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Experimental Investigation of the BIPV System under Şanlıurfa Meteorological Conditions

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Abstract: In this study, under the meteorological conditions of Şanlıurfa, Turkey, some parameter studies were conducted to more efficiently utilize Building Integrated Photovoltaic BIPV systems placed on different facades of a building. For this purpose, one single-sided (monofacial) panel was placed on both the roof and the east facade. As an innovation brought about by this study, both bifacial and monofacial panels with the same production potential were compared under the same conditions on the south facade. In addition, to enhance the production performance of the rear surface of the bifacial panel, a reflector was placed on the wall surface by leaving a gap between the wall and the panel. The experimental study was conducted between February and July. In addition, the building model created experimentally was analyzed monthly using the PVsyst program for a duration of one year. According to the study results, in the 6-month BIPV experimental application, the electrical production of the bifacial panel was found to be 15.1% higher than that of the monofacial panel under the same conditions. In addition, based on the 1-year results in the PVsyst analysis, the bifacial panel demonstrated a 5.86% higher production performance compared with the monofacial panel. This demonstrates that the efficiency of the bifacial panel in the experimental setup was enhanced by placing a reflective surface on the structure wall behind it. According to the complete annual analysis results obtained from the PVsyst analysis, the bifacial panel in the south produced 401.65 kWh, the monofacial panel produced 379.41 kWh, the panel on the eastern facade produced 313.34 kWh, and the rooftop panel, where the highest production was recorded, generated 505.64 kWh of energy. Therefore, it is anticipated that the use of bifacial panels with reflective surfaces on the roof under the meteorological conditions of Şanlıurfa will demonstrate the highest performance for the BIPV system.

Keywords: building integrated photovoltaic; PVsyst; bifacial panel; monofacial panel; reflective surface

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1. Introduction

1.1. Background

Solar energy systems, as renewable energy sources, offer high potential in the pursuit of clean and sustainable energy. Recently, efforts were made to reduce costs and increase the efficiency of PV panel technology, which is known to have no emission release [1].

Photovoltaic, in its literal sense, refers to the conversion of solar energy into electricity using silicon-based solar cells. Electric energy is produced by PV modules. The modules consist of subunits called solar cells that absorb the radiation emitted by the sun [2]. The primary reason for the increased use of PV systems is the depletion of fossil fuels and the global warming threat facing the world. [3]. PV systems are environmentally friendly because they do not emit any hazardous gases. Buildings account for approximately 39% of CO_2 emissions with the amount of energy they consume [4]. For this reason, the transition to safe and sustainable energy production systems like PV systems is being encouraged. [5]. The efficiency of a PV panel generally depends on factors such as the type and kind of the panel, cell temperature, material, climate of the region where it is installed, and its orientation. Therefore, to gain insights into the characteristics affecting the power production of a PV system, it is necessary to study or analyze these factors [6].

Approximately 30% of the global energy production is used by the construction sector. It is aimed at meeting the energy consumption of buildings, which consume such a high amount of energy, with PV systems integrated into the facade of the building [7]. The integration of PV panels into building facades is referred to as building-integrated photovoltaic (BIPV) systems. Integrated PV panels have some advantages over nonintegrated systems. Placing PV panels in place of building materials, such as windows, walls, and roofs, during the initial construction both saves on materials and results in financial gains while also reducing labor costs [8]. Since PV panels are mounted on unused areas of the building, like walls or roofs, there is no need to prepare new land [9]. In addition, passive heating and lighting of the interior environment with the use of semitransparent panels are among the primary benefits of the BIPV system. Today, the fact that many countries have targets related to net zero energy buildings (NZEBs) is increasing interest in the BIPV. However, when PV systems are integrated into building facades, there is not as much space available as in conventional solar power plants, leading to the need to achieve high efficiency in a small area [10]. Therefore, certain improvements are being made to increase the efficiency of PV panels.

There are various parameters that affect the design of BIPV applications. Among these parameters are the orientation of the PV panel, radiation intensity, tilt angle of the PV panel, PV panel technology (thin film, crystalline), and the type and permeability of the material used in the panel, such as opacity and transparency [8]. In addition to these, meteorological parameters such as solar radiation intensity, sunshine duration, and wind speed are considered the most important parameters since they affect both the electrical efficiency of the BIPV system and the energy performance of the buildings where BIPV systems are installed [11].

1.2. Literature Review

The angle and facade direction of PV panels are important to obtain more electrical energy from the BIPV system. In this context, there are many studies. Abotaleb et al. [12] found that in a desert environment, between bifacial PV panels oriented at a 22° tilt facing south and those oriented 90° facing east, the ones facing south produced 14% more energy. Cronemberger et al. [13] concluded in their experiment with different facades across 78 cities that BIPV systems could be considered not only for roofs but also for facades in places located at lower latitudes. Sun et al. [14] found that the PV panel can produce more electrical energy at a smaller tilt angle and that the annual production might decrease with an increase in the tilt angle. Elghamry et al. [15] demonstrated that BIPV windows mounted on south-facing roofs in Egypt produced the maximum annual power, while north-facing BIPVs produced the minimum power. In an experiment conducted by Yang et al. [16] in Hong Kong, a BIPV system was installed on the roof, south, west, and east facades of a building, and it was found that the best production was from the roof. In the BIPV study conducted by Song et al. [17], panels mounted vertically on the facades were compared with those mounted on the roof, and panels mounted at a 30° angle facing south on the roof were recommended for the highest performance. Many researchers have noted that, because of the low radiation on the north, west, and east-facing facades of BIPV systems, the electric energy economically produced is particularly low on the north and east-facing facades, taking into account the amount of radiation on these facades [18–26].

