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The Effect of Solar Radiation on the Performance of Tilted Bifacial Photovoltaics

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ABSTRACT

A solar panel technology known as bifacial photovoltaics (PV) allows sunlight to reach both the front and rear of the module. The purpose of this study is to assess how temperature and solar radiation affect tilt-mounted bifacial photovoltaic systems' performance in tropical regions, particularly in Indonesia. The experiment was conducted in an outdoor location in Bandung. The bifacial PV modules were installed a 15˚ tilted angle facing north, with the PV modules positioned 1.2 meters above ground level on an asphalt base. The experiment was conducted under three different weather conditions: sunny, cloudy, and partly cloudy. Based on the experimental results under sunny conditions, the average solar radiation, surface temperature, and PV power generated were 923.8 W/m², 51.1 °C, and 245.7 W, respectively. Under cloudy conditions, the average solar radiation, surface temperature, and PV power generated were 458.9 W/m², 43.1 °C, and 91 W, respectively. Meanwhile, under partly cloudy conditions, the average solar radiation, surface temperature, and PV power output are 661.6 W/m², 50.2 °C, and 215.8 W, respectively. The highest efficiency was achieved during partly cloudy weather at 15.85%, followed by sunny weather at 11.99%, and the lowest during cloudy weather at 7.73%.

1. INTRODUCTION

The annual increase in energy consumption is expected to be 1.5% by 2030. Developing countries in Asia, including Indonesia, are suffering from this situation and need to explore the use of energy other than fossil energy (Zhukovskiy *et al*., 2021; Resosudarmo *et al*., 2023). The energy in question is renewable and includes solar, geothermal, wind, biomass, and ocean waves (Rahman *et al*., 2022).

The Indonesian government, while attending the 26th COP on November 2, 2021, committed to reducing emissions and contributing faster to a net-zero emission world (Bhat, 2024). One of the steps to reduce emissions is to diversify fossil fuels into renewable energy sources. By 2025, the Government targets a new and renewable energy share of 23% (Erdiwansyah *et al*., 2019). To achieve this target, the Ministry of Energy and Mineral Resources (ESDM) is encouraging the construction of Solar Power Plants (PLTS), both small-scale rooftop PLTS, floating PLTS, and large-scale PLTS spread throughout Indonesia (Rochmad *et al*., 2023).

Photovoltaic (PV) modules are a technology that converts energy from sunlight into electricity (Dambhare *et al*., 2021: Husni *et al*., 2022). However, because it depends on a number of variables, such as temperature and solar radiation levels, the energy generated by PV panels is somewhat erratic (Alami *et al*., 2022). Weather, the sun's position, and other factors affect the amount of solar radiation that reaches the PV panel's surface (Yao *et al*., 2022; Farahmand *et al*., 2021). Meanwhile, the temperature of the PV panel is influenced by the ambient temperature and the heat generated by the panel when operating (Dong *et al*., 2025). Thus, the purpose of this study was to ascertain if temperature and solar radiation have a beneficial or detrimental impact on the electricity produced by PV panels.

The latest innovation in PV technology is the use of bifacial panels. Bifacial photovoltaic is a solar panel technology that can capture sunlight on both sides of the panel, both the front side and the back side (Guerrero-Lemus *et al*., 2016). This is different from monofacial solar panels that only capture light on the front side. Studies comparing the performance of bifacial and monofacial photovoltaic modules have found that bifacial PV can improve energy by up to 20%. Thus, bifacial PV modules are much more effective and efficient compared to monofacial PV modules (Ayu *et al*., 2024).

Bifacial PV offers the potential for significant energy improvements, but there are still some challenges that need to be overcome to increase its use. Non-optimal orientation and placement of panels can reduce panel performance, especially the inclination angle which can create shading and then affect the performance of bifacial panels. As a result, even if bifacial solar panels are now more efficient overall, some elements could still use innovation and development. In one instance, the tilted bifacial module outperformed the monofacial module by 7.85%. The energy output of the bifacial module was 16.2% higher than that of the monofacial module when its albedo was increased. It may be inferred that bifacial modules installed with consideration for albedo and a specific slope will have a better energy output than panels positioned flat since albedo is the capacity of the surface surrounding the solar panel to reflect sunlight back to the panel (Alam *et al*., 2023). This is the basis of this research to solve the challenges and accelerate the adoption of bifacial panels into a wider renewable energy potential considering that renewable energy is currently increasingly competitive (Raina & Sinha, 2022). Bifacial panels have capabilities that can be a consideration for people or agencies that will install solar power plants, namely from the special feature that distinguishes them from conventional solar panels is that they can absorb solar radiation from both sides, both from the direct direction and from the reflection of the surrounding surface (Prasad and Prasad, 2023). Therefore, it makes bifacial PV more efficient because it can produce more electrical energy compared to conventional solar panels (Raina & Sinha, 2021). Furthermore, due to the bifacial panel's ability to absorb light from both sides makes it more tolerant to the shadow effect which means that if one part of the panel is covered by a shadow, the other part can still generate electricity, resulting in a reduction of the impact of shadows on the overall performance of the system and making bifacial PV more effective than monofacial PV (Abotaleb & Abdallah, 2018).

