ANALYSIS AND COMPARISON BETWEEN BIFACIAL AND MONOFACIAL PHOTOVOLTAIC MODULES USING DIFFERENT INSTALLATION PARAMETERS IN LOW LATITUDE REGIONS: A CASE STUDY FOR NORTHEASTERN BRAZIL

Ryan Neves[1], Janis J. B. Galdino[1,2] and Emerson Torres[1,2]

[1] Federal University of Pernambuco, Recife (Brazil)

[2] Center for Renewable Energy (CER-UFPE), Recife (Brazil)

Abstract

In recent years, photovoltaic bifacial modules (bPV) became the main technology in the PV market share due to their higher irradiation capture capability. The bifacial gain of bPV in comparison with monofacial modules highly depends on the incident irradiance in its rear surface, which varies with many environmental aspects. This research evaluates how the albedo and module's tilt angle influence its efficiency and energy production. Experiments were conducted by varying the tilt of two bifacial photovoltaic modules (bPV), with one of them configured to simulate a monofacial module. Different reflective surfaces—such as white tarp, white pebble, and aluminum tarp—were tested. The results aim to show the energy gain the bifacial module can produce under different conditions compared to the monofacial module. These findings provide guidelines for optimizing the design and installation of large-scale solar power plants, contributing to the maximization of renewable energy generation.

Keywords: Bifacial modules (bPV), Monofacial modules (mPV), albedo, reflective surfaces, rear irradiance, module's til angle.

1. Introduction

The growing global demand for clean and sustainable energy sources has driven the development and adoption of technologies based on the photovoltaic conversion of solar energy. The evolution of photovoltaic technology over the last decades has resulted in significant advances in the efficiency and performance of solar modules, among which bifacial technology stands out. This technology allows the capture of radiation from both the front and back faces of the module, which makes it possible to increase power generation per unit area compared to conventional monofacial modules (GANESAN et al., 2023).

According to the International Technology Roadmap for PV (ITRPV), bifacial modules show a significant growth trend in the global market, with a forecast to reach 35% share by the year 2027. This expansion is due to its greater energy efficiency and the ability to take advantage of the radiation reflected by the soil and surrounding surfaces. However, the effective performance of bifacial PV systems depends on several geographical and installation factors, such as ground albedo, tilt angle, module elevation, orientation, and row spacing (MEKEMECHE; BEGHDAD, 2021).

Recent studies show that tilt angle configuration can contribute significantly to the performance of bifacial modules. Asgharzadeh et al. (2018) point out that the optimal angle of inclination of bifacial modules tends to be higher than that adopted in monofacial systems, since it is necessary to consider the contribution of the posterior face. In addition, according to Asgharzadeh et al. (2023), the increase in the albedo of the soil must be accompanied by an increase in the angle of inclination, in order to enhance the capture of radiation on both sides of the module.

Although most studies on bifacial technology have been conducted in regions of medium and high latitudes, where the solar elevation angle is smaller, there is still little research addressing the behavior of these systems

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in low-latitude regions, such as the Brazilian Northeast. In these regions, direct solar incidence is predominant, and the sun's elevation angle remains high throughout most of the year, which reduces the fraction of reflected radiation that reaches the back of the modules. This characteristic can significantly impact the energy efficiency of bifacial systems, making it necessary to evaluate installation strategies that maximize the use of reflected radiation.

In this context, the present study aims to investigate the performance of bifacial photovoltaic modules in a low-latitude region, Recife, Brazil (approximately 8° S), under real operating conditions and considering variations in the modules' tilt angle and different ground surface materials. The scientific contributions of this research are expected to provide insights for improving the energy performance of these systems under tropical conditions, enabling the optimization of local photovoltaic projects.

2. Methodology

The experiment was carried out in the city of Recife, Pernambuco, located at 8.05° S and 34.9° W, with a Köppen–Geiger climate classification of Tropical Monsoon (Am), characterized by high annual solar irradiance and a humid tropical climate, with an average temperature of approximately 26 °C. The city is located at a low latitude, which results in high solar elevation angles throughout most of the year.

2.1 Experimental setup

The experimental arrangement consisted of two identical bifacial photovoltaic modules with a nominal power rating of 450 W and monocrystalline technology. Both modules were installed at a height of 1 m above the ground, oriented toward geographic north in order to maximize daily sun exposure (Figure 1).

Figure 1: Front and rear face of the modules.

For comparative purposes, one of the bifacial modules was modified to operate as a monofacial module. This was accomplished by installing a black, opaque EVA sheet on the rear surface in order to block the incident radiation.

Under the installation area of the modules, three types of surface materials — aluminum tarpaulin, white plastic tarpaulin, and white pebbles — with different reflectance levels (albedo) were tested to analyze their impact on the rear-side energy absorption. These materials were alternated under the modules on different measurement days, while maintaining similar irradiance and ambient temperature conditions. Figure 2 illustrates the experimental setup for the three surface materials analyzed.

