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Energy yields and performance analysis of vertical and tilted oriented bifacial photovoltaic modules in tropical region

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ABSTRACT

This study experimentally investigates the performance of bifacial photovoltaic (bPV) modules under vertical and tilted orientations in a tropical region. Related studies are reviewed, then performance metrics including solar radiation, module temperature, bifaciality gain, and energy yield were monitored and analyzed over a specified period. The aim is to determine the optimal orientation for maximizing output power generation, temperature module, and understanding the bifaciality factor through real-world conditions. The experimental setup consisted of three different bifacial photovoltaic module configurations: two vertically mounted with facing East-West (E/W) and North-South (N/S) respectively, while the third was tilted 15° facing North. The study findings revealed that the tilted orientation produced the highest energy yield of 1951 Wh, followed by the vertical East-West (E/W) and vertical North-South (N/S) orientations with 1504 Wh and 609 Wh, respectively. While tilted bPV module benefit from higher irradiance, they also experience elevated temperatures (39% above ambient) compared to vertically bPV modules (8-21%). This can negatively affect efficiency, especially during peak solar hours. The results also show that differences in bPV installation orientation affect the bifaciality factor and gain. These findings offer valuable guidance for optimizing bPV system design and deployment in tropical regions with low latitude, supporting sustainable energy solutions.

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1. INTRODUCTION

In recent years, bifacial photovoltaic (bPV) module has garnered significant attention as a groundbreaking advancement in solar energy technology. Traditional PV modules, however, have limitations in terms of energy harvesting efficiency due to their ability in solar absorbing only from front side. Unlike their monofacial photovoltaic (mPV), bPV modules are capable of generating electricity from both their front and rear sides. By incorporating materials that allow light penetration, bPV module can capture additional energy from reflected sunlight, ambient light, and even light reflected from the ground or surrounding surface. The innovative design of bPV module offers the potential to significantly increase energy yield, increasing efficiency by 6.5% - 11% compared to mPV module, especially in environments with high albedo or reflective surfaces [1]–[3]. Furthermore, recent advancements in bifacial cell design and manufacturing have unveiled several benefits. Notably, these cells operate at cooler temperature due to reduced infrared absorption on the rear surface, and they exhibit improved temperature coefficient, collectively enhancing their lifespan and decreasing levelized costs of electricity (LCOE) [4].

Obviously, bPV module performance is significantly influenced by solar radiation and its reflection. The type of surrounding objects, acting as reflectors, plays a crucial role in boosting energy output of module. To optimize bPV performance, precise module orientation is essential. The orientation can be either vertical or tilted, depending on location and environmental conditions which has various results in many parts of the world. Several studies in subtropical countries in Europe, South Africa, North America and North Asia show that there is an increase in energy acquisition of bPV module with results varying from 2%-12% [5]–[7] . Other studies conclude that the influence of location (latitude position) are very dominant in determining the installation angle, and the change from summer to winter also affects the optimum installation angle [8]. Meanwhile, for tropical regions, several studies have concluded that for bPV modules installed on rooftops in Singapore can generate nearly 10% more energy compared to traditional mPV modules. However, their performance dropped significantly when installed vertically facing East/West, compared to an optimal tilt angle facing South [9]. Similar results were observed in performance evaluations of bPV modules in Nigeria. Energy gains from these modules vary depend on the climate and significantly influenced by factors such as surface reflectivity (albedo), module tilt angle, and ground clearance [10]. A related study in Brazil emphasized the critical role of albedo in bPV module performance. By optimizing ground condition, significant power gains are possible. Installing modules over soil/vegetation (albedo of 0.20) yielded an average bifacial gain of 7%, and an increase of 3.5% when mounted over polymer with an albedo of 0.50 [11], [12].

The existence of bVC module is one of the new breakthroughs that should be explored and evaluated in improving the weaknesses of existing mPV module, especially in tropical areas such as Indonesia which have abundant sunlight and diffusion content of more than 50% of total irradiation. Several studies in subtropical region demonstrated that energy gain varies significantly based on geographic location and surrounding environmental factors such as reflective surfaces and indirect light diffusion. To address the knowledge gap in tropical regions, this study evaluates the performance of bPV modules under the specific conditions in Bandung, Indonesia. The research aims to compare the performance of bPV modules both vertical and tilted orientations across different climate zones, analyzing energy yields, albedo effects, and the impact of shading on module performance. By filling these research gaps, this study contributes to the advancement of bifacial PV technology and its broader application in various geographic locations.