One of the most important parameters for increasing the efficiency obtained per unit area is the PV panel technology. In their study conducted in India, Sharma et al. [27] demonstrated that a-Si cells produced 14% less energy compared with p-Si cells during summer and 6% less during winter. In their experiment conducted in Spain, Canete et al. [28] supported the findings of the study carried out in India. In a study conducted by Urbanetz et al. [29], when a BIPV system using a-Si technology was compared with a PV system composed of curved thin-film a-Si laminates, the annual energy gain of the second system was approximately 88% of the first system. Sorgato et al. [21] demonstrated that in six Brazilian cities, the annual energy needs of a building can be met by using the building's roof and facade for BIPV application with thin-film Cadmium telluride (CdTe) materials. Saadon et al. [30] investigated three different transparency types (opaque, 30%, and 50%) of BIPV systems in Nice, Paris, and Lyon. In their BIPV experiment conducted in Italy, Yoon et al. [31] found that the CIGS and c-Si used in the photovoltaic module exhibited 45% and 20% less energy production, respectively, compared with a-Si. In the a-Si-based BIPV study conducted by Zhang et al. [32] in Zhuhai City, China, ventilated BIPV showed 0.2–0.4% higher performance compared with its nonventilated counterpart. They found that the highest production was obtained from the opaque PV panel type, and the lowest production was obtained from the PV panel type with the highest permeability. Lopez and Sangiorgi [33] found, in a BIPV test facility consisting of two identical 10 m^2 rooms, that m-Si PV modules produced better results in energy production than CIS PV modules.

One of the panel types that can be used in BIPV systems to obtain a higher amount of energy per unit area of the panel is the bifacial panel. In programs like Pvsyst, the analysis of ventilated systems of BIPV cannot be performed. [34]. In the ventilated bifacial BIPV system studied by Tina et al. [34], a power gain of 2.9% compared with the ventilated BIPV system and 4.4% compared with the nonventilated BIPV configuration was achieved. In their study, Assoa et al. [35] produced 63.8 kWh/m^2 of electrical energy in the BIPV model with a bifacial panel, achieving an average efficiency of 6.3% and a performance ratio of 0.7. Kim et al. [36] investigated the nonhomogeneous rear reflection results of different colors in the bifacial panel in their mini module BIPV experiment. They found that the cell with a low reflection ratio heated up, resulting in power loss in the modules. A similar study was conducted by Kim et al. [37] on transparent PV panels in a BIPV system. According to the study, an increase in efficiency was achieved with various background colors (14% blue, 25% red, and 35% white). Chen et al. [38] concluded that the highest production of bifacial panels integrated into the outer shell of a building was on the roof. Additionally, the improvement in electricity production was increased between 4.7% and 18.8% through simulation.

Many studies have presented simulation models to calculate the energy efficiencies of BIPV facades [39]. However, in the literature, there has been no comparison between monofacial and bifacial panels under the same conditions. In addition, a reflective surface has not been used to significantly increase the contribution of the rear side of the bifacial panel applied to BIPV. However, in our study, this situation was different for the bifacial and monofacial panels located in the southern part. The connection between the exterior environment and the rear side of the panel was severed using a transparent material between the wall and the panel frame. In the study, a comparison of three facades with panels having the same production potentials both experimentally and numerically under Şanlıurfa conditions has also been made.

1.3. Contribution of the Research

This study proposes an innovative approach by researching the potential of bifacial panels to meet the energy demands of buildings in Şanlıurfa, Turkey. What distinguishes this study is the comparison of bifacial and monofacial panels with the same production potential under the same conditions in the BIPV system. In addition, to enhance the production performance of the back surface of the bifacial panel, a reflector was placed on the wall surface by leaving a gap between the wall and the panel. This study, which compares the performance of the bifacial panel with the monofacial panel under the same conditions, provides valuable insights into the potential benefits of bifacial panels for meeting the electricity energy needs of residential and industrial buildings in Şanlıurfa conditions.

1.4. Structure of the Paper

When looking at the literature studies in general, it is observed that bifacial panels are used in limited amounts in BIPV systems. For this reason, in the conditions of Şanlıurfa, the bifacial panel technology—a new panel technology—was used to increase the amount of electrical energy obtained per unit area in BIPV systems.

Bifacial panels are two-sided panels. Bifacial PV panels produce electrical energy by collecting radiation from both the front and back surfaces. Monofacial panels, on the other hand, are traditional single-sided panels and produce electrical energy only from the radiation received from their front surface. Bifacial panels are named based on the peak electric power produced by their front surface, similar to monofacial panels. Moreover, there is no significant price difference between bifacial and monofacial panels with the same peak production. However, because of the radiation reflected or scattered on the back surface of the bifacial panel, additional electricity production is achieved [40].

