space mission. The company ISOFOTON was responsible for introducing them to the market, and in 1983 it started selling bifacial solar cells based on n-PERT technology [Eguren et al., 2022; Lorenzo, 2021].

Bifacial photovoltaic modules have the active surface of the cells on the both sides – front and back (Figure 1), which also requires the access to solar radiation in order to achieve the rated parameters in accordance with the manufacturers' technical data. Difficulties in obtaining satisfactory results due to bifaciality may occur if the inclination angle of the modules is incorrect, the distance from the ground from which the incoming solar radiation should be reflected is too small, or the coefficient of reflection of radiation from the ground called the albedo coefficient is too low. For urban environments, this coefficient ranges from 0.09 to 0.35, and for snow or aluminum it may exceed 0.8 [Langels and Gannedahl, 2018].

By using bifacial solar cells, it is possible to increase energy production by providing an appropriately adapted environment and basis for the modules [Badran and Dhimish, 2024 a]. Bifacial photovoltaic modules can also be installed at an angle of 90° in the form of a PV-wall as an equivalent to east-west oriented installation. This installation of modules allows for more rational use of the space between the rows of modules and reduces their susceptibility to dirt or snow remaining on their typically steep surface [Alam et al., 2017].

For a long time, monofacial monocrystalline silicon cells have been dominating the photovoltaic market due to innovations aiming in improvement of the performance [Kwaśnicki et al., 2023]. Now the switch to bifacial modules is observed as evidenced by data showing increased market share of bifacial technology from 20% in 2019 to predicted 70% in 2030 [ITRPV, 2024]. Bifacial photovoltaic modules are quickly replacing monofacial PV technologies on the market. Bifacial cells come in many varieties (e.g., PERC+, n-PERT, HIT, etc.) and many manufactures have switched to producing bifacial cells [IEA Report, 2021].

Bifacial photovoltaic technology proved to be beneficial in different climatic zones on the Earth both in small installations and large plants. There are numerous examples of photovoltaic systems consisting of bifacial modules.

At low latitude, under hot dry climate of Qatar the annual increase of energy production of 16.3% was observed [Baloch et al., 2020]. A gain up to 15% was provided by bifacial modules in Saudi Arabia in comparison to monofacial technology [Katsaounis et al., 2019]. Studies carried in photovoltaic plants in five different climatic zones in India also showed up to 34.93%/year increase of performance due to bifaciality [Johnson and Manikandan, 2024]. The role of ground albedo was demonstrated experimentally in Italy (Milano) where placing a white plastic under the bifacial modules led to 20% gain in performance ratio [Ogliari et al., 2023].

At high latitude, the experimental investigations carried in Sweden [Granlund et al., 2019] and Alaska [Pike et al., 2021] indicated beneficial energy production results dependent on tilt angle and azimuth of the bifacial modules. An interesting research on the influence of ground albedo on the performance of bifacial technology in UK demonstrated that bifacial module mounted in stand-alone installation provided 14.3–25% energy gain due to favorable albedo of white smooth tiles, which made ground reflective surface [Alam et al., 2023]. Also in UK, studies showing high degradation rates of glass/glass and glass/transparent backsheet bifacial modules, reaching -2.3% per year, highlighted the need to improve the quality of bifacial modules [Badran and Dhimish, 2024, b]. At high latitude, in Poland the experimental research showed that additional energy yield can exceed 35% [Dobrzycki et al., 2021]. With regard to wide applications, currently bifacial photovoltaic modules accounted for as much as 48% of the power of new photovoltaic installations in 2023, compared to 20% of new added PV power in 2022 and 11% in 2021 [IEO, 2024]. It is expected that their share in the Polish market will exceed that of standard monocrystalline modules, which current share is 51%, leaving only 1% for polycrystalline modules.