2. METHOD AND PERFORMANCE PARAMETERS

2.1. Module orientations

In this study, various orientations of bPV modules were tested and some typical parameters were compared as a method to determine the best performance. The bPV module orientation refers to the direction a module faces. This is a crucial factor in determining the plane of array (POA) of solar radiation captured by both the front and rear surfaces of the module. For tropical regions, especially along the equator and its surroundings, its generally experience sunlight where its position is exactly perpendicular to the ground. In testing the performance of bPV modules, three orientations of bPV module installation can be carried out, including: vertically with North-South orientation (N/S), the second was installed vertically with East-West orientation (E/W), and the last one was a module with tilted orientation. To visualize it, there are three possible installations to test the bifacial module with various orientations and compare their performance as shown in Figure 1.

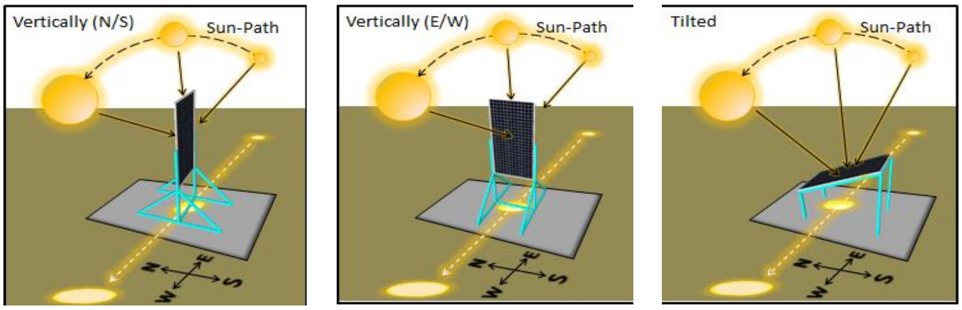
The geographic location including latitude and longitude for the installation location affects the optimal orientation whether the module is mounted vertically or tilted influenced by seasonal periods [13], [14]. Vertically oriented modules offer advantages such as reduced soiling, easier cleaning, and lower wind resistance, making them suitable for space-constrained areas [15], [16]. However, module with tilted oriented generally capture more sunlight, especially when combined with ground surface reflectivity improvements. The application of bifacial module orientation also varies depending on the field area where the module application will be used.

2.2. Module temperature

The cell temperature (T_c) is estimated with reference module temperatures measured during nominal operating cell temperature (NOCT) with the (1) [17]–[19]:

$$Tc = \left[\frac{I_{tot}}{800}.\frac{9{,}5}{(5{,}7+3{,}8\,.v)}.\left(1-\frac{\eta_c}{0{,}9}\right).(T_{NOCT})-20\right]+T_a \quad (1)$$

where, T_a is the ambient temperature, I_{tot} is the incident solar radiation consists of the sum of the front (I_f) and rear (I_r) currents with a bifaciality factor (BF), v is the wind velocity, η_c is the efficiency of module, and T_{NOCT} is the module temperature at normal operating conditions. Bifacial glass-glass modules experience a notably higher heat input as rear irradiance increases compared to monofacial modules with white rear sheets. While this additional heat input generally leads to higher module temperatures, the effect is mitigated by heat transfer processes. Consequently, bPV module only exhibit higher temperatures than their mPV counterparts when rear irradiance exceeds 15% of total irradiance. Despite this temperature increase, due to the large bifacial gain results in significantly higher energy yield [20].



(a) (b) (c)

Figure 1. Possibilities of bPV module orientation (a) vertical (N/S), (b) vertical (E/W), and (c) tilted (N)

2.3. Albeldo

Albedo is represented as the ratio of light reflected from various sources of surface compared to incident radiation. It is expressed as a value between 0% equates to no reflected light and 100% that represents perfect reflection or it reflects all light [21], [22]. In the context of solar energy, albedo refers to the proportion of solar radiation reflected by a surface. Albedo (λ) is typically expressed as a percentage that represents the ratio of sunlight reflection (R_L) to direct (incident) sunlight (I_L) on a surface, as calculated by (2) [23]:

$$\lambda = \frac{R_L}{I_L} \quad (2)$$

The electric power can be generated from both their front and rear surfaces. They capture not only direct sunlight but also light reflected from the ground and diffused light from surrounding objects such as clouds and other air particles. This dual-sided design, utilizing` standard silicon cells, significantly increases energy yield by harnessing additional light. Performance is particularly enhanced in environments with high ground reflectivity, such as those with engineered reflective ground covers [24]. Albedo significantly impacts bifacial module performance in several ways. Higher albedo surfaces reflect more sunlight onto the rear of bifacial modules, increased energy yield. Areas with high albedo, such as snow-covered fields or deserts, are prime locations for maximizing bifacial module efficiency. Table 1 shows the ground surface materials including their albedo values [25]. By carefully considering module angle and orientation, system designers can optimize the capture of reflected sunlight, further increasing energy yield.