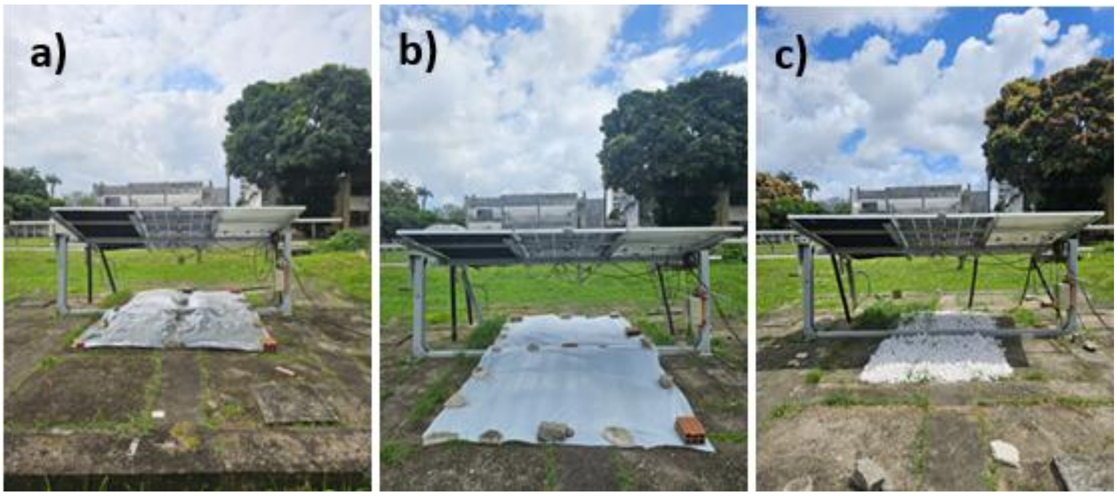

Figure 2: Experimental setup with the surface material of a) aluminum tarp, b) white plastic tarp, and c) white pebbles.

The experiments were carried out with two distinct module tilt angles, 8° and 15°. The value of 8° was chosen because it is close to the local latitude, which is commonly used in fixed PV systems in Recife, while the 15° angle was adopted to investigate the behavior of incident radiation on the rear side of the modules.

To ensure a systematic evaluation of the effect of surface material and tilt angle, the measurements were performed on different days for each configuration. Table 1 presents the measurement periods for each surface material and tilt angle, indicating the specific days on which the data were collected.

Table 1- “Measurement periods for each surface material and module tilt angle

Material	**Tilt Angle (°)**	**Start Date**	**End Date**
Concrete	8	29/03/2025	05/04/2025
Aluminum Tarpaulin	8	16/09/2025	21/09/2025
Aluminum Tarpaulin	15	09/09/2025	15/09/2025
White Plastic Tarpaulin	8	22/09/2025	26/09/2025
White Plastic Tarpaulin	15	27/09/2025	04/10/2025
White Pebbles	8	09/10/2025	13/10/2025
White Pebbles	15	13/10/2025	18/10/2025

This arrangement allowed for a comprehensive comparison of bifacial module performance under consistent irradiance and temperature conditions, ensuring that the influence of both surface reflectivity and tilt angle on energy generation could be systematically evaluated.

2.2 Data acquisition system

For each system configuration, data acquisition was performed for one week. Both modules were connected to separate inputs of a photovoltaic inverter, allowing the simultaneous measurement of their instantaneous power. The inverter recorded the modules’ electrical output, including power, voltage, and current, every 6 minutes.

In addition to the electrical parameters from the inverter, two LI-200 photovoltaic pyranometers were used to measure the front-side (GTI_F) and rear-side (GTI_R) solar irradiance in the plane of the modules. They were mounted one on top of the other (one facing the sky and the other facing the ground) near the module frame (Figure 3). Moreover, the module operating temperature was monitored using LM35 temperature sensors installed on the rear side of each module. These data were recorded using a CR310 (Campbell Scientific) datalogger with one-minute resolution.

Figure 3: Photovoltaic pyranometer

From these measurements, the datalogger also provided the instantaneous albedo (α), calculated by the ratio between the rear and front irradiance, as shown in Equation (1):

$$Albedo = \frac{GTI_{\mathrm{R}}}{GTI_{\mathrm{F}}} \qquad \textit{(eq.1)}$$

2.4 Data processing and modeling

The data obtained from the inverter and the datalogger were processed and integrated using Python scripts, employing libraries such as Pandas, NumPy, and Matplotlib. This stage aimed to consolidate a unified database for the energy and thermal analysis of the modules.

Initially, the data from the datalogger (1-min intervals) and the inverter (6-min intervals) were temporally synchronized. The process consisted of associating each power record with an averaged set of irradiance and temperature values corresponding to the same time interval. After alignment, inconsistent data (such as null or anomalous readings at night) were removed.

Due to the thermal absorption of EVA on the rear side, the simulated monofacial module exhibited consistently higher temperatures compared to the bifacial module, as observed in the operating temperature versus power graph shown in Figure 4.