Currently, research on PV performance has been carried out. However, research on bifacial PV is still rarely done, especially in tropical climates such as Indonesia (Abojela *et al*., 2023). Where sunlight exists throughout the year but weather conditions are mostly cloudy and relatively high rainfall and some areas in Indonesia with high ambient temperatures so it is necessary to research bifacial PV which has a higher efficiency than monofacial PV. This research assesses how temperature and solar radiation affect the performance of a bifacial photovoltaic system mounted on a tilted in the tropics, especially in Indonesia.

The photoelectric effect is the same concept that powers mPV and bifacial PV technology. In contrast to mPV, bPV cells have a rear contact on the back side of the PV cell in place of the rear surface field, as well as an anti-reflection layer. Its ability to collect sunlight from both sides is the cause of this. Light from both sides of the PV cell passes through the anti-reflection layer when it is exposed to sunshine. Photons with energies higher than the band gap partially transfer their energy to electrons to form electron-hole pairs. Instead of recombining, carriers produced close to the semiconductor's depletion area diffuse to the substrate and emitter. The internal electric field pulls the carriers in, causing electrons to flow into the N-type semiconductor and holes to flow into the P-type semiconductor. The front and rear contacts consequently create an electromotive force. Once the PV cell's two sides are linked, electrons move via the external load (Kopecek & Libal, 2021).

In contrast to the mPV module, Figure 1 displays the bPV module's appearance from both the front and back perspectives. Since most bifacial modules are made of double glass, they can be constructed with or without a frame. Because they are easier to install and more stable, bifacial modules with frames are becoming more and more popular. The junction box's shallow form prevents shadows from falling on the rear side. Ethylvinylacetate (EVA) is utilized as an encapsulant for p-type cells, but polyolefin elastomer (POE) is employed for n-type cells to reduce PID (Potential Induced Degradation), which is more difficult for n-type cells to lower at the cellular level than for p-type cells. To

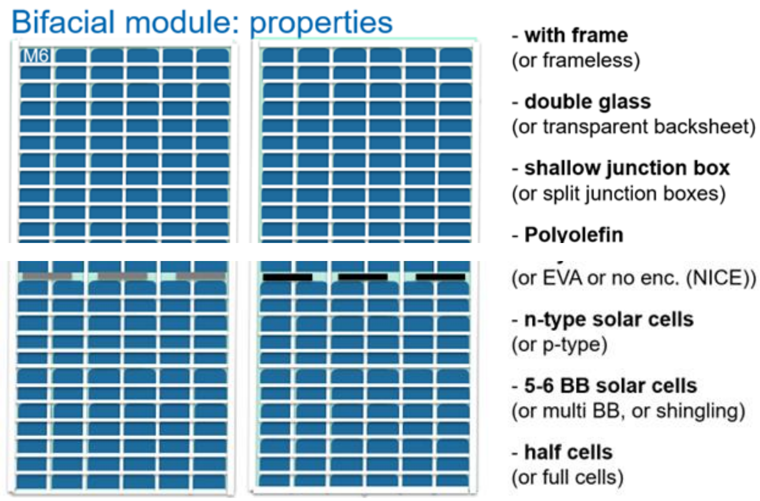

Figure 1. Bifacial PV module and its parts: Left side is rear view and Right side is front view

prevent rising resistive power losses in the junction tape, as the current increases with greater efficiency and bifaciality, the cells must be split into two or even smaller sections and the number of busbars must be increased. Bifacial modules differ mainly in that they have white reflectors between the cells to prevent the front side power from being reduced because light exits through the gaps between the solar cells instead of being reflected back into the module as is the case with monofacial modules with a white backsheet.