Table 1. Albedo values by surface type [25]

Surface Type	Albedo (%)	Surface Type	Albedo (%)
Corrugated roof	10 – 15	Red/brown roof tiles	10 – 35
Colored paint	15 – 35	Brick/stone	20 – 40
Trees	15 – 18	Oceans	5 – 10
Asphalt	5 – 20	Old snow	65 – 81
Concrete	25 – 70	Fresh snow	81 – 88
Grass	25 – 30	White paint	50 – 90
Ice	30 – 50		

Meanwhile, the module elevation refers to the height of the module above the ground. This seemingly simple parameter has a significant impact on the overall performance of a bifacial solar system. A higher elevation allows the module to capture more reflected light from the ground and then increase the overall energy yield. Module height (H) refers to the vertical distance between the ground and the bottom of a mounted solar module which is determinates by (3) [26]:

$$H = \frac{H_{ag}}{L_m} \quad (3)$$

where H_{ag} is the height above ground and L_m is the length of the module. While there's no one-size-fits-all answer for the optimal elevation, studies and industry recommendations suggest a range of 1 to 1.3 meters as a good starting point [27]. By carefully considering these factors and conducting site-specific analysis, it is possible to determine the optimal elevation for a bifacial solar project to maximize energy yield while minimizing costs and risks

2.4. The bifaciality factor and gain

The bifaciality factor (φ) is the ratio of the power generated (P_{max}) by the rear side to the front side of the module under identical light conditions. It is a crucial metric in the realm of solar energy, specifically pertaining to bifacial solar modules. In addition to electrical power, the bifacial factor can also be determined based on efficiency (η) approaches that generate from both its front and rear surfaces as expressed in (4) and (5) [2]:

$$\varphi P_{Max} = \frac{P_{M,r}}{P_{mf}} \times 100\% \quad (4)$$

$$\varphi\eta = \frac{\eta_r}{\eta_f} \times 100\% \quad (5)$$

The bifaciality factor helps determine the overall energy yield of a bifacial module. By considering the rear-side power generation, system designers can optimize the module's placement and orientation for maximum efficiency and gain. Meanwhile the bifaciality gain (BG) is a metric that quantifies the performance improvement of a bifacial (bPV) module compared to a monofacial (mPV) module under the same conditions. It represents the percentage increase in energy output due to the ability of the bifacial module to capture sunlight from both its front and rear surfaces as expressed in (6) [28]:

$$BG(\%) = \frac{Y_{bPV} - Y_{mPV}}{Y_{mPV}} \times 100 \quad (6)$$

where Y_{bPV} and Y_{mPV} are the energy yield of bPV and mPV module, respectively. The higher bifaciality gain leads to increased energy production and potentially lower levelized cost of electricity ($LCOE$). By carefully considering this metric, system designers can optimize module orientation and spacing to maximize energy output, while solar energy system owners and developers can make informed decisions to enhance the performance and profitability of their installations. Comparing the bifaciality gain of different module models also aids in selecting the most efficient option.

3. EXPERIMENTAL SETUP

In this study, the specific location and time of testing were performed in the city of Bandung, Indonesia on October 2th, 2024, which is located precisely at -6.8990° South latitude and 107.6465° West longitudinal. In accordance with the observation results at the test location, the position of the sun motion at that time was exactly perpendicular above region of the site location from morning to evening. The first module was installed vertically with N/S orientation, the second was installed vertically with E/W orientation, and the last one was a module with 15° tilt oriented to the North. All modules were installed on an asphalt surface with a certain albedo (λ_m) at an elevation (H_m) of 1 m and with actual environmental conditions that surrounded by random structures. The module type with electrical and mechanical specifications according to STC- Standard (1000 W/m^2, 25 °C, and AM1.5) was as shown in Table 2.