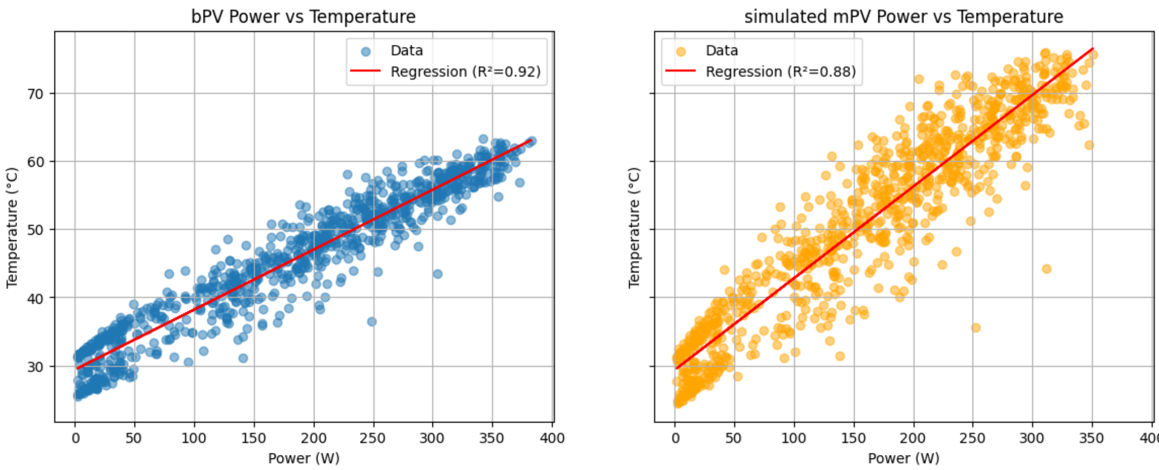

Figure 4: Power *versus* Temperature graph of bPV and mPV module

As the module operating temperature strongly influences PV power production, a temperature correction procedure was applied to compare the electrical output of the monofacial and bifacial modules. This procedure consisted of simulating the power generated by the monofacial module using the operating temperature of the bifacial module. The temperature-corrected power of the monofacial module was obtained using Equation 2.

$$P_2 = P_1 \cdot (1 + \gamma(T_2 - T_1)) \qquad (eq.2)$$

Where P_2 is the simulated monofacial power at the bifacial module's operating temperature (T_2), P_1 is the measured monofacial power at its actual operating temperature (T_1), and γ is the module's power temperature coefficient, which was 0.35%/°C, as provided by the manufacturer. This procedure allows recalculating the electrical power as a function of operating temperature, normalized to the bifacial module's temperature.

After data processing and temperature correction, several performance parameters were calculated based on the front- and rear-side irradiance and the bifacial performance models available in the literature.

The total effective irradiance in the plane of the modules was calculated according to Equation 3:

$$G_T = GTI_F + GTI_R \cdot b_f \qquad eq.3)$$

Where GTI_F is the global tilted irradiance on the front side, GTI_R is the global tilted irradiance on the rear side, and b_f is the bifacial reference factor (value of 70%, according to the module datasheet).

One way to compare the two modules is through the bifacial energy gain (BG). This parameter represents the percentage increase in energy production of the bifacial module compared to a monofacial module with the same characteristics. BG is defined according to Equation 4.

$$BG = \frac{E_b - E_m}{E_m} \times 100 \qquad (eq.4)$$

Where E_b e E_m represent the total energy integrated in the same time interval, for the bifacial and monofacial modules, respectively.

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For a deeper investigation of how bifacial gain behaves during the day, the solar zenith angle was calculated. This angle represents the angle between the observer's vertical line (zenith) and the line to the sun. Equation 5 shows the calculation, obtained from the geometric relationship between the solar position and the local latitude, where *Φ* is the local latitude, *δ* is the solar declination, and *ω* is the hour angle.

$$\cos(\Theta z) = \sin(\Phi)\sin(\delta) + \cos(\Phi)\cos(\delta)\cos(\omega) \qquad (eq.5)$$

Finally, the clarity index on the tilted plane (Kt) was calculated using Equation 6. It represents the ratio of the global tilted irradiance on the surface facing the sky (GTI_F) to the effective solar extraterrestrial irradiance projected onto the plane of the modules ($I_{ef_{tilted}}$). The tilted Kt was used to analyze the influence of sky conditions on albedo and bifacial gain. Similar to the traditional clarity index (calculated for the horizontal plane), sky conditions were classified according to the tilted Kt as clear sky (Kt > 0.7), partly cloudy sky (0.4 < Kt < 0.7), and cloudy sky (Kt < 0.4).

$$Kt = \frac{GTI_f}{I_{ef_{\text{tilted}}}} \qquad (eq.6)$$

3. Discussion of Results

3.1. Bifacial Gain by Material and Angle

Figure 5 shows the average bifacial gain obtained for the different materials and inclination angles of the photovoltaic modules. It is observed that, in general, the bifacial gain was higher when the module was positioned at 8°, compared to the angle of 15°.

