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Research Article

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Performance of bifacial PV modules under different operating conditions in the state of minas gerais in Brazil

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Abstract. Brazil's cumulative photovoltaic (PV) installations have now surpassed 32 GWp. The fastest growing and most prevalent PV technology is the bifacial photovoltaic module, which is now being incorporated in more than 2/3 of new power plants. These modules collect solar radiation on both front and rear sides, providing gains in electricity production compared to traditional monofacial modules. The market acceptance and quality control of this technology requires standard methods to accurately determine the nominal power of the bifacial modules. The energy production from the bifacial backside is complicated due to critical factors such as albedo, separation, height, and positioning of the modules, shading of the rear surface, and the specific geographic and climate conditions. This paper addresses these issues in determining the performance of bifacial PV modules in the tropical conditions of the State of Minas Gerais, Brazil, particularly, the bifacial gain for modules assessing the effects of albedo, site maintenance, climate/environmental conditions, thermal behavior, and rear-surface shading. These studies were performed on real power plants having different operating conditions (e.g., tracking, non-tracking, ground cover). The methodology includes I-V characterization of modules and string and thermal imaging/mapping under existing climate and meteorological conditions.

Keywords: Photovoltaics / bifacial / bifaciality / albedo / climate zones / shading / performance / standards

1 Introduction, background, and objectives

Brazil's cumulative photovoltaic (PV) installations have now surpassed 32 GWp [1,2]. In 2022, Brazil ranked 4th in the world added PV power [3,4]. The fastest growing and most promising PV technology is the bifacial photovoltaic module —which is now being incorporated in more than 2/3 of new power plants. These modules collect solar radiation on both front and rear sides and provide gains in electric power production compared to traditional monofacial modules in the range of 5% to 30% under most site conditions.

The prevailing module type in the industry is currently the monofacial module and is expected to account for approximately 65% in 2023, as shown in Figure 1. Nevertheless, the market trend for bifacial modules is poised to increase significantly in the coming years, expected to reach approximately 70% in the next decade [5]. The significant growth in deployment of these modules in world markets and rapid decease in module price over the last 6 yr is also indicated—with the gap between the price of conventional monofacial and bifacial technologies closing to almost the same values [3,4]. Thus, the use of bifacial cells for both monofacial and bifacial applications has become financially and technologically feasible.

The major technological events in the evolution of the bifacial solar PV technology are summarized in Figure 2. Among the earliest references to this cell is the theoretical analysis and patent by Mori in the early 1960s [6]. The Soviets further developed this technology with work by Bordina et al [7,8] resulting in prototype experiments on Soviet satellites Salyut 3 and 5 in the 1970s [9,10]. This attracted the attention of researchers in Spain, and the early patents of Luque [11–15] laid the foundation for major device understanding and improvements in the 1980s and early 1990s. During the 1980s, a series of pioneering publications provided for the advancement of the technology [16–35]. This research turned the emphasis to terrestrial PV and the fabrication of bifacial cells on larger-area Si wafers. A turning point was the demonstration of the first practical high-efficiency bifacial Si solar cell by Mohlecke, Zanesco, and Luque in 1994 [36].

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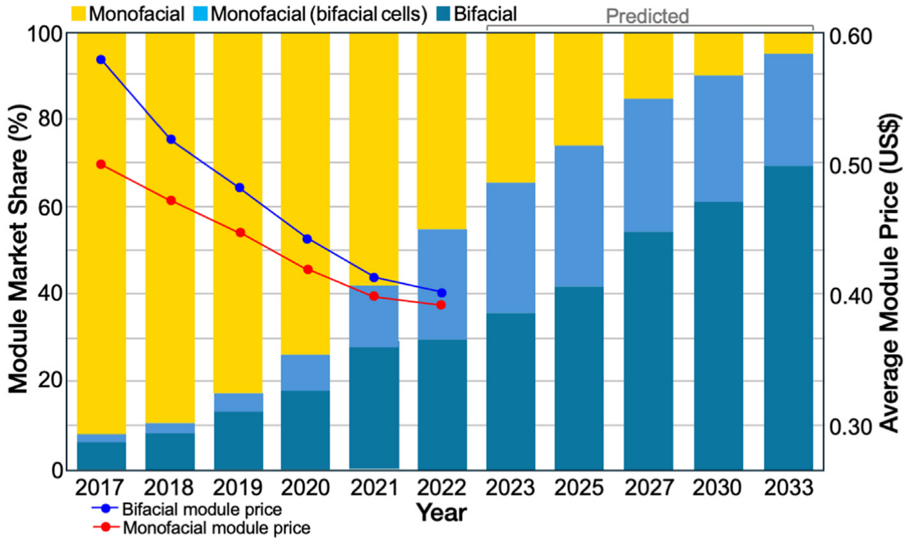

Fig. 1. World market share of monofacial and bifacial modules as function of time, showing growth from 2017 through 2022 and prediction of distribution from 2023–2033. The monofacial and bifacial module prices are shown for 2017–2022, indicating closing of gap between prices for these module types. (After data provided in Ref. [5] and Ref. [3]).