Most PV panels, especially silicon-based ones, experience a decrease in efficiency as the temperature increases. Each PV panel has a temperature coefficient that indicates how much its efficiency decreases with increasing temperature. Typically, a temperature increase of about 1 °C can reduce the output efficiency by about 0.4% to 0.5%. Higher temperatures cause the electrons produced by the PV panel to move faster, but with more energy lost as heat, which reduces the panel's ability to generate electricity.

2. MATERIALS AND METHODS

This experiment was conducted in an open space located in Bandung, Indonesia (6.9215˚, 107.611˚). In this experiment, the bifacial PV module was installed at an angle facing north with a PV module tilted of 15˚, where the angle of inclination is the optimal PV angle in Indonesia (Sugirianta *et al*., 2020). The height of the bifacial PV from the ground was 1.2 m² with an asphalt base. The experiment was conducted under three different weather conditions: clear, cloudy, and partly cloudy. Electrical and environmental parameters were measured using a data logger from 9:00 AM to 4:00 PM, with data collected every minute.

(A) (B) (C) (D)

Figure 2. Exsperimental setup: (A) System scheme; (B) Modul PV facing north, tilted 15˚; (B) data logger ; (C) Load

Figure 2 shows a schematic drawing of the bifacial PV system followed by experimental setup consisting of PV modules, data loggers, and loads. The PV module as a power source is directly connected to the load. The power supply from the PV module to the load is recorded in a data logger. In this research, it was conducted without battery because the aim was to observe the pure electrical source generated by the PV module under various weather conditions.

A Bifacial PV Module with a 440 WP capacity and a 2.1 m² surface area was used in this experiment. Table 1 provides further information on the Bifacial PV specs. Bifacial PV module loading uses Pure resistive with a capacity of 400 W. While the Datalogger functions to measure the parameters of Solar Radiation, Voltage, Current, Environmental Temperature, Front PV Temperature, and Back PV Temperature.

Table 1. Bifacial PV Module Specifications

Testing Condition	**STC (Standard Test Conditions)**
Maximum Power (Pmax) [W]	440
Power Tolerance [%]	± 3
Open Circuit Voltage (Voc) [V]	49.09
Short Curcuit Voltage (Isc) [A]	11.13
Voltage at Maximum Power (Vmp) [V]	41.84
Current at Maximum Power (Imp) [A]	10.54
Module Efficiency [%]	20.24
Dimension [mm]	2094 x 1038 x 35

Table 2. Specifications and measuring instrument

Instrument	**Spec / Range**
Pyranometer	SEM228, 0-1800 W/m²
Temperature sensor	DS18B20
Temperature ambient	DHT 22
Power meter	0.1 – 3 kW

Testing of tilted bifacial PV modules uses several measurement parameters, including: solar radiation intensity, ambient temperature, front and rear module temperatures, and bifacial PV module power generation. The specifications of the measuring instruments used can be seen in Table 2. The efficiency of a PV module is the ratio of output power to input power. Here are the details of the PV module efficiency equation.

$$\eta = \frac{P_{out}}{G \ x \ A} \tag{1}$$

where η is the electrical efficiency of the PV module (%), P_out is the PV output power (W), G is the solar radiation (W/m²), and A is the surface area of the PV module (m²).

3. RESULTS AND DISCUSSION

3.1. Solar Radiation and Ambient Temperature

Global solar radiation measurements were taken using a pyranometer positioned to follow the upward slope of the PV, while measurements of the surrounding environmental conditions were also taken. This can be seen in Figure 3. Based on Figure 3a, solar radiation under clear weather conditions peaks at 11:52 a.m. with a range of 1332 W/m². The average solar radiation is around 923 W/m². Meanwhile, the ambient temperature from morning to midday increases from 30 ℃ to 36 ℃. From midday to evening, as solar radiation tends to decrease, the opposite occurs with the ambient temperature, which remains stable at an average of 37 ℃ despite the decrease in solar radiation. The intensity of solar radiation and ambient temperature in cloudy conditions can be seen in Figure 3b. Solar radiation under cloudy weather conditions peaks at 12:57 p.m. with a range of 929 W/m². The average solar radiation is around 458 W/m². Meanwhile, the ambient temperature from morning to noon, coinciding with the surge in solar radiation, also increases from 26.9 ℃ to 35.4 ℃. The average ambient temperature under cloudy weather conditions is around 30.5 ℃. The intensity of solar radiation and ambient temperature in clear cloudy conditions can be seen in Figure 3c.