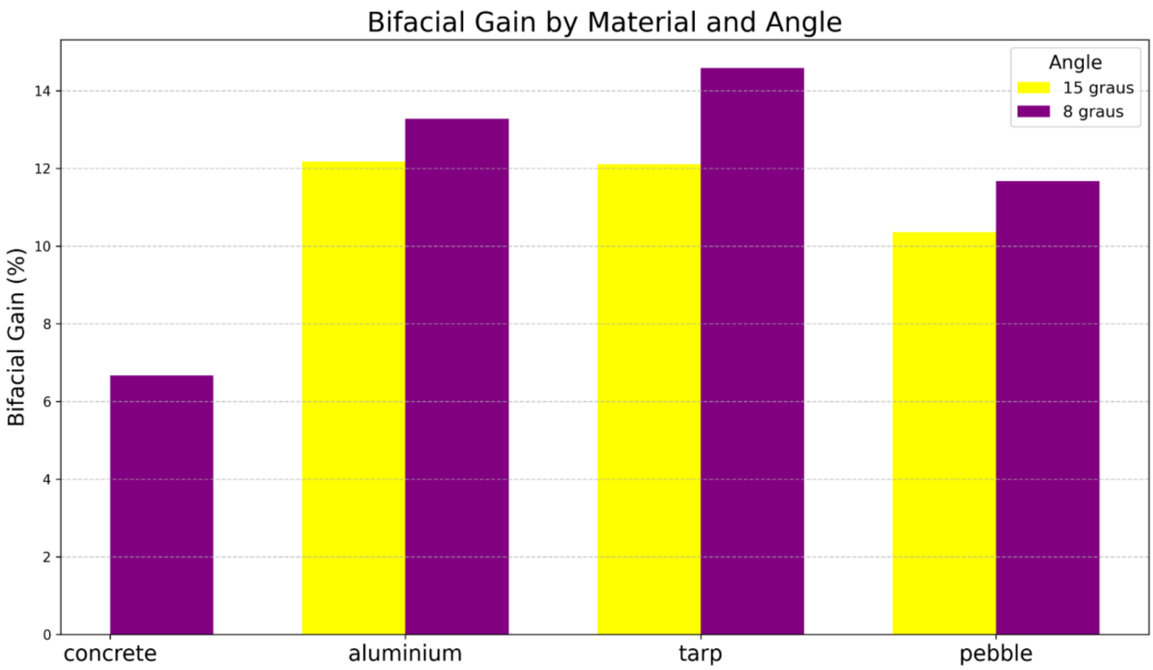

Figure 5 – Graph of bifacial gain by material type at module angle

This trend indicates that, during the measurement period, the 8° tilt angle favored energy production, possibly because, at this inclination, the angle of incidence of the irradiance on the front surface — which has the greatest influence on the power generation of the bifacial module — is closer to the normal.

The graph also includes the performance of the concrete surface as a reference, showing that the other materials — aluminum tarpaulin, white tarpaulin, and white pebbles — exhibited significantly higher bifacial gains, highlighting the direct influence of the albedo of each surface.

Table 2 – Bifacial gain values by type of material at module angle

Material (surface)	Angle (°)	Bifacial gain (%)
Concrete	8	6,67
Aluminium tarp	8	13,28
Aluminium tarp	15	12,18
White tarp	8	14,58
White tarp	15	12,10
White pebble	8	11,67
White pebble	15	10,36

3.2 Influence of the Clarity Index on the tilted plane (Kt) on Bifacial Gain

Figure 6 illustrates the behavior of the bifacial gain for the aluminum tarpaulin under different ranges of the tilted clarity index (Kt). A decreasing trend in bifacial gain is observed as Kt increases, which represents a typical "ladder effect" behavior.