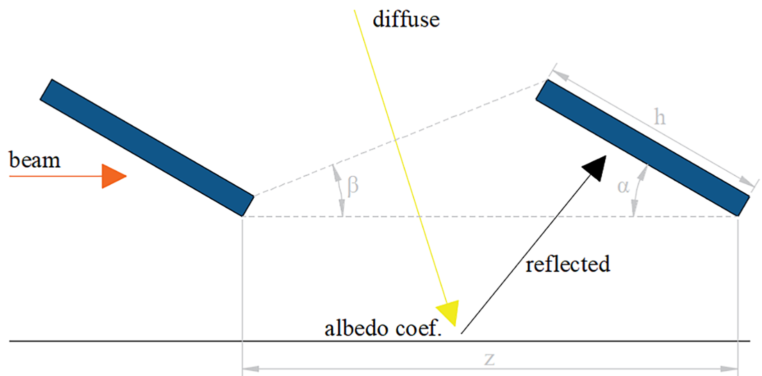

Figure 1. Distribution of radiation reaching the back side of the bifacial PV module. Symbols are explained in Equation 4

This work presents the energy rating of the photovoltaic installation operating in Poland in two-year period and the analysis is carried out in terms of output energy and final yield. The simulation of the installation was also performed, in which the modules used in actual currently operating installation were replaced by bifacial modules. The aim was to answer the question if it is worth installing bifacial modules and what conditions have to be met to benefit from it in considered location. The paper adds knowledge on the performance of bifacial modules in high latitude locations and serves as a guide for investors regarding the details of installation requirements such as ground albedo, height of the modules above ground level and their inclination.

METHODS

Experimental setup and data acquisition

The studied photovoltaic on-grid, rooftop system consists of three types of modules: monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si) and monocrystalline silicon bifacial (bifacial-Si). Monocrystalline silicon BEM 290 modules and polycrystalline silicon BEP 280 modules are based on M2 solar wafer. Monocrystalline silicon bifacial solar modules BEM 290 GG were encapsulated in a glass/glass technique (glass with anti-reflection coating, tempered, thickness 2 mm, encapsulant type – EVA). The both sides of these module structure is the same; however, the rear-side structure has a direct impact on the module current. Like monofacial modules, this bifacial solar cells uses M2 (156.75 × 156.75 mm) solar wafer. In each module there are three bypass diodes and 60 PV cells.

The building is located in Rzeszów (Poland) with the coordinates N 50°1’35.26’’ E 21°59’1.902’’. The azimuth of the building is 38°, the length is 52 m, the width is 11.6 m and the height is 17.5 m. The building is located in the third climatic zone of the country. The total nominal installed power is 14.04 kWp, the modules of each type are connected into separate strings and one three-phase inverter was used. The SolarEdge SE 12.5k inverter is characterized by maximum efficiency of 98% and maximum DC power of 16.85 kW. The technical data of the modules are presented in Table 1.

The electrical parameters of each string of modules were collected directly. The ambient temperature and irradiance sensors as well as thermocouples on the back side of each module types were used to register environmental parameters. The electrical and temperature parameters were collected directly by SolarEdge monitoring system. Irradiance was measured by Si-V-1.5TC silicon solar irradiance sensors of IMT Technology’s.

Assumptions of simulation performed in PV-Syst v.7.4

The licensed computer program PV-Syst v.7.4 was used to simulate the operation of photovoltaic installations with specific parameters. Based on access to meteorological and geographical data of the selected location, it allows to design the whole building where the installation is located. It is also possible to upload other components to the program’s internal database, which results in greater consistency between the project assumptions and final output data. When the program works with installations based on double-sided modules it is possible to adjust the selected albedo coefficient both for the installation surroundings and directly under the modules. Real-time simulations of the mutual shading of the rows of installation allow to adjust the appropriate distance between them.

To perform the simulation, weather data collected from a meteorological sensors located next to the current photovoltaic installation were used. The imported data uploaded to the PV-Syst v.7.4 program included: solar radiation intensity, ambient temperature, wind speed and air humidity, which values are presented in Table 2.

All the simulations of the analyzed variants of the installation were performed for systems consisted of the components presented in Table 1. When designing new variants, it was decided to maintain the same installation power and the presence of power optimizers due to the unusual shading of the entire system. In order to ensure the reliability of the presented results the final conclusions refer to the yield expressed in kWh/kWp.