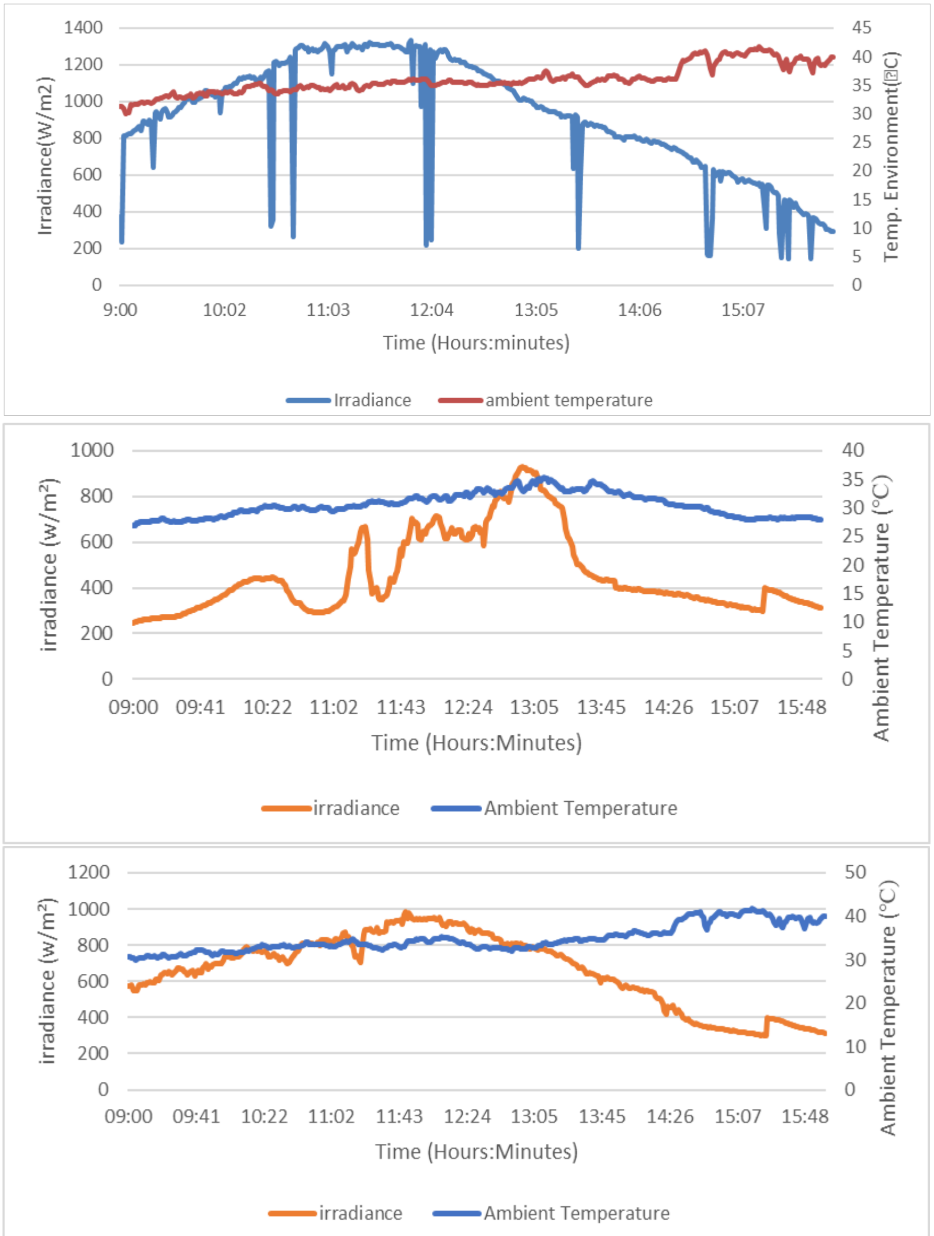

Figure 3. Solar radiation intensity and ambient temperature at three sky conditions: (a) sunny, (b) cloudy, (c) clear cloudy

Based on Figure 3c, solar radiation under clear and cloudy weather conditions peaks at 11:47 a.m. with a range of 986 W/m². The average solar radiation is around 661 W/m². Meanwhile, the ambient temperature remains relatively stable at 33 °C from morning until the afternoon. The average ambient temperature under clear and cloudy weather conditions is around 34 °C.