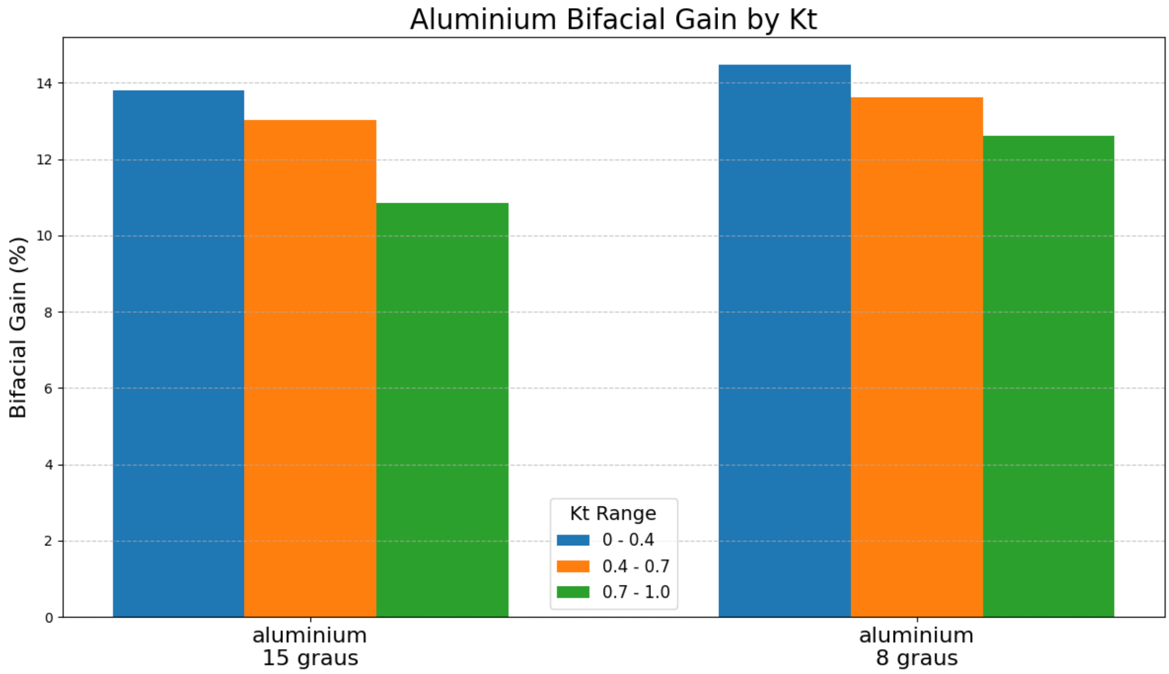

Figure 6 – Bifacial gain of the aluminum tarpaulin by Kt strip

This pattern occurs because, as the clarity index increases, direct irradiance becomes predominant while diffuse irradiance decreases. Diffuse irradiance, which propagates in multiple directions, is more favorable to the rear surface of bifacial modules. Therefore, under cloudy sky conditions (low Kt), the contribution of reflected radiation is greater, resulting in higher bifacial gain.

3.3 Average Albedo by Material and Angle

Figure 7 illustrates the average albedo calculated for each surface material and tilt angle. It was observed that the albedo was slightly higher when the module was tilted at 15°, regardless of the surface type. This behavior may be associated with the greater exposure of the reflective surface within the sensor's field of view, although the bifacial gain in this case was lower.

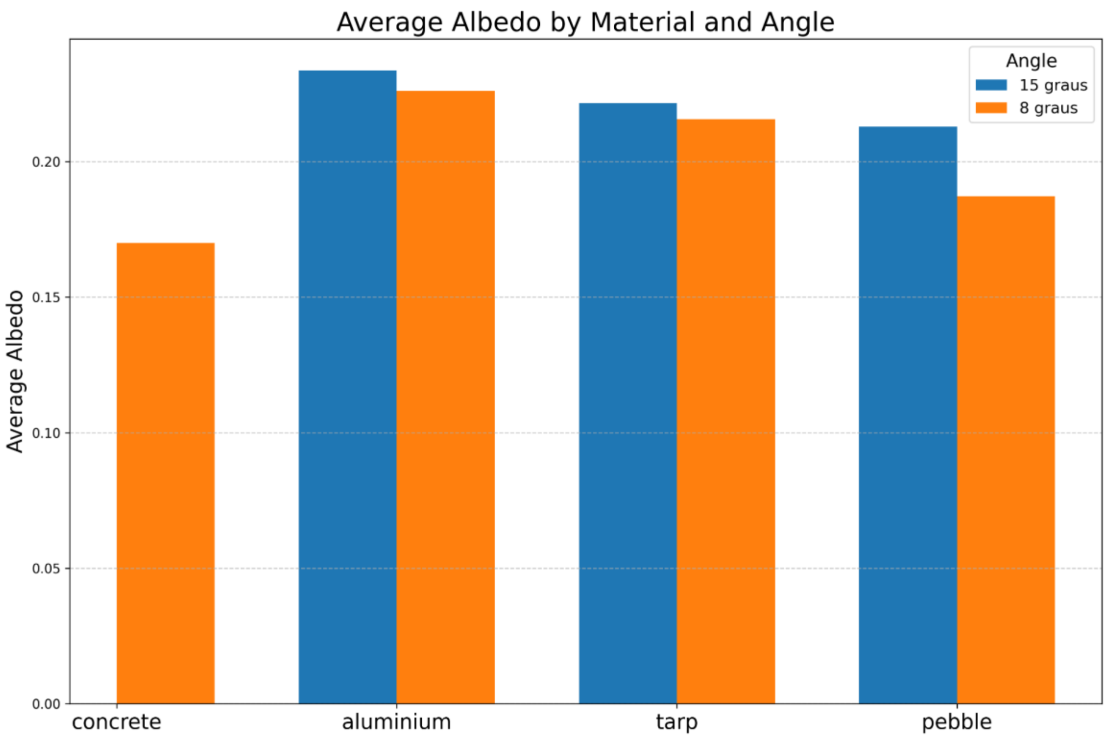

Figure 7 – Average albedo by material type at modulus angle

This difference indicates that a higher albedo does not necessarily guarantee greater bifacial gain, as increased angular losses and specular reflection can reduce the fraction of irradiance effectively captured by the rear surface of the module.