RESULTS AND DISCUSSION

Weather data in considered location

The analyzed photovoltaic installation is located under warm summer continental climate, according to Köppen’s climate classification. The weather varies significantly in subsequent seasons of the year, as it is presented in Table 2. Global

Table 1. Components of the PV system

Parameter	Actual components			New components	
Pv module model	CSUN 290-60M-DG	BEP-280	BEM-290	Trinasolar DUOMAX	[-]
Type	Bifacial Si-mono	Si-poly	Si-mono	Bifacial Si-mono	
Nominal DC power	290	280	290	350	[Wp]
Quantity	16	17	16	40	[-]
Efficiency	19.69	19.00	19.72	19.79	[%]
Optimizers	SolarEdge P320-EU			SolarEdge P370	[-]
Quantity	49			40	
Inverter	SolarEdge 12.5kW – SE12.5K				
Nominal AC power of inverter	12.5				[kW]

horizontal irradiation changes from 21.5 kWh/m^2 in January to 165.6 kWh/m^2 in July which is accompanied by the increase of average ambient temperature from negative values in winter to over 20 °C in August. The raise of temperature in summer months is unfavorable for the photovoltaic performance taking into account that temperature coefficient of most silicon modules is around -0.4%/K.

Real data energy production

The real energy production of the analyzed installation was determined based on the current and voltage in the given time period. The power was calculated according to the following expression:

$$P_M = I_M U_M \tag{1}$$

where: I_M – current at the maximum power, U_M – voltage at the maximum power. Then the energy AC output produced over time was determined as:

$$E_{out} = \sum P_M t \tag{2}$$

The performance indicator of the photovoltaic system, which represents the number of hours per given time period, during which a system would have to operate at its rated power P_0 is final yield Y_F.

The final yield is ratio of the energy output to the rated power of the system. The monthly averaged final yield of the PV system $Y_{F,m}$ can be calculated as an average of the sum of the daily values:

$$Y_{F,m} = \frac{1}{\mathrm{N}} \sum_{d=1}^{N} \frac{E_{out,\mathrm{d}}}{P_0} \tag{3}$$

Figure 2 depicts the energy production of the installation in 2021 and 2022 year. Over 70% of annual energy is produced in sunny, warm part of the year, from April to September. The fluctuations between months within the same season of the year are mostly dependent on the changes in irradiation.

Table 2. Monthly weather data used in simulation

Month	Global horizontal irradiation [kWh/m^2]	Horizontal diffuse irradiation [kWh/m^2]	Temperature [ºC]	Wind velocity [m/s]	Relative humidity [%]
January	21.5	12.7	-1.0	3.75	83.2
February	40.5	23.9	2.2	3.55	79.6
March	91.9	44.6	6.6	3.23	73.5
April	121.2	62.6	9.3	2.61	75.8
May	172.0	75.6	13.7	2.72	67.0
June	147.4	77.7	16.8	2.91	78.2
July	165.6	81.9	19.4	2.53	71.9
August	160.0	66.1	20.6	2.41	72.2
September	112.8	53.7	15.2	2.88	72.7
October	74.5	33.1	11.3	3.30	72.8
November	32.9	20.5	7.2	3.66	80.7
December	25.5	12.8	2.6	3.64	86.0
Year	1165.8	565.2	10.3	3.10	76.1

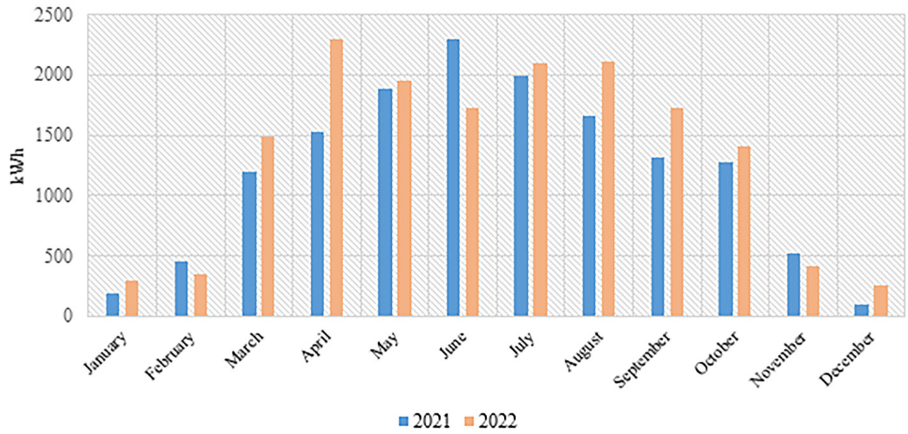

Figure 2. Energy produced in 2021 and 2022 year

The final yield of the whole analyzed system, presented in Figure 3, was 936.76 kWh/kWp in 2021 year and 1070.94 kWh/kWp in 2022 year, which is close to values of 990 kWh/kWp obtained in Sweden, 1047 kWh/kWp in the UK, 1000 kWh/kWp in Germany and 936-1130 kWh/kWp per year in southeast Poland [Zdyb and Gułkowski, 2020; Zdyb and Sobczyński, 2024].