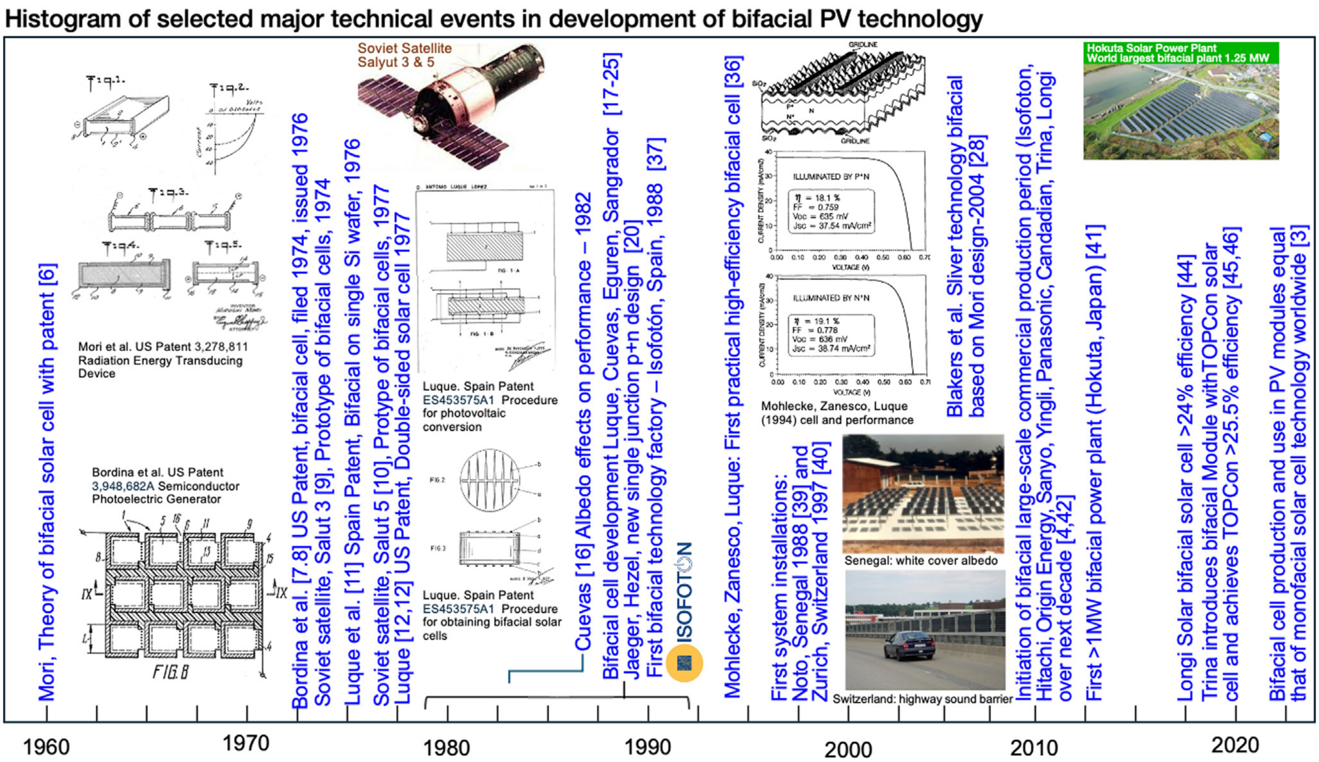

Fig. 2. Selected major technical contributions to the development of bifacial PV technology from 1960 through 2021. Progress shows the evolution from theoretical analysis through the realization of large-scale power plants.

The initiation of commercial production for bifacial photovoltaic modules can be traced back to 1984 with the establishment by ISOFOTON, a Spanish company that emerged as a startup from the Solar Energy Institute of the Polytechnic University of Madrid [37]. At that time, the world annual shipments were 24 MW—contrasted by the >260 GW/year dispatched in 2022 and the cumulative installed capacity of 1185 GW attained at that year's end [3,4,38]. The development of bifacial technology included interest in concentrating PV technology [37]. Figure 2 highlights the first modest system installations leading to MW-level power plants [39–41] with the rapid growth of the industry in the 2000–2020 timeframe.

In the initial terrestrial technology concept stages from 1980–2000, academic institutions and research organizations primarily have led in the understanding, research

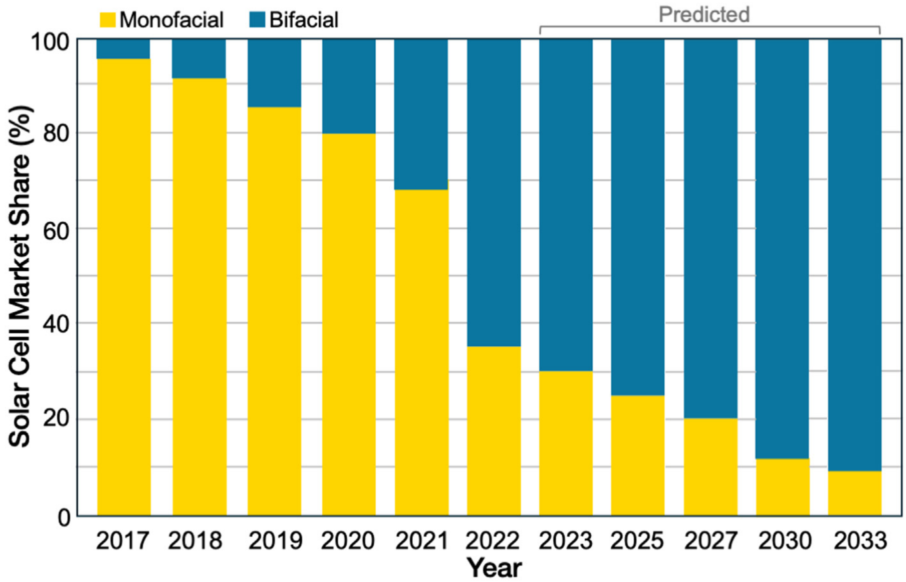

Fig. 3. Market share for bifacial and monofacial PV solar cells for current (2017–2022) and predicted (2023–2033) annual installations (from accumulated data in Ref. [5]).

demonstration and low-cost device development for bifacial solar cells. This research has paved the way for leading commercial Si manufacturers such as Solar Wind, PVGS, Yingli, Canadian, BYD, Trina, Longi, and many others to become pioneers in producing standard bifacial solar cells using cost-effective manufacturing processes [42]. Recently, a commercial bifacial thin-film module was introduced by First Solar [43].

However, despite the advancements in cell design studies during subsequent years, bifacial photovoltaic technology did not achieve widespread popularity until the industrial-scale production of efficient Passivated Emitter and Rear Cell (PERC) cells [44]. The bifacial industry has adopted PERC with trends toward Tunnel Oxide Passivated Contact (TOPCon) technology [45–47].

Figure 3 summarizes the past and anticipated market trajectory for bifacial solar cells. It is projected that the current 70% market dominance will progress to beyond 90% within the coming decade. As already noted, bifacial cells possess the performance and financial capabilities to be employed in both traditional monofacial modules and bifacial modules designed with transparent rear surfaces [5].

The increase in energy production from the rear side of a photovoltaic generator is directly influenced by several key parameters. These include the albedo of the location, defined by amount of sunlight reflected from the ground or surrounding surfaces onto the back of the bifacial panels. Additionally, the physical distance between rows of modules and the installation height of the modules in relation to the ground are also crucial in maximizing energy production from the rear side of the module. Together, these parameters have a significant impact on the overall performance and efficiency of the photovoltaic system.

Currently, most manufacturers and developers designate bifacial gain on their specifications. This parameter considers the energy produced by the device rear side as an additional fraction of the energy produced by the front side of the module. When consulting a technical data sheet, the designer finds a nominal power ratio for the front side under standard STC conditions and a possible power gain considering the rear side, without clearly defined reference conditions. However, this can result in significant uncertainties in project system sizing, cabling, and inverter specifications. Standard approaches would reduce errors and enhance the technical and financial confidence in system performance. However, there is no current consensus on how to better define the concepts and bifaciality gain (i.e., how much more energy the total panel produces with the rear bifacial component) or bifaciality factor (i.e., the measure of how much energy the rear of the panel will produce compared to the front of the panel) in the device technical data sheets. Though a new technical standard, IEC 60904-1-2 is under development to address differences between bifacial and conventional or monofacial modules, the complicated specification of energy production from the bifacial backside under specific climate and operating conditions needs addressing for assuring installation quality [48,49].

This case study provides a specific focus on a larger study we have reported on the quality and reliability of PV installations in Minas Gerais recently [50] covering a variety of crystalline-Si and thin-film PV technologies. This investigations surveys results for 3-representative sites in Minas Gerais State, the locations shown in Figure 4, with specific to bifacial PV performance comparisons and concerns. Iguatama and Itaguara are bifacial tracking and fixed, respectively. Itaguara additionally provides the investigation of various commonly encountered albedos [51–54] using the same bifacial panels. Três Marias affords the evaluation for the potential power enhancement of bifacial technology over the existing monofacial PV installation. This paper addresses these issues in determining the performance of bifacial PV modules in Brazil's