In addition, the inclusion of the concrete surface in the graph serves as a reference parameter, reinforcing that its albedo is considerably lower than that of the other materials.

Table 3 - Albedo values by material type at modulo angle

Material (surface)	Angle (°)	Medium albedo
Concrete	8	0,170
Aluminium tarp	8	0,226
Aluminium tarp	15	0,234
White tarp	8	0,216
White tarp	15	0,222
White pebble	8	0,187
White pebble	15	0,213

3.4 Average Albedo by Material, Angle, and Ranges of Kt

Figure 8 complements the previous analysis by presenting the average albedo as a function of the K_t ranges. The ladder-like behavior is again observed, with albedo values decreasing as the clarity index increases.

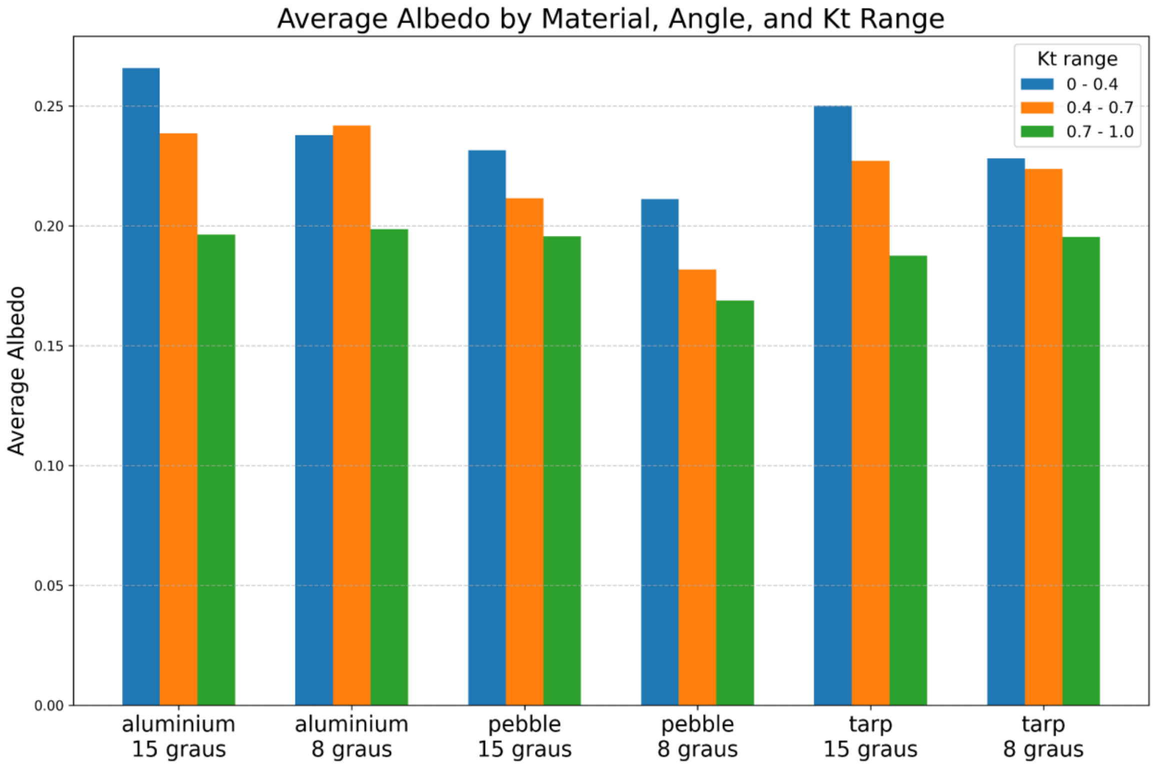

Figure 8 – Graph of the mean albedo by material type and angle in Kt bands

This effect is consistent with the reduction in diffuse irradiance under clearer sky conditions (high Kt). Therefore, the variation in albedo also reflects the direct influence of the spectral composition of the incident radiation on the reflective surfaces.

3.5 Total Irradiance to Power Generated Ratio

Figures 9, 10, and 11 illustrate the linear relationships between the total irradiance and the electrical power generated by the monofacial and bifacial modules for the different surface materials and tilt angles.