Simulation of energy production

The simulation performed in PV-Syst v.7.4 software includes 9 variants of the installation, each of them located on the same building as the real one. During the simulation, a zero variant was distinguished, and 8 remaining variants which parameters are shown in Table 3. The analyzed variants differ in: the angle of inclination of the photovoltaic installation, the reflection coefficient of solar radiation from the ground and the height of photovoltaic modules above the roof surface. It is worth mentioning that the albedo coefficient for the surroundings of the modules was constant and amounted to 0.2, while for the surface directly under the modules the albedo coefficient was changed. The height above the roof was determined as a distance between roof surface and the lower edge of the photovoltaic module. The 30.83 m high building located next to it and the 18 m high telecommunications mast have a significant impact on the shading of the installation. The performance ratio presented in Table 3 is the output energy produced with respect to the energy which would be produced if the installation works with the nominal efficiency. The variants were selected that allowed the existing installation to be modified without changing the inverter and the total power of the installation.

As can be seen in Figure 4, variant “0” represents the real operating installation, while variant 2A is a proposal for an installation with the same power while maintaining design standards.

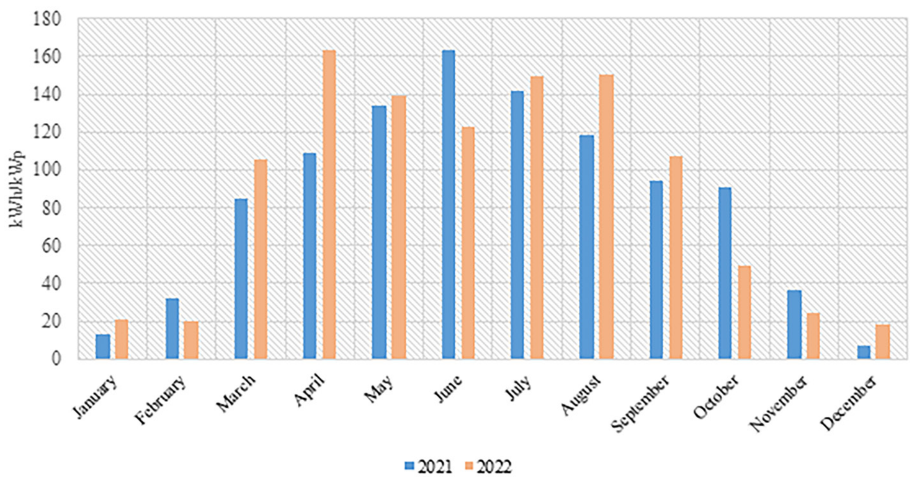

Figure 3. Final yield in 2021 and 2022 year

Table 3. List of simulated variants

Variant	Inclination angle [º]	Albedo [-]	Height above the roof surface [m]	Energy produced [kWh/year]	Performance ratio [-]	Increase of energy produced compared to "0" variant	Increase of performance ratio compared to "0" variant
0	25	0.2	0	15 417	0.83	-	-
1A	15	0.2	0	15 451	0.86	0.2%	4.0%
1B			1.5	15 955	0.89	3.5%	7.5%
1C		0.8	0	16 097	0.90	4.4%	8.4%
1D			1.5	18 083	1.01	17.3%	21.7%
2A	45	0.2	0	16 786	0.90	8.9%	8.2%
2B			1.5	17 181	0.92	11.4%	10.7%
2C		0.8	0	18 884	1.01	22.5%	21.7%
2D			1.5	20 342	1.09	31.9%	31.1%