In comparing its performance, each electrical output of module directly connected to the grid-tie inverter (GTI). GTI used to maximize power generation from solar modules by utilizing the maximum power point tracking (MPPT) mechanism within its control system, then it converts the DC voltage from the module and synchronizes it with the AC voltage of the utility grid. In essence, the GTI takes the solar energy captured by bifacial modules and transforms it into electricity that can be fed into the grid. Each GTI in this installation has a rated power output of 1000 W, operating with an input voltage range of 20-60 VDC and producing an output voltage of 220 VAC ±5% as grid synchronized voltage. In detail, the test setup of each module was equipped with a measurement system as shown in Figure 2. For analysis purposes, the measuring system was equipped by several sensors that record parameters and their changes including: solar radiation intensity, module temperature on both front and rear sides, ambient temperature, humidity, voltage and current. The entire experimental setup can be shown as in Figure 3.

Two SEM228 Pyranometers have been used to read the intensity of solar radiation (W/m^2) installed on the front side of the module related to direct light and the rear side related to diffuse light including reflection. Likewise, the temperature reading on both sides of the module surface is carried out using two K-type temperature sensors. Meanwhile, a DHT22 sensor used to read the ambient temperature (°C) and humidity (%) which can affect the module temperature, then the output voltage (V) and current (A) of the module are measured by the sensor integrated in the PZEM-017 as an energy meter. These parameter values were recorded and stored in memory using a data logger (VSCLAR, SM-02) for further investigation and analyzed.

Table 2. Electrical and mechanical specifications of bPV module, model: ISG-SGBi144

Electrical specifications		Mechanical specifications	
Item	Descriptions	Item	Descriptions
Maximum power (W)	440	Cell type	Mono-Si PERC
Voltage maximum (V)	41.84	Number of cell (pcs)	144
Current maximum (A)	10.54	Cell arrangement	2×(6×12)
Voltage at open circuit (V)	49.09	Dimension (mm)	2094×1038×35
Current short circuit (A)	11.13	Weight (Kg)	22.7
Efficiency	20.24 - 0.42	Frame	Anodized Aluminum Alloy
Temp. Coefficient of P_{max} (%/°C)	-0.42		

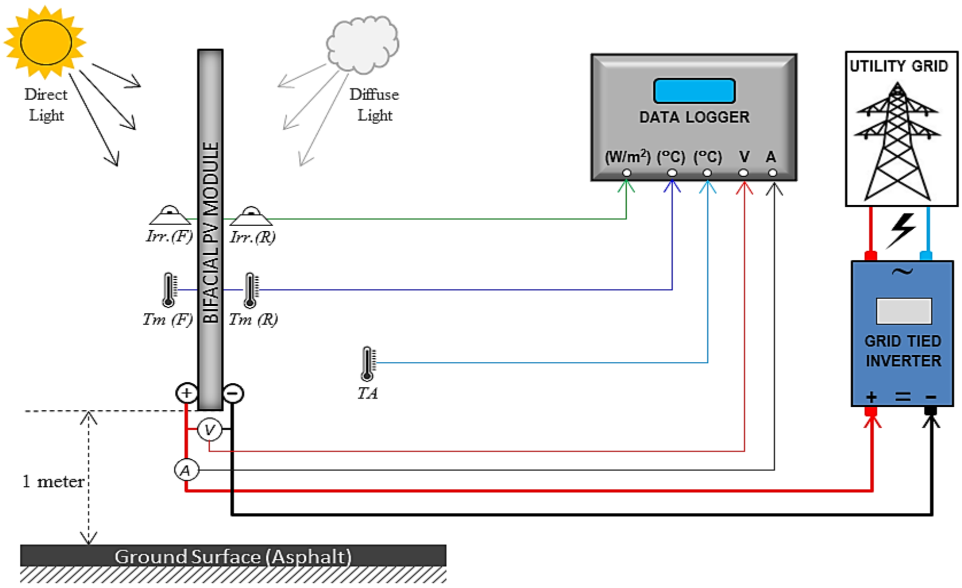


Figure 2. Measurement system scheme

Figure 3. Three bPV orientations and measurement system setup

4. RESULTS AND DISCUSSION

4.1. Solar irradiance and albedo under different module orientation

Figure 4 depicts these in-plane irradiance, including direct and diffuse radiation components. Direct radiation was captured by a pyranometer facing the front of each module. While diffuse radiation was measured by a pyranometer on the rear side, capturing light reflected from surrounding objects and the sky.