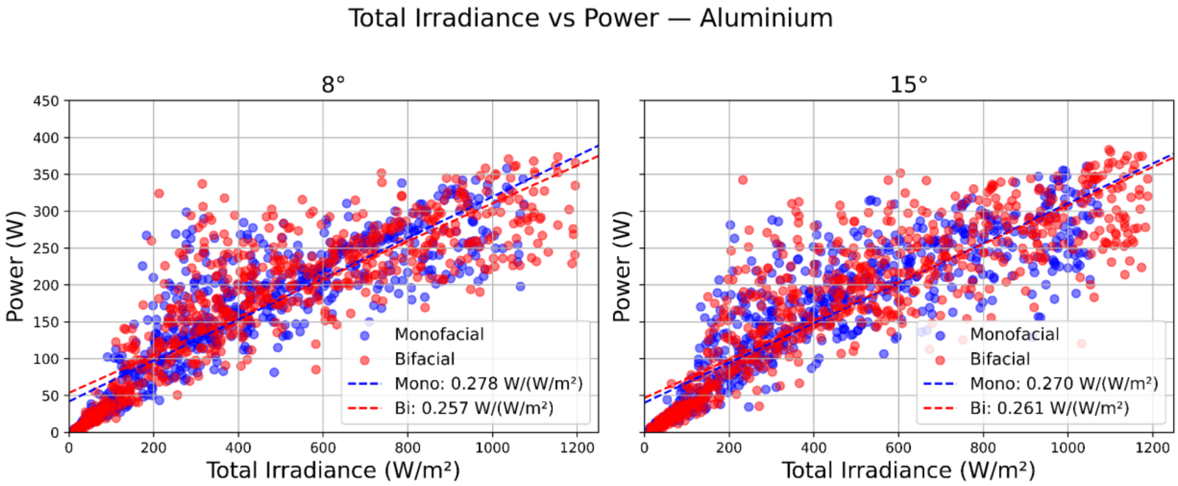

Figure 9 – Total Irradiance x Power Graphs of Aluminum Tarp

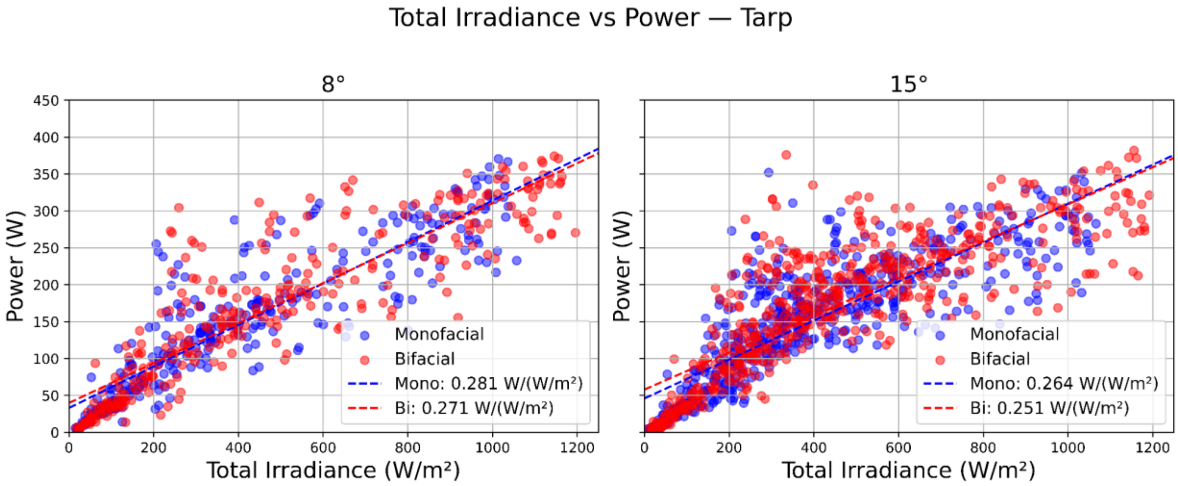

Figure 10 - Total Irradiance x Power Graphs of White Tarp

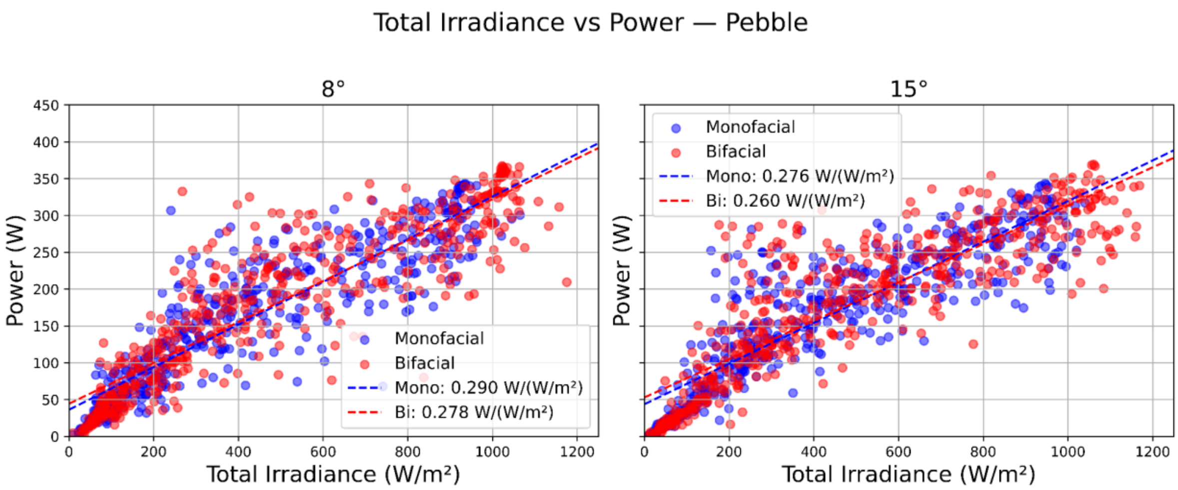

Figure 11 - Total Irradiance x Power Graphs of White Pebble

In all cases, the slope (W/W·m²) of the monofacial curve is slightly higher than that of the bifacial curve, indicating that the monofacial module converts direct irradiance with greater efficiency. However, it is observed that, at low irradiances, the bifacial curve lies above the monofacial curve, suggesting better performance under diffuse irradiance conditions.

As the irradiance increases, the curves converge, and at high irradiances, the monofacial module outperforms the bifacial module — a behavior consistent with the relative decrease in diffuse contribution and the partial shading of the rear surface.

It is also observed that, when increasing the tilt angle from 8° to 15°, the slope coefficient decreases in both cases, indicating a general reduction in photovoltaic efficiency associated with the geometric variation of radiation incidence.

4. Conclusions

The analysis of the performance of bifacial photovoltaic modules on different reflective surfaces and tilt angles, under the irradiance conditions of the Recife (PE) region, allowed a detailed understanding of the influence of albedo, installation geometry, and atmospheric conditions on the energy gain achieved.

The results demonstrated that the bifacial modules exhibited better performance when installed at a lower tilt angle (8°) compared to 15°. This difference is directly associated with the higher incidence of direct irradiance on the front surface of the module, which is more effectively utilized because it is closer to normal incidence.

Regarding the materials, it was observed that surfaces with the highest reflectivity, such as aluminum tarpaulin and white tarpaulin, provided the greatest bifacial gains, followed by white pebbles and, finally, concrete, used as a reference with the lowest albedo. This trend confirms the importance of selecting reflective materials around the modules to maximize the use of incident irradiance, since reflected irradiance plays a fundamental role in the additional energy generation on the rear surface.

The analysis of the clarity index (Kt) revealed that both bifacial gain and mean albedo exhibited similar behavior, with a progressive reduction as Kt increased. This is due to the decrease in diffuse irradiance under clearer sky conditions, which reduces the contribution of radiation from multiple directions — a condition that favors the rear surface of bifacial modules. Therefore, the best bifacial performance was observed under atmospheric conditions with a greater presence of clouds, where diffuse irradiance becomes predominant.