When analyzed compared with monofacial cells, bifacial PV panels are seen as a potential opportunity to reduce the cost of solar energy conversion. The bifacial panel is a new technology that increases the electrical energy production per square meter of the PV module by utilizing light absorption from albedo [41].

In this study, PV panels with the same potential were installed on various facades of a building. Using panels of the same capacity on different facades, the energy production levels on the facades were investigated. The aim of this study was to compare the effect of panel technology by comparing bifacial panel technology with monofacial panels of the same direction and capacity. In addition, after obtaining experimental data, the aim was to verify the data using the PVsyst program on the computer and to determine the annual production amount.

2. Materials and Methods

2.1. Experimental Design and Setup

In this study, the aim was to evaluate the performance of BIPV systems under the meteorological conditions of Şanlıurfa. The experimental setup was established at Harran University's GAP-YENEV Research and Application Center. The design of the PV panels and the experimental setup is shown in Figure 1. The width, length, and height of the building structure where the experimental setup was located were 1.98 m, 2.96 m, and 2.45 m, respectively. The BIPV experimental setup shown in Figure 1 was designed to determine the electrical energy that can be generated from three different facades, namely east, roof, and south. There are a total of four PV panels in the BIPV system.

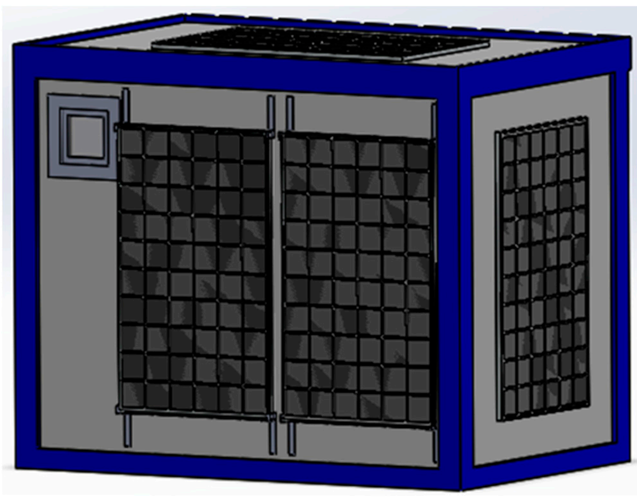

Figure 1. External design of the experimental setup.

Two of these panels consist of bifacial and monofacial panels located on the south facade to be compared under the same conditions. The panel closer to the east facade on the south side is the bifacial panel. The panels on the south facade are positioned approximately 11.5 cm away from the wall. The wall surface behind the bifacial panel is covered with aluminum foil. The 11.5 cm gaps between the panel and the wall were sealed with transparent material. Thus, sunlight was allowed to reach the rear surface of the bifacial panel. In addition, monofacial PV panels of the same capacity were placed on the east facade and the roof of the experimental setup. Thus, it became possible to comparatively observe the electrical production effects on different facades.

The technical specifications of the panels used in the experimental setup are provided in Table 1.

Table 1. Bifacial and monofacial panel specifications.

Properties	**Bifacial Panel**	**Monofacial Panel**
Max power (1000 W/m^2)	335 Watt	335 Watt
Maximum power voltage (Vmp)	34.56 V	34.97 V
Maximum power current (Imp)	9.7 A	9.63 A
Open-circuit voltage Voc (V)	40.65 V	42.33 V
Short-circuit current Isc (A)	10.69 A	10.18 A
Performance (%)	20.05%	20.07%
Temperature coefficient P_{MAX}	−0.38%/K	−0.37%/K
Temperature coefficient V_{OC}	−0.29%/K	−0.28%/K
Temperature coefficient I_{SC}	0.04%/K	0.048%/K
Nominal operating temperature	46 °C	45 ± 2 °C
Transparency	Translucent	Opaque
Front cover	2 mm low iron tempered solar glass	Glass
Cell matrix	60 Cells (6 × 10)	60 Cells (6 × 10)
Module dimensions	1670 mm × 1000 mm	1665 mm × 1002 mm
Weight	20.1 kg	19 kg

The bifacial panel used on the south facade of the BIPV experimental setup was glass–glass and had semitransparent properties. Thus, the solar radiation hitting the bifacial panel passes through to the back wall. The solar radiation that reached the back wall was reflected thanks to the reflective surface coating on the wall. Thus, a higher amount of radiation was directed to the back surface of the bifacial panel.

Energy production values were measured on all facades of the established BIPV system. For this purpose, the electrical circuit shown in Figure 2 was established. As can be seen from the figure, the PV panels are connected to the Hoymiles brand MI-1500 model microinverter using DC cables. The microinverter converts the incoming direct current to alternating current and transfers it to the grid. To record the amount of electrical energy produced by the panels, the micro inverter is connected to the Hoymiles brand Data Transfer Unit (DTU) device via its own Wi-Fi. The micro inverter calculates the amounts of both power and electrical energy produced by each panel separately and sends it to the DTU device. The DTU records the amount of electrical energy produced by the micro inverter every 15 min. It transfers the recorded data to the cloud system, and access to the data can be achieved wherever there is an internet connection. To measure the amount of radiation received by the PV panels, an Eko brand MS-602 model pyranometer was placed on each facade. The data from these pyranometers were collected in a HIOKI brand data logger (Figure 2).