3.2. Front and Rear Temperature of the Bifacial PV Module

PV module measurements are taken on the front and rear. High solar radiation intensity can cause relatively high ambient temperatures, which can affect the surface temperature of the PV module. In general, PV modules have a negative temperature coefficient (NTC) that affects the reduction in PV module efficiency. Figure 4 shows the profile of a bifacial PV module on the front and rear sides in sunny conditions.

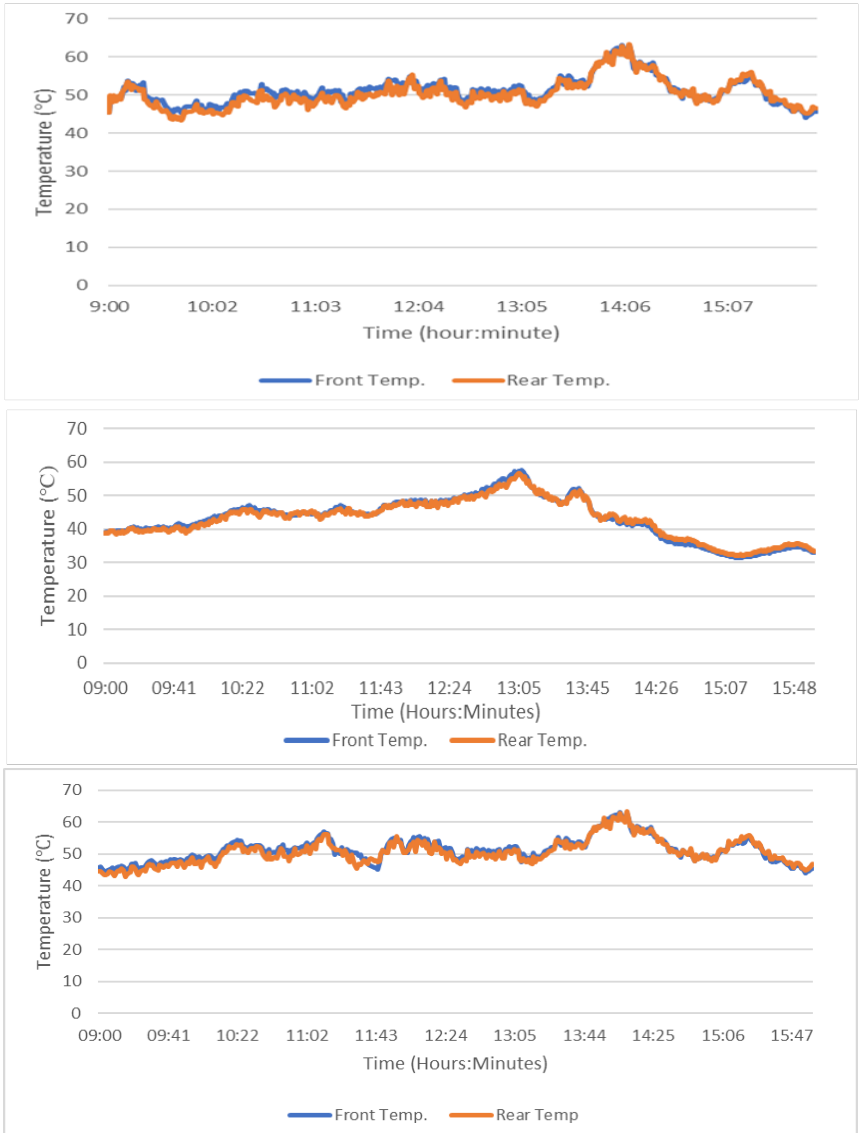

Figure 4. Front and rear temperature of bifacial PV module at three sky conditions: (a) sunny, (b) cloudy, (c) clear cloudy

Based on Figure 4a, the temperature of the front of the bifacial PV module tends to be stable from 9:00 a.m. to 12:00 p.m. at 49 °C, while the temperature of the rear of the PV module is at 48 °C. Meanwhile, the average temperature of the PV module from 12:01 PM to 4:00 PM WIB shows that the front side of the PV module is at 52 °C and the rear side at 51 °C. Despite the decrease in solar radiation, the temperature remains stable and does not drop immediately because the bifacial PV module does not cool down quickly nor heat up quickly. The average temperature of the front side is slightly higher than the rear side, though the difference is not significant, only around 1 °C.