Vertically bPV with N/S orientation receives the lowest in-plane irradiance both front side (G1_F) and rear side (G1_R) as shown by blue path. The total irradiance obtained by the module with this orientation in single day is 1740 Wh/m^2 with the highest maximum radiation of front side around 157 W/m^2 occurring at 3:08 - 3:10 pm. The energy yield comes mostly from the capture of diffuse radiation, which is sunlight scattered by the atmosphere, clouds, and random surrounding objects.

Vertically bPV with E/W experiences two peak solar radiation periods, resulting in a double peak power output profile. This orientation was positioned perpendicular to the sun's path at sunrise (front side) and sunset (rear side). This means they receive direct sunlight at these times, leading to the first irradiance peak (G2_F) of 810 W/m^2 occurring at 08.14 am. During the mid-morning and late afternoon, when the sun was lower in the sky, vertically bPV with E/W orientation can capture more diffuse radiation than direct radiation (11:30 am – 12:30 pm). This scattered sunlight, combined with the direct sunlight, can contribute to a second peak (G2_R) occurring at 02:59 pm in the irradiance profile. The total irradiance gain of this orientation of 4426 W/m^2, greater than the total irradiance of the bPV with N/S orientation.

The tilted bPV module to North (T-N) receives the most in-plane radiation in a single day compared to other vertically oriented modules, as shown by green curves. The total irradiance obtained by the module with this orientation is 6306 Wh/m^2 and exceed 1000 W/m^2 occurring at 10:10 am - 1:13 pm. Even though in the morning the direct solar radiation received still very low because the angle of the sun light incident still low, it then increases as time goes by until it reaches its peak in the middle of the day. Regarding Figure 4, the comparison of direct radiation received on the front side (G3_F) to diffuse radiation on the rear side (G3_R) of the module shows a very large difference. The average irradiance of the front side (G3_F) is 715 W/m2 while the rear side (G3_R) is 50 W/m^2, resulting in an albedo value of 6.9%. This value is in accordance with the albedo reference values as shown in Table 1 that the asphalt surface has an albedo value of 5-20%. The module with this orientation typically exhibits a single-peak irradiance curve, with the peak occurring at midday.

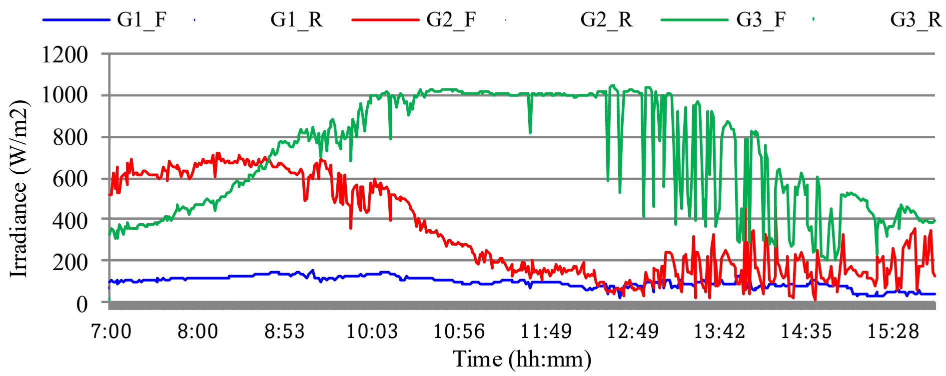


Figure 4. Irradiance profile of bPV orientations (a) North/South, (b) East/West, and (c) tilted

4.2. Temperature analysis of bPV modules

The high intensity of solar radiation in tropical areas causes the average daily environmental temperature to be relatively high compared to subtropical areas. The orientation of bPV module can significantly influence its module temperature. Figure 5 shows the surface temperature profiles of the front and rear module under different orientations.

Among all orientations, vertically-N/S bPV exhibited the lowest temperatures on both its front (T1_F) and rear (T1_R) sides throughout the day, as shown by blue path. The temperature increase from morning to midday was gradual, and the decrease from midday to afternoon was similarly slow. The temperature difference between T1_F and T1_R sides remained around 2 °C during the morning and afternoon. However, at midday, the temperature difference was minimal, with a maximum of 42 °C occurring at 12:30 PM. While the module temperature can exceed the ambient temperature (TA) by 5 °C at peak irradiance values, while the average module temperature exceeded the TA by 8.37 % on N/S orientation.