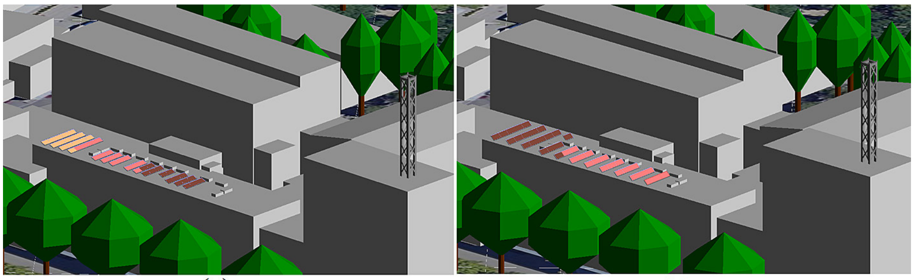
(a) (b)

Figure 4. View from PV-Syst v.7.4 of variant "0" (a) and "2A" (b)

Therefore, the same inverter was retained and the arrangement of photovoltaic modules was based on the least shaded area of the roof, in this case the key shading element is an 18-meter-high mast and the side ventilation devices of the building.

The mentioned distance between the rows of modules that was used in the simulations was calculated using the following formula:

$$z = \frac{h \times \sin[180° - (\alpha + \beta)]}{sin\beta} \quad (4)$$

where: z – distance between rows of photovoltaic modules, h – height of the photovoltaic module field, α – angle of inclination of photovoltaic modules relative to the horizontal, β – minimum angle of incidence of sunlight.

It is important that the height of the PV module field h in the presented simulations is 1 m because the modules are located horizontally. If they were placed the other way around, this dimension would be 2 m, which would double the distance between the rows and, as a consequence, it would make it impossible to arrange all the modules without meeting the basic requirement of maintaining the same power of the photovoltaic installation. The calculated distances z between subsequent rows of PV modules are, for their inclination angles of 15° and 45°, 1.93 m and 3.35 m, respectively. The length of the building on which the simulations were performed is 52 m, so with the largest distance between the rows it will fit their maximum is 15. The number of rows in the simulation was a maximum of 11.

The change of the angle of inclination of photovoltaic modules is directly related to their height above the ground, because it influences the area of absorption of solar radiation on the back side of the photovoltaic module. As a result, the incoming radiation first reduces its value due to the low reflection coefficient and then due to reflection from the module itself. Figure 5 show that for the variants marked with the letters "B" and "D", the view factor is higher than the others. These markings indicate a height of 1.5 m above the roof surface. All heights above 0 m allow the reflected radiation to reach the rear side of the module also from its front side, hence the increase in these values. The highest radiation value that reaches directly

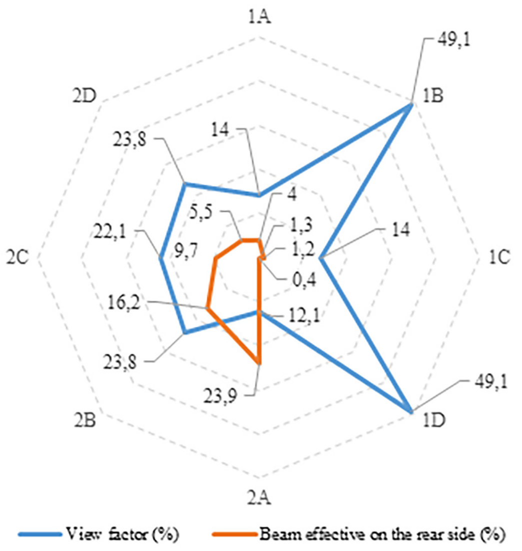

Figure 5. View factor and beam effective on rear side for new variants

the rear side of the module occurs for the variant with the following parameters: module inclination 15°, height above the ground 0 m. In this case, the albedo coefficient has no influence on the beam effective value. This means that in this location, the lower foundation of the installation increases the use of direct radiation, which in higher installations could bypass it and become reflected radiation what can be noticed in Figure 1. For installations consisting of bifacial modules with an azimuth close to the "0" variant, it is recommended to increase the angle of inclination of the modules because increasing the beam effective allows for reducing the losses of incoming solar radiation during the day when the Sun is behind the front side of the module and during the winter, when the Sun is low on the horizon a higher angle of inclination of the modules will increase the angle at which solar radiation reaches the modules.