Figure 4b shows the profile of a bifacial PV module on the front and rear under cloudy conditions. The temperature of the front side of the bifacial PV module tends to rise from 9:00 a.m. to 1:00 p.m., increasing by approximately 18.8 °C from 38.8 °C to 57.6 °C. From 1:00 p.m. to 4:00 p.m., the temperature gradually decreases in tandem with the decline in solar radiation. The average front temperature of the bifacial PV module is 43.1 °C. Meanwhile, the rear temperature of the bifacial PV module is generally the same as the front temperature, but with a very slight difference of approximately 1–2 °C. Figure 4c shows the profile of a bifacial PV module on the front and rear under sunny cloudy conditions. The temperature of the front of the bifacial PV module tended to be stable from

9:00 a.m. to 1:15 p.m. at 50 °C, while the temperature of the rear of the PV module was 49 °C. While, the average temperature of the PV from 1:15 p.m. to 4:00 p.m. was 50.2 °C for the front of the PV and 50.6 °C for the rear of the PV.

3.3. Bifacial PV Power Generation

PV power generation measurements are performed at DC voltage in order to eliminate losses caused by the GTI control system or AC voltage. PV power generation under sunny conditions can be seen in Figure 5a. The power generation of the bifacial PV module is shown under sunny conditions. The power follows the intensity of solar radiation, where there is a significant decrease in power due to solar radiation being blocked by clouds. The maximum power generated is 392.3 W at 09:52. Meanwhile, the average power generated is 245.7 W. PV power generation under cloudy conditions can be seen in Figure 5b. The power generation of the bifacial PV module in cloudy weather is shown. The maximum power generated was 321.91 W at 12:57 p.m. Meanwhile, the average power generation from morning to afternoon was around 91 W. PV power generation under sunny cloudy conditions can be seen in Figure 5c.