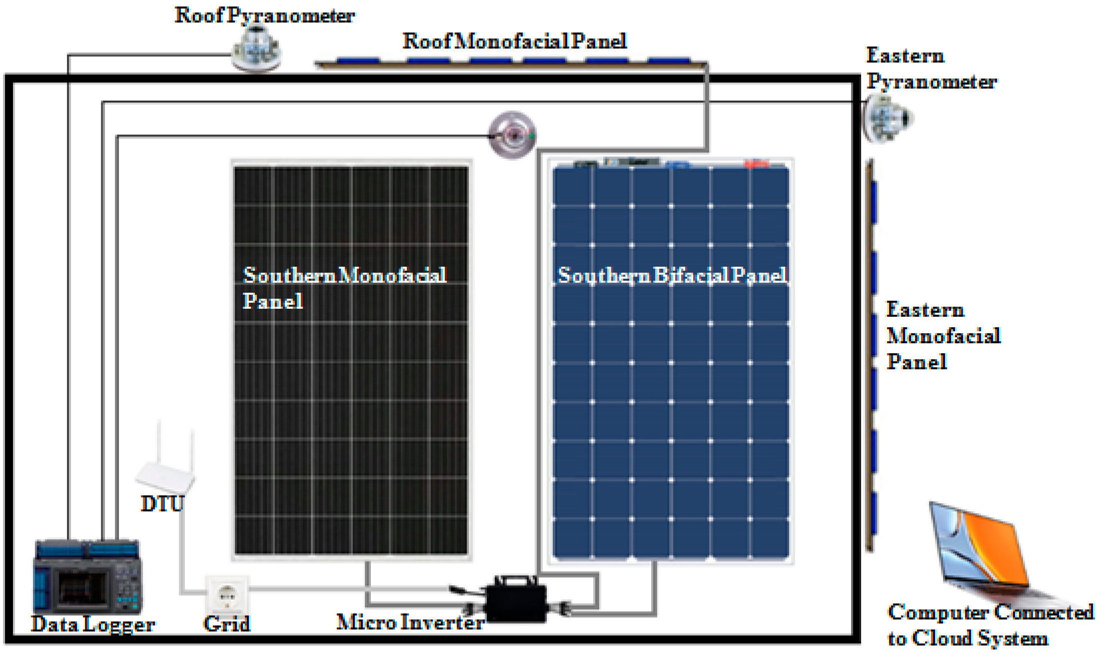

Figure 2. Measurement instruments and schematic representation of the experimental setup.

2.2. Calculation Method

Electric energy production values (P) of the PV panels were recorded every 15 min. The unit of P was W (Watts). Along with power, the total produced energy values, such as daily and monthly in the study, were found using Equation (1); the unit was Wh [42].

$$E\ (\text{kWh}) = P(\text{kW}).\ h\ (\text{hour}) \tag{1}$$

In general, the electrical efficiencies (ηe) of PV panels are calculated using Equation (2). Here, the P value represents the daily average power (watt), I_T represents the daily average amount of solar radiation received per unit area, and its unit is W/m^2, A represents the panel area, and its unit is m^2 [43].

$$\eta_e = \frac{P}{I_T.A} \tag{2}$$

The capacities of bifacial PV panels were determined on the basis of the front face of the panel under standard test conditions (STC), just as in monofacial panels. A new rating was made to account for the effect of the back surface. The number known as bifaciality, denoted by B, is the ratio of the energy produced by the back surface of the panel to the energy produced by the front surface as measured under STC. The bifaciality ratio (B) is given by Equations (3) and (4) below [44]. In this study, the bifaciality ratio was used to indicate the percentage increase in production of the bifacial panel compared with the monofacial panel on the south facade, both having the same production potential.

$$B = {}^{E_{back}}/E_{front} \tag{3}$$

$$E_{total} = E_{front}(1 + B) \tag{4}$$

2.3. Experiment Procedure and PVsyst Simulation Study

In this study, experiments were conducted over a span of 6 months, including February, March, April, May, June, and July of 2023, to determine the effectiveness of the BIPV application under the meteorological conditions of Şanlıurfa. The micro inverter calculated the monthly electrical energy produced by each panel and sent it to the DTU device for recording.

After obtaining the experimental data, an analysis was conducted using the PVsyst software. With the software, the location of the experimental setup at Harran University GAP-YENEV Research and Application Center was marked on the map to simulate the meteorological conditions of Şanlıurfa. The structure on which the panels were placed was drawn on the program according to its dimensions. For the two panels to face south in the initial orientation, the tilt angle of the first orientation was set to 90° and the azimuth angle to 0°. For the second orientation based on the east facade, the tilt angle was set to 90° and the azimuth angle to −90°. For the roof direction, in the third orientation, both the tilt and azimuth angles were set to 0°. In the simulation, as in the experiment, panels were chosen as three monofacial and one bifacial panels, each with a capacity of 335 watts. The panels on the roof and the east facade were positioned with no distance between them and the building wall. On the south facade, a gap of 11.5 cm was left between the bifacial and monofacial panels and the building wall, as in the experimental setup. For each panel, an individual Hoymiles brand micro inverter with a value of MI-350 watts was chosen. The surface areas of the panels were entered as equal to each other and as 1.67 m^2, as in the experimental setup. The simulation-based experiment was conducted to determine the annual production quantity over monthly periods (Figure 3).