The most advantageous of the presented variants turned out to be the 2D variant characterized by the following parameters: inclination angle of 45 degrees, albedo coefficient of 0.8, installation height of 1.5 m above the ground, performance ratio of 1.09 and electricity production of 20.3 MWh. Due to the location of the installation above the Tropic of Cancer and the position of the Sun in certain seasons, the optimal angle [Krawczak, 2023] of the installation in summer is less than 35˚ and in more than 40° in winter. Despite this, in case of bifacial modules in each month the highest electricity production occurred for the 2D variant, which can be seen in the Figure 6. During the summer, the second variant with the highest energy production is the 1D variant with albedo coefficient parameter and height above the ground such as 2D, which indicates that with such a high albedo of 0.8, a change in the angle of inclination of the bifacial modules is more beneficial than a change in the height above the ground.

The performance ratio obtained for different variants have high values, even exceeding 100% due to bifaciality which provides additional gains contributing in energy output. The highest PR value is for 1D, 2C and 2D which common feature is albedo of 0.8. Overall annual yield of variant "0" is 1101.2 kWh/kWp and optimal variant "2D" delivered 1453 kWh/kWp. Real data collected in 2021–2022 years indicate the yield of 1003.85 kWh/kWp.

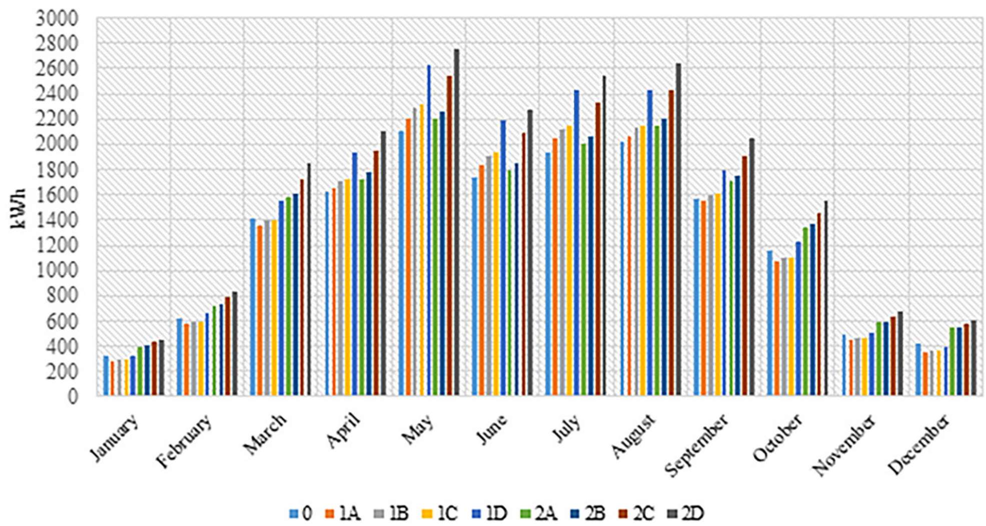

Figure 6. Energy produced in each variant divided into months

CONCLUSIONS

The presented work was devoted to the analysis of the performance of the PV system consisting of three types of modules based on silicon solar cells, including bifacial modules, operating in the south-eastern part of Poland. The experiments conducted in outdoor environment were juxtaposed with the results of various simulation variants of the PV system performance in the same location. The study leads to the following conclusions:

- the energy yield is higher in each variant of the simulated bifacial installation compared to the yield of the actual, currently operating installation;
- for the given type of surface coverage characterized by the albedo coefficient, increasing the height and angle of inclination results in better energy production;
- both at small and large angles of inclination of the modules, it is beneficial to increase the height and improve the albedo coefficient;
- the optimal variant is 2D: albedo coefficient – 0.8, height above roof – 1.5 m, inclination angle – 45°;
- even with a small inclination angle bifacial modules provide power gains in summer if they are mounted at the right height on the surface of beneficial albedo;
- in order to benefit from energy gains, a special mounting structure is necessary to ensure the required height above the ground or roof surface.

The prediction of system performance presented in this study can serve as a reliable reference and guide for manufacturers, investors and experts working in the field of photovoltaics. Since the beginning of 2024 year, the prices of bifacial and mono-facial modules are very similar, the difference rarely exceeds 20%.

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