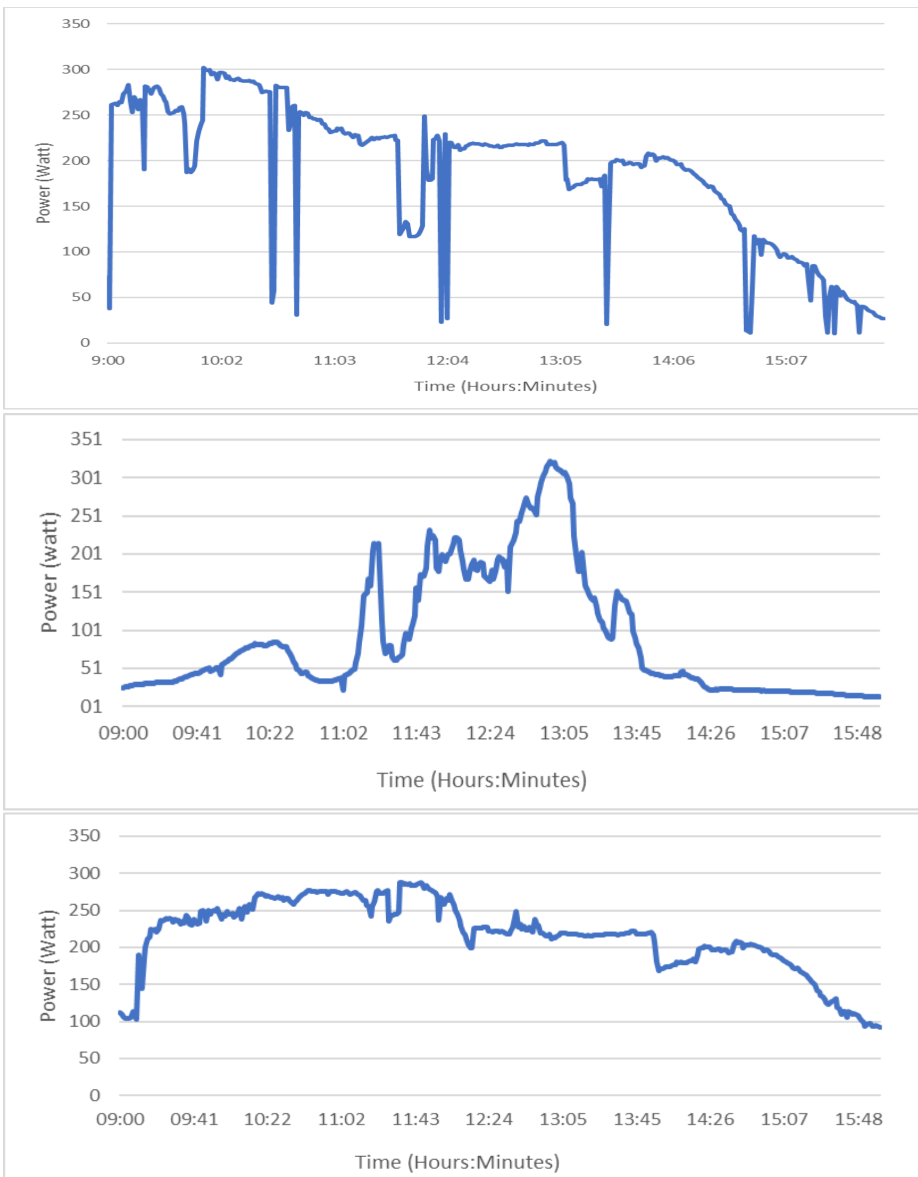

Figure 5. Power output of bifacial PV module at three sky conditions: (a) sunny, (b) cloudy, (c) clear cloudy

Based on Figure 5c, the power generation of the bifacial PV module is shown in sunny and cloudy weather. The maximum power generation produced is 288 W at 11:36 a.m. Meanwhile, the average power generation from morning to afternoon is around 215 W.

3.4. Energy Efficiency

Based on the results of solar radiation measurements under clear, cloudy, and partly cloudy conditions shown in Figures 3 and the PV output power visible in Figures 5, with a PV module cross-sectional area of 2.17 m², the efficiency of the PV module can be determined using equation (1). The efficiency graphs for the PV module can be seen in Figures 6.