The vertically-E/W bPV reached its maximum temperature of 49 °C at the first peak (T2_F) on the front side at 8:50 AM as shown by red path. The second peak occurred on the rear side (T2_R) at 3:15 PM, reaching a temperature of 48 °C, with a temperature difference between the T2_F and the T2_R of 1-2 °C. During these two peak temperature periods, the difference between the module temperature and the TA can reach 10 – 15 °C, with an average temperature increase of 21.65% during the day.

The tilted bPV exhibited the highest average temperature, reaching a maximum of 59 °C at 12:33 PM. At midday, the average temperature exceeded 50 °C with an irradiance of approximately 1000 W/m², reflecting optimal sunlight incidence. The temperature difference between the front (T3_F) and rear (T3_R) sides remained within 1 °C – 4 °C as shown by green path. While the difference between the module temperature and the ambient temperature at peak irradiance can reach 15 °C – 19 °C and an average temperature increase of 39.57% during the day. This disparity contrasts with the significant irradiance difference (tens of times) between the front (G3_F) and rear (G3_R) sides. This is particularly true due to internal reflections for modules with transparent rear sheets such as the bPV modules tested in this study. Some of the solar radiation absorbed by the front surface of the module can be internally reflected and transmitted to the rear surface.

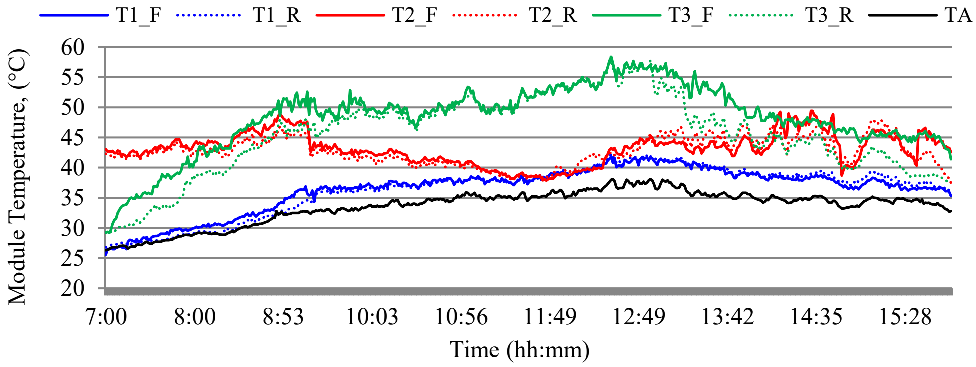


Figure 5. Temperature profile of bPV orientations, (T1_F; T1_R) North/South, (T2_F; T2_R) East/West, (T3_F; T3_R) tilted, and (TA) ambient temperature

4.3. Energy yield and efficiency

Energy yield is the primary objective of most studies evaluating the performance of PV modules, both bifacial (bPV) and monofacial (mPV). Energy output obtained in this test was calculated by multiplying the voltage and current readings at the module terminals. A grid tie inverter (GTI) was preferred for module loading tests due to its simplicity and MPPT control, which ensures maximum power extraction at various irradiance levels. Using a resistive load can be challenging, as temperature changes can affect its resistance, making it difficult to achieve optimal power output without a complex cooling system.

Figure 6 reports the power output profiles of bPV modules under different orientations in single day test. The output power profile of each bPV module mirrors the shape of its combined front and rear side irradiance profile, as output power is directly proportional to irradiance. In a one-day sunny weather test, the tilted oriented bPV module achieved the highest energy gain of 1951.41 Wh, as illustrated by green path. Its maximum power exceeded 300 W at midday. The power profile of the tilted oriented bPV module, P3 (Tilted, N) depicts the module's performance: starting at over 60 W in the morning, it steadily increased until surpassing midday, then gradually declined to 115 W by late afternoon. This pattern clearly demonstrates the impact of temperature on output power. Despite relatively stable irradiance at around 1000 W/m^2 after 12:30 pm, the module temperature rose, causing a slight decrease in output power during this period. This period is the most appropriate in determining the negative temperature coefficient of the module (-0.42 %/°C) as shown in the Table 2.

The second largest energy gain was experienced by the vertical-E/W bPV of 1504.44 Wh. This value was achieved predominantly in the morning conditions approaching noon (first peak) where the front side of the module received maximum solar radiation, while in the mid-afternoon (second peak) where the rear side of the module received maximum one. However, in midday, even though the vertically-E/W bPV was directly facing the sun with the smallest angle to zero degrees between direct radiation and the module's surface, it still produced power in the range of 50 W. This indicates that at that time, the power generated was significantly influenced by the accumulation of diffuse radiation and reflected radiation from surrounding objects.