The results of mean albedo by material and tilt angle indicated that, although albedo was slightly higher at 15°, this increase did not translate into higher bifacial gain. This suggests that the increase in reflectivity was offset by greater angular and geometric losses, particularly in capturing reflected irradiance at higher angles. Consequently, optimization of bifacial performance depends not only on the reflectivity of the surface but also on the system geometry and the spectral distribution of the incident irradiance.

The analysis of the relationship between total irradiance and generated power reinforced these observations. It was found that the slope of the power curves for the monofacial modules was slightly higher than that of the bifacial modules, indicating higher conversion efficiency under high direct irradiance. However, under low irradiance conditions, the curves of the bifacial modules were above the monofacial ones, demonstrating better performance under diffuse irradiance. This difference, although small, highlights the potential of bifacial modules to optimize energy generation under variable irradiance conditions, which are common in the studied region.

Overall, the results confirm that the use of bifacial modules is technically advantageous in regions with high global irradiance and a significant diffuse component, as is the case in Recife. The 8° tilt angle proved to be the most suitable for maximizing bifacial gain, particularly when combined with high-albedo surfaces such as aluminum tarpaulin or white tarpaulin. In contrast, higher tilt angles and low-reflectivity materials reduced the expected benefits of bifacial technology.

Therefore, it can be concluded that bifacial performance is strongly conditioned by the combination of the optical characteristics of the reflective surface, the installation angle, and local atmospheric conditions. This finding reinforces the importance of regional studies for the optimized design of bifacial systems, contributing to the advancement of photovoltaic solar generation in tropical climates with high diffusivity, such as the Brazilian Northeast.

4.1 Future work

As a continuation of this research, it is recommended to conduct long-term studies covering complete annual cycles to evaluate the seasonal impact of variations in global and diffuse irradiance on bifacial module performance.

Another important aspect would be to perform computer simulations using specialized software, such as

PVsyst or bifacial Radiance, employing experimentally measured parameters to validate predictive models and extrapolate the results to different latitudes and system configurations.

Finally, it is recommended to include spectral and thermal analyses to understand how module temperature and the spectral distribution of irradiance affect the quantum efficiency of bifacial cells. Such complementary investigations are essential to consolidate knowledge on the behavior of bifacial modules in tropical regions and to provide technical guidance for the design of more efficient and durable photovoltaic systems adapted to local climatic conditions.

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