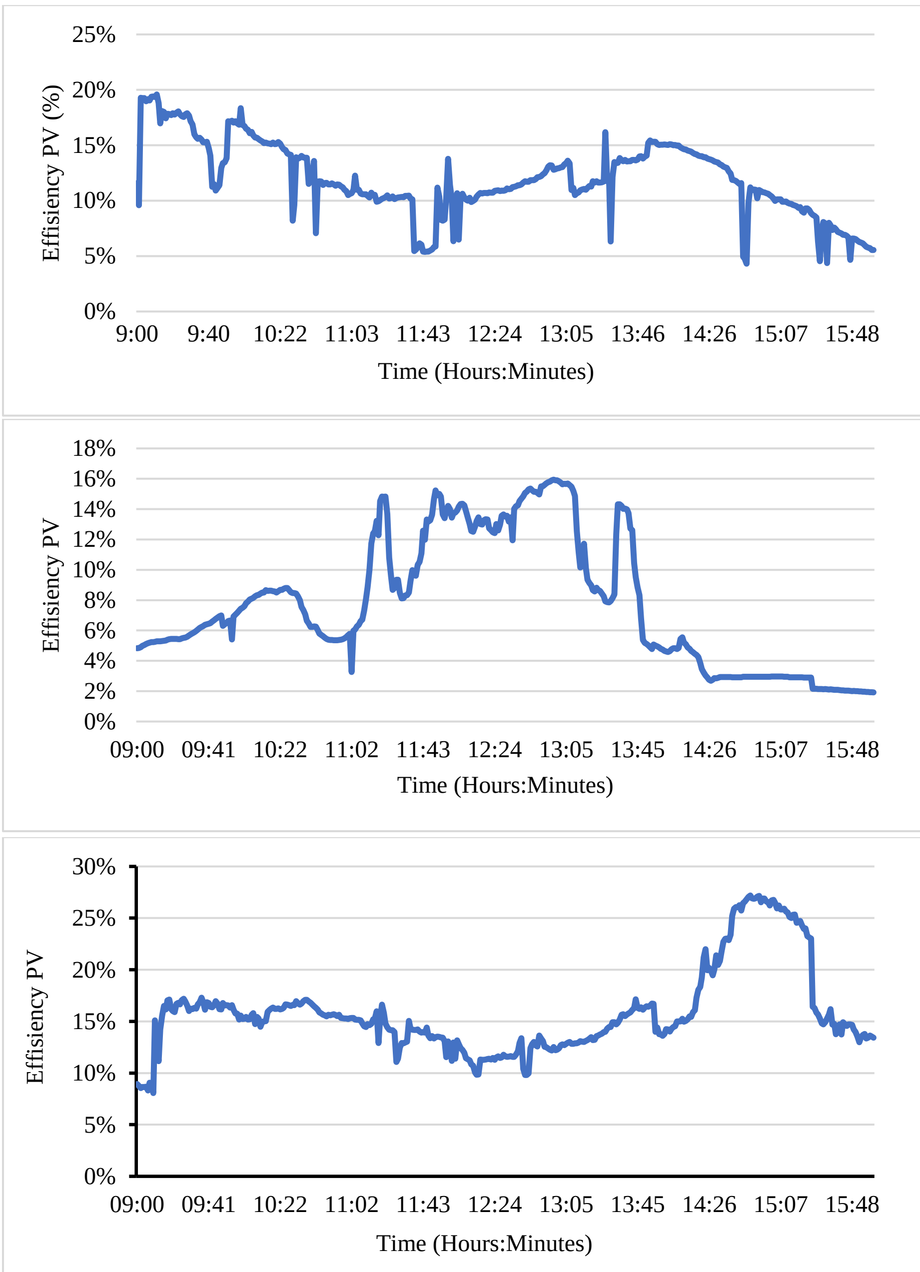

Figure 6. Efficiency of bifacial PV modules at three sky conditions: (a) sunny, (b) cloudy, (c) clear cloudy

Based on Figure 6a, the minimum efficiency of the bifacial PV module is 4.32% at 14:48, with a maximum efficiency of 19.58% at 09:11 and an average efficiency of the bifacial PV module of 11.99%. The efficiency of PV modules in cloudy weather can be seen in Figure 6b. The minimum efficiency of the bifacial PV module is 1.92% at 15:59, with a maximum efficiency of 15.94% at 12:57 and an average efficiency of the bifacial PV module of 7.73%. The efficiency of the PV module in partly cloudy weather can be seen in Figure 6c. The minimum efficiency of the bifacial PV module is 8.06% at 09:09, with a maximum efficiency of 27.19% at 14:50, and an average efficiency of the bifacial PV module of 15.85%.

Regardless of weather conditions, the maximum efficiency of BPV in our study reached 15.94–27.19%. These results are within the range reported by other researchers. In bifacial PV testing in Pakistan, Mahmood et al. (2023) reported a maximum efficiency of 18.1%. Meanwhile, Almarshoud et al. (2024) reported bifacial PV efficiencies ranging from 18 to 22% depending on the background type, higher than the monofacial PV efficiency of only 16%. Based on research conducted by (Braga *et al*., 2023), it is stated that the maximum efficiency of bifacial PV in the tropical climate of Brazil ranges from 18% to 19%. Meanwhile, in Indonesia, which also has a tropical climate, the efficiency of PV modules ranges from 15.36% to 19.58%. Therefore, results of our research are reasonable.

4. CONCLUSION

The tilted bifacial PV module installed shows that on a sunny day with maximum solar radiation of 1332 W/m² (11:52) and an average of 923 W/m², on a cloudy day with a maximum of 929 W/m² (12:57) and an average of 458 W/m², and on a partly cloudy day with a maximum of 986 W/m² (11:47) and an average of 661 W/m². The temperature module of bifacial PV tends to be stable in sunny weather, with the front at 51 °C and the back at 50 °C. In cloudy weather, the front is 43.1 °C and the back is 43 °C. In partly cloudy weather, the front is 52.7 °C and the back is 52.6 °C. The temperature difference between the front and back is only about 1 °C. The power generation of the bifacial PV module in maximum clear weather is 392.3 W (09:52) with an average of 245.7 W. In cloudy weather conditions, the maximum power is 321.91 W (12:57) with an average of 91 W. And in partly cloudy weather conditions, the maximum power is 288 W (11:36) with an average of 215 W. Based on the measurement results, the energy efficiency of bifacial PV modules varies according to weather conditions. The highest efficiency was achieved during partly cloudy weather at 15.85%, followed by sunny weather at 11.99%, and the lowest during cloudy weather at 7.73%. This indicates that sufficient radiation intensity with even light distribution can increase the efficiency of bifacial PV modules. Further research could be conducted by developing a cooling system for PV modules or varying the surface base, such as using white paint, to improve the performance of the PV modules.

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