In simultaneous testing of the three modules with different orientations, the vertically-N/S bPV has the smallest total energy gain of approximately 609.13 Wh. Even during peak sunlight hours, the angle of the sun relative to the module's surface cannot vary significantly throughout the day, leading to inconsistent energy production and resulting output power never exceeding 80 W. The vertically-N/S bPV results in significantly reduced sunlight exposure compared to East-West (E/W) orientations. This is particularly problematic in tropical regions with high levels of solar radiation.

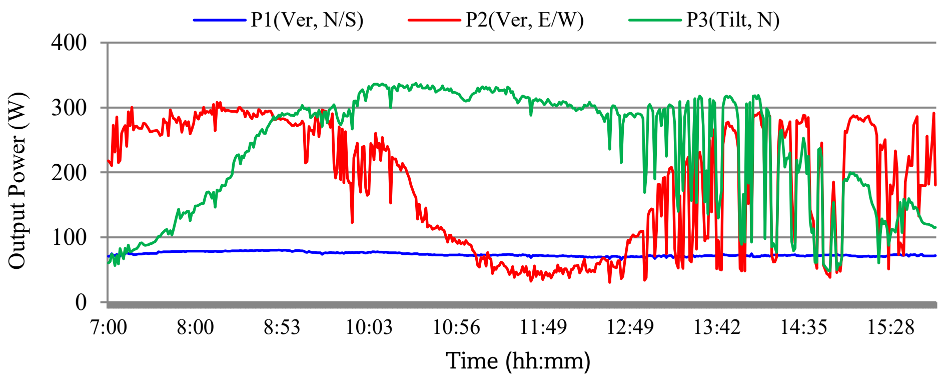


Figure 6. The power output profiles of bPV modules under different orientations

4.4. Overview of bifaciality factor and gain

Figure 7 shows the bifaciality factor values and their effect on the bifaciality gain from testing three modules under different orientations. The tilted oriented bPV module (T, N) have the lowest BF at around 5-10%. While this module has a larger surface area exposed to direct solar radiation on the front side than others, especially at midday, it also creates large shadows on the ground and affect the light intensity on the rear side. This results in a small BG around 3-14 %, as the increased front-side irradiance is offset by the reduced rear-side irradiance. However, bPV modules with this orientation can obtain radiation power of more than 1000 W/m^2 where the efficiency reaches its optimum around 15.7%, especially at midday. Vertically oriented bPV modules can achieve higher BF and BG due to their increased exposure to diffuse radiation from the sky, clouds, and surrounding objects. While vertically-E/W bPV may experience fluctuating of BF, with a maximum of around 83%, they can still achieve significant BG, reaching up to 67% at midday. However, their overall power output may be lower compared to tilted modules because of their reduced exposure to direct sunlight during this period. The opposite condition experienced by the vertically-N/S bPV, while this orientation often exhibit high BF and BG, exceeding 80% in some cases, their overall power output tends to be lower compared to other orientations. It primarily due to their reduced exposure to direct solar radiation throughout the day. While they may benefit from increased albedo and diffuse light capture, the lack of peak solar radiation exposure can limit their overall energy generation. Without special methods and treatments, the vertically-N/S bPV is difficult to apply in tropical regions with low latitude primarily due to the sun's path across the sky. In summary, comparison of more specific parameter values from the results of various bPV modules installation test under different orientations can be seen in Table 3.

In terms of energy yield, the tilted bifacial PV module outperforms both vertically-E/W bPV and vertically-N/S modules. However, tilted orientations may be preferable for maximizing peak power output, while vertical orientations can be advantageous for achieving higher bifaciality factor and gains. Careful consideration of the specific site conditions and energy goals is essential for selecting the most suitable module orientation in tropical environments. Other crucial factors like environmental conditions, weather patterns, site constraints, and peak load periods must also be carefully considered to optimize bPV module performance. For larger spaces, a tilted orientation with a lower angle is generally more optimal in tropical regions. This maximizes energy capture due to the sun's higher position. In limited spaces, a vertical, East-West (E/W) orientation can be available alternative, capturing sunlight both morning and evening for more consistent energy production. A North-South (N/S) orientation is less practical in low-latitude tropical areas. While it may benefit from increased albedo and diffuse light, the lack of peak solar radiation can limit overall energy generation. Without specialized techniques, North-South (N/S) oriented bPV modules are challenging to implement in tropical regions due to the sun's path. Other efforts can be made to optimize the energy yield of both vertical and tilted modules. One of them is by making the ground surface and surrounding objects brighter in color to increase the albedo and bifaciality gain.