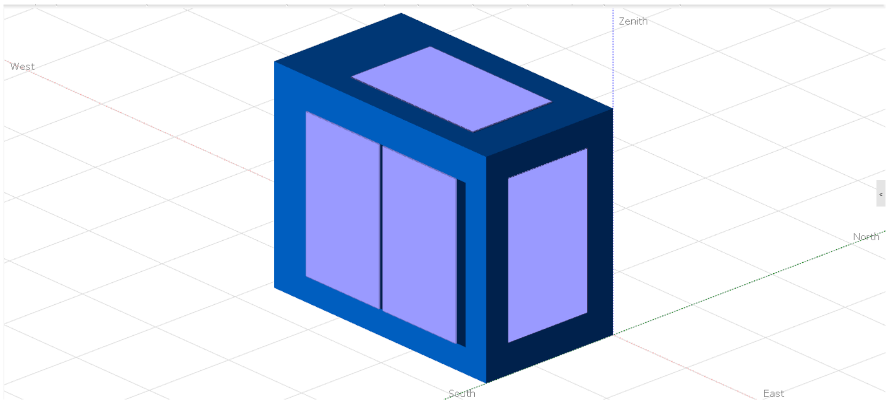

Figure 3. Preparation of the experiment in the PVsyst software.

When the results from the experimental setup are compared with the production data in PVsyst, the results are close to each other, as shown in Table 2 in percentage terms. However, in March, the production in the experimental setup was lower than that in the PVsyst program because of unusual meteorological conditions (floods and heavy rains). Except for March, the calculated results were generally quite close to each other. Therefore, it can be concluded that the electricity production values in the PVsyst analysis are very close to the actual values unless there is an extraordinary situation.

Table 2. Amounts of energy produced in the experimental setup in kWh for February, March, April, May, June, and July, and error rates (%) of the PVsyst analysis.

	Bifacial Panel (kWh)	Error Rate of PVsyst Analysis	South Monofacial Panel (kWh)	Error Rate of PVsyst Analysis	East Monofacial Panel (kWh)	Error Rate of PVsyst Analysis	Roof Monofacial Panel (kWh)	Error Rate of PVsyst Analysis
February	35.74	11.8%	32.20	6.37%	14.71	−11%	25.88	2%
March	31.41	−19%	28.13	−27.6%	17.43	−47.2%	33.10	−23.1%
April	30.31	2.8%	26.69	−5.9%	25.14	−14.3%	45.08	−9.4%
May	27.89	13.2%	24.01	7.7%	30.28	−8.2%	52.28	−6.8%
June	24.78	11.3%	20.21	6.6%	33.06	−8.3%	57.24	−9.5%
July	26.44	12.3%	22.21	8.2%	35.65	−2%	58.58	−6.5%
Total	176.57		153.45		156.27		272.16	

3. Results and Discussion

The data collected from the experiment conducted on 5 May 2023, between 7:00 a.m. and 7:00 p.m., with intervals of 30 min, regarding solar radiation (W/m^2) and electricity energy production (W), are presented in Figure 4. On the east-facing panel, the power generated in the early hours of the day reached 211.3 W at 8:00 a.m. and then decreased toward 12:00 p.m. The electrical efficiency of the panel placed on the east facade was found to be an average of 15.98% daily. The total energy produced daily was 1.09 kWh.

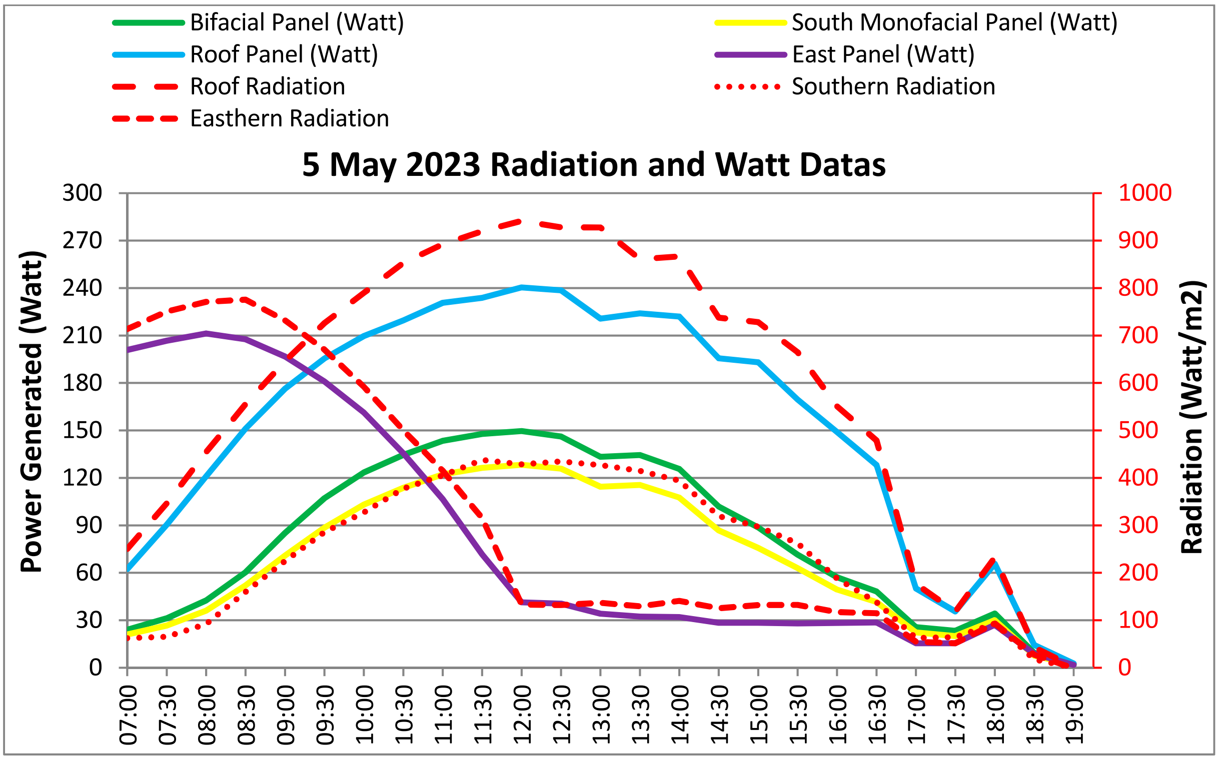

Figure 4. Power and radiation data produced by the experimental setup on 5 May 2023.

For the panel on the roof, as the sun rose, both radiation and power production increased. The highest power production was measured at 240.4 W at 12:00 p.m. As the sun was setting, production decreased. The electrical efficiency of the panel on the roof was found to be an average of 15.65%, and the total daily energy produced was 1.95 kWh. The panel on the roof produced 79% more electrical energy on this date than the panel on the east-facing side. On the south facade, both the monofacial and bifacial panels increased their production parallel to the radiation values as the sun rose, and at 12:00, the monofacial panel produced a maximum power of 128.3 W, while the bifacial panel produced 149.6 W. In the subsequent hours, these values began to decrease. At the hour with the highest power generation of the day, the bifacial panel produced 16.6% more electrical power than the monofacial panel. As seen in Figure 4, the power production curve of the bifacial panel followed a higher trajectory compared with the monofacial panel under the same conditions on the south facade. On this facade, the daily average electrical efficiency of the monofacial panel was 17.53%, while the bifacial panel's average efficiency was found to be 20.54%. The increased production of the bifacial panel compared with the monofacial panel was supported by a 2.9% power difference in the study conducted by Tina et al. (2021) [34]. Because of the influence of its rear surface, the highest efficiency among the four panels was observed in the bifacial panel. In terms of daily average efficiency, the bifacial panel showed a 17.1% gain compared with the monofacial panel on the same facade. In our study, the bifacial panel showed a higher performance compared with the bifacial panel tested in the study by Tina et al. (2021) [34]. Additionally, when comparing the total amount of daily generated energy, the bifacial panel produced 1.04 kWh of energy, while the monofacial panel on the south side produced 0.886 kWh on the same day. Here, too, it was found that the bifacial panel produced 17.3% more energy.

Because of the Sun hitting the Earth at a steeper angle on 5 May compared with the winter months, the highest electricity production on the roof was observed on this date. It was observed that the superiority of the bifacial panel's performance is higher compared with the monofacial panel of the same capacity, and its use in BIPV systems can make production more efficient.

In the experimental setup, the monthly electrical energy data produced in February, March, April, May, June, and July, as well as the error rates of the PVsyst analysis, are provided in Table 2. Because of Şanlıurfa's location in the northern hemisphere, in February, the south-facing façade achieved higher electricity production compared with other facades, as observed in Table 2 and supported by Cronemberger et al. (2012) [13]. During the spring and summer months, a higher level of production was achieved on the roof than on other facades. Additionally, it was observed that the bifacial panel produced more electrical energy compared with the monofacial panel by 11% in February, 11.66% in March, 13.56% in April, 16.16% in May, 22.61% in June, and 19% in July.

The results of the PVsyst analysis for each panel are shown in Table 3. As seen in the results, in terms of energy supplied to the grid, the bifacial panel consistently produced more electricity than the monofacial panel on the south facade, with amounts varying between 4.15% and 16.4% monthly. This situation confirms that more energy is obtained per unit area from the bifacial panel compared with the monofacial panel under the same conditions. In the PVsyst analysis, the panels on the south facade showed high production during autumn and winter. This situation is also supported by the study conducted by Cronemberger et al. (2012) [12], which encourages the installation of BIPV systems on building facades in locations at low latitudes. However, during the summer months, they exhibited low production because of the angle of incoming sunlight. Therefore, it was concluded that systems considered for use as building-integrated photovoltaic thermal (BIPV/T) in Şanlıurfa conditions could be installed on the south facade to produce both thermal and electrical energy more efficiently during the winter.

In winter, the roof panel produces energy ranging from 21.30 to 25.34 kWh monthly, while in summer, it produces monthly energy ranging from 57.17 to 62.8 kWh. Similarly, the panel on the eastern facade produces approximately 15 kWh of energy monthly in the winter, while in the summer, it increases to a monthly production of approximately 36 kWh. In the summer months, the monthly production of the panels on the roof and eastern facade increased more than twice compared with their winter production because of the angle of the sun's arrival. The PV panel on the roof achieved its highest production in June and July as the angle of incoming sunlight increased. This situation is supported both in the experimental setup and in the PVsyst analysis.

The roof facade was identified as the most suitable facade for BIPV installation during the spring, summer, and September (Figure 3). It was found that the east facade also produced better in May and during the summer than the south facade. Especially in June, the panel on the eastern facade, because of the angle of solar radiation, produced approximately twice as much electrical energy as the monofacial panel in the south. The eastern panel reached its highest production value both in the experimental setup (35.65 kWh) and in the PVsyst analysis (36.38 kWh) in July. However, when looking at the annual total, it was observed that the lowest production was on the east side, with 313.35 kWh. Therefore, under the conditions of Şanlıurfa, as found in the studies of researchers such as [18–26], it was observed that the east facade is not suitable for the use in BIPV systems.

Table 3. Annual PVsyst analysis results for the 4 panels.

	Panel Type and Direction	Global Horizontal Irradiation (kWh/m^2)	Horizontal Diffuse Irradiation (kWh/m^2)	Global Incident in Coll. Plane (kWh/m^2)	Effective Global, Corr. for IAM and Shadings (kWh/m^2)	Effective Energy at the Output of the Array (kWh)	Energy Injected into Grid (kWh)
January	Bifacial	77.5	28.30	128.4	122.9	41.29	39.78
	Monofacial	77.5	28.30	128.4	121.9	39.57	38.16
	Eastern	77.5	28.30	54.4	50.2	16.88	16.17
	Roof	77.5	28.30	77.4	69.9	23.43	22.53
February	Bifacial	86.7	42.02	101.9	96.7	32.73	*31.52*
	Monofacial	86.7	42.02	101.9	95.8	31.27	*30.15*
	Eastern	86.7	42.02	55.5	51.2	17.04	*16.33*
	Roof	86.7	42.02	86.6	79.7	26.35	*25.35*
March	Bifacial	142.6	55.15	125.8	116.5	38.78	*37.38*
	Monofacial	142.6	55.15	125.8	115.8	37.18	*35.89*
	Eastern	142.6	55.15	88.0	82.1	26.70	*25.66*
	Roof	142.6	55.15	142.5	132.6	42.26	*40.75*
April	Bifacial	177.0	68.11	103.6	92.3	30.63	*29.46*
	Monofacial	177.0	68.11	103.6	92.6	29.35	*28.27*
	Eastern	177.0	68.11	100.4	93.9	29.89	*28.74*
	Roof	177.0	68.11	177.0	166.4	51.19	*49.34*
May	Bifacial	208.3	73.72	85.5	73.3	25.20	*24.22*
	Monofacial	208.3	73.72	85.5	74.5	23.05	*22.16*
	Eastern	208.3	73.72	118.4	110.8	34.08	*32.79*
	Roof	208.3	73.72	208.2	196.4	57.95	*55.86*
June	Bifacial	243.9	55.32	77.1	63.9	22.91	*21.98*
	Monofacial	243.9	55.32	77.1	65.5	19.68	*18.88*
	Eastern	243.9	55.32	133.8	125.5	37.16	*35.79*
	Roof	243.9	55.32	243.9	231.0	65.04	*62.68*
July	Bifacial	249.2	52.31	84.5	70.6	24.14	*23.20*
	Monofacial	249.2	52.31	84.5	72.3	21.21	*20.39*
	Eastern	249.2	52.31	139.3	130.8	37.78	*36.38*
	Roof	249.2	52.31	249.1	235.6	64.69	*62.36*
August	Bifacial	226.3	47.86	110.8	96.0	29.96	28.83
	Monofacial	226.3	47.86	110.8	97.0	28.35	27.31
	Eastern	226.3	47.86	135.8	127.7	37.16	35.77
	Roof	226.3	47.86	226.3	213.3	59.27	57.17
September	Bifacial	182.9	38.80	142.1	129.1	39.71	38.27
	Monofacial	182.9	38.80	142.1	128.7	38.08	36.75
	Eastern	182.9	38.80	111.1	104.0	30.95	29.77
	Roof	182.9	38.80	182.8	171.2	49.50	47.71
October	Bifacial	130.3	42.08	149.2	140.7	44.48	42.90
	Monofacial	130.3	42.08	149.2	139.4	42.36	40.91
	Eastern	130.3	42.08	85.8	79.8	24.91	23.95
	Roof	130.3	42.08	130.2	120.4	36.83	35.50
November	Bifacial	89.2	31.01	140.9	134.6	43.74	42.17
	Monofacial	89.2	31.01	140.9	133.4	41.74	40.28
	Eastern	89.2	31.01	58.9	54.3	17.61	16.88
	Roof	89.2	31.01	89.2	80.8	26.07	25.08
December	Bifacial	74.3	26.79	136.2	130.7	43.48	41.93
	Monofacial	74.3	26.79	136.2	129.6	41.72	40.26
	Eastern	74.3	26.79	51.5	47.5	15.81	15.13
	Roof	74.3	26.79	74.2	66.5	22.15	21.30
Year Total	Bifacial	*1888.2*	*561.47*	*1386.1*	*1267.3*	*417.04*	*401.65*
	Monofacial	*1888.2*	*561.47*	*1386.1*	*1266.5*	*393.56*	*379.41*
	Eastern	*1888.2*	*561.47*	*1132.9*	*1057.9*	*325.96*	*313.35*
	Roof	*1888.2*	*561.47*	*1887.2*	*1763.7*	*524.74*	*505.64*

As shown in Table 3 of the PVsyst analysis, the four panels produced a total of 1600.05 kWh of electrical energy in one year under the meteorological conditions of Şanlıurfa. The annual sunshine duration of Şanlıurfa is approximately 3055.75 h [45]. The monofacial panel located on the southern facade produced 21% more in the PVsyst analysis, with an annual total electrical energy production of 379.41 kWh, compared with the panel on the eastern facade, which produced 313.35 kWh of energy. Similar to the study conducted by Abotaleb et al. (2018) [12] under the conditions of Şanlıurfa, it was observed that the southern facade has a higher energy potential compared with the eastern facade.

According to the PVsyst analysis, the highest annual total amount of electrical energy—505.64 kWh—was produced on the roof. The highest production being observed on the roof supports the findings of studies conducted by [14,16,17,38]. Under the conditions of Şanlıurfa, the most suitable facade for the BIPV system was determined to be the roof with tilt and azimuth angles set at 0 degrees.

In the PVsyst analysis, the bifacial panel on the south facade produced a total of 401.65 kWh of electrical energy in one year, while the monofacial panel produced 379.41 kWh. In the PVsyst software, the bifacial panel produced 5.86% more electrical energy in one year compared with the monofacial panel. In the experimental setup, over a span of 6 months, the total energy produced by the bifacial panel was 176.57 kWh, while the energy produced by the monofacial panel was 153.45 kWh. In the experimental setup, considering the total energy produced over 6 months, the bifacial panel produced 15.1% more than the monofacial panel. In both cases, the bifacial panel was more efficient compared with the monofacial panel under the same conditions, as found in the study conducted by Tina et al. (2021) [34].

The production of the bifacial panel in the experimental setup, which was 15.1% higher than that of the monofacial panel, was higher than the 5.86% ratio in the PVsyst analysis. The difference in the experimental setup was found to be 9.24% higher compared with the difference in the PVsyst analysis. The reason for this is the placement of a reflective surface with reflecting properties on the back wall of the bifacial panel in the experimental setup. Because of the reflective surface, the solar radiation that seeps behind the panel strikes the reflective surface instead of the wall, elevating the production level of the rear surface of the bifacial panel to higher values. Contrary to the experiment conducted by Kim et al. (2021) [36], the efficiency of the bifacial panel was enhanced by providing a uniform reflection to the panel's rear side through the reflective surface.

When looking at Table 2, the energy amounts produced by all monofacial panels in the experimental setup were found to be higher or lower (error rates) compared with their productions in the PVsyst analysis. However, in Table 2, the amount of energy produced by the bifacial panel in the experimental setup was consistently higher than the production results of the bifacial panel in the PVsyst analysis for every month of the 6-month period, with the exception of March. Thus, it was proven that the aluminum foil used in the experimental setup is an effective reflecting agent, and it enhances the efficiency of the bifacial panel.

As can be seen from the results of the PVsyst analysis (Table 3), the highest annual production was found on the roof, amounting to 505.64 kWh. In addition, in the experimental setup (Table 2), the highest production over 6 months was also observed on the roof. In the experimental setup, it can be anticipated that using the bifacial panel in conjunction with the reflective surface on the roof might produce a greater amount of electrical energy. In general terms, using bifacial panels in BIPV systems enhances the efficiency of the panel. Since there is no significant price difference between bifacial panels and monofacial panels, it does not increase the installation costs either.

4. Conclusions

This study investigated the enhancement of BIPV system efficiency through new technologies and various parameters under Şanlıurfa conditions. The results of the experimental setup conducted between February and July were found to be consistent with the experiment results under the same conditions in the PVsyst software—PVsyst 7.4.

One of the most significant findings in the study is that the bifacial panel on the south facade always operated at a higher efficiency compared with the monofacial panel on the same facade. In the PVsyst analysis, when comparing the total annual electrical energies produced by the bifacial panel and the monofacial panel on the south facade, the bifacial panel produced 5.86% more electrical energy. However, in the experimental setup over 6 months, the bifacial panel provided 15.1% higher production than the monofacial panel. When compared with the PVsyst analysis, the gain of 9.24% in the experimental setup was attributed to the reflective surface used in the experimental setup, which increased the amount of radiation reflected from the building wall, thus resulting in increased efficiency. Furthermore, in the study conducted on 5 May 2023, considering the amount of incoming radiation, it was found that among the four panels, the bifacial panel had the highest efficiency.

During the winter months, solar radiation coming from a more southern direction is expected to increase both electrical energy production and thermal energy production. For this reason, it was determined that it is appropriate to install the BIPV/T system on the south facade during winter under the conditions of Şanlıurfa. For the BIPV system, the direction with the best production was observed to be the horizontally oriented roof, both in the experimental setup and in the PVsyst analysis. Considering that the bifacial panel, in conjunction with its reflective wall surface, achieves a higher electrical efficiency compared with the monofacial panel, it was concluded that the best outcome under the conditions of Şanlıurfa would be a BIPV system implemented on the roof using a bifacial panel.

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