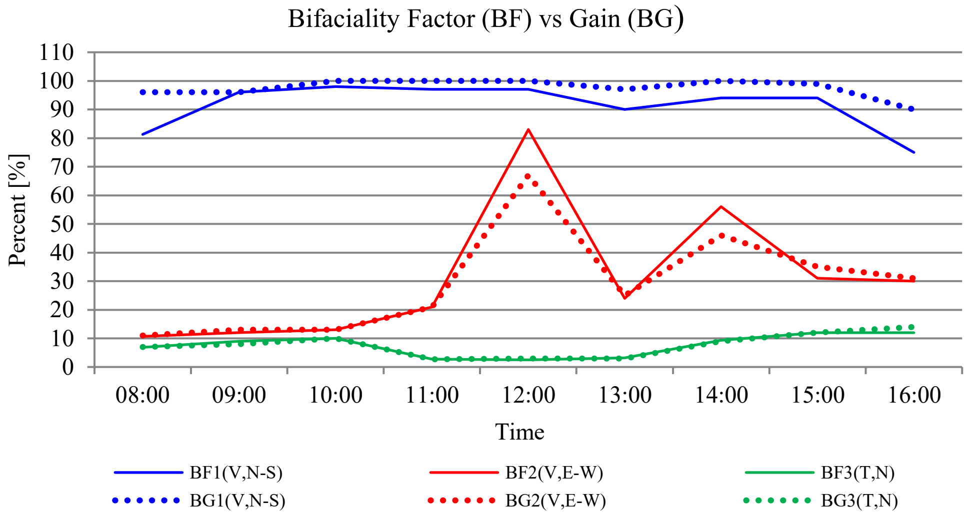


Figure 7. Bifaciality Factor vs Gain of bPV modules under different orientation

Table 3. The values of performance parameters

Unit	Module orientations			Remark
	Vericaly North-South (N/S)	Vericaly East-West (E/W)	15° Tilted North (N)	
$G_{tot, f+r}$ [Wh/m^2]	1740	4426	6306	
$G_{max, f+r}$ [W/m^2]	253	810	1117	
$T_{ave,f/r}$ [°C]	36.5/36.4	43.1/42.7	48.3/45.5	TA_{ave}. 33.6
$T_{max, f/r}$ [°C]	41.7/41.9	49.4/46.8	58.7/58.7	TA_{max}. 38.1
$E_{tot, f+r}$ [Wh]	609	1504	**1951**	
$P_{max, f+r}$ [W]	74	308	**337**	
λ, [%]	70	34	8	
BF, [%]	75 - 98	10 - 83	3 - 12	
BG, [%]	90-100	11 - 67	3 - 14	

5. CONCLUSION

Proper module orientation is crucial to maximizing energy yield from bifacial photovoltaic systems. The optimal mounting angle and direction can vary significantly based on location, especially in tropical regions with higher solar radiation levels. This study investigated the impact of orientation on the energy yield of bifacial photovoltaic (bPV) modules in a tropical region with high solar irradiance during a sunny day. Three different orientations-vertical facing N/S, vertical facing E/W, and tilted 15° facing North—were evaluated under real-world site conditions. All modules were installed at a height of 1 meter above the asphalt surface with random low-albedo objects nearby to determine the minimum energy yield generated by each module. The study findings revealed that the tilted orientation produced the highest energy yield of 1951 Wh per day, followed by the vertically-E/W and vertically-N/S orientations with 1504 Wh and 609 Wh, respectively. These values directly related to module temperature, which is influenced by the difference in irradiance experienced by each module. Vertically-E/W bPV module can maximize the BF and BG by capturing more diffuse radiation from the sky, clouds, and surrounding environment. However, their overall power output may be lower than tilted bPV module, especially during peak sunlight hours. While vertically-N/S bPV module typically produces the lowest energy output due to its limited exposure to direct solar radiation throughout the day, but it has greater diffuse radiation capture and lower module temperature. Energy gain can be enhanced by ensuring that the floor and surrounding objects, which act as direct reflectors of radiation are brightly in color. For example, a white floor or a lighter-colored building can significantly increase the reflection of sunlight to the bPV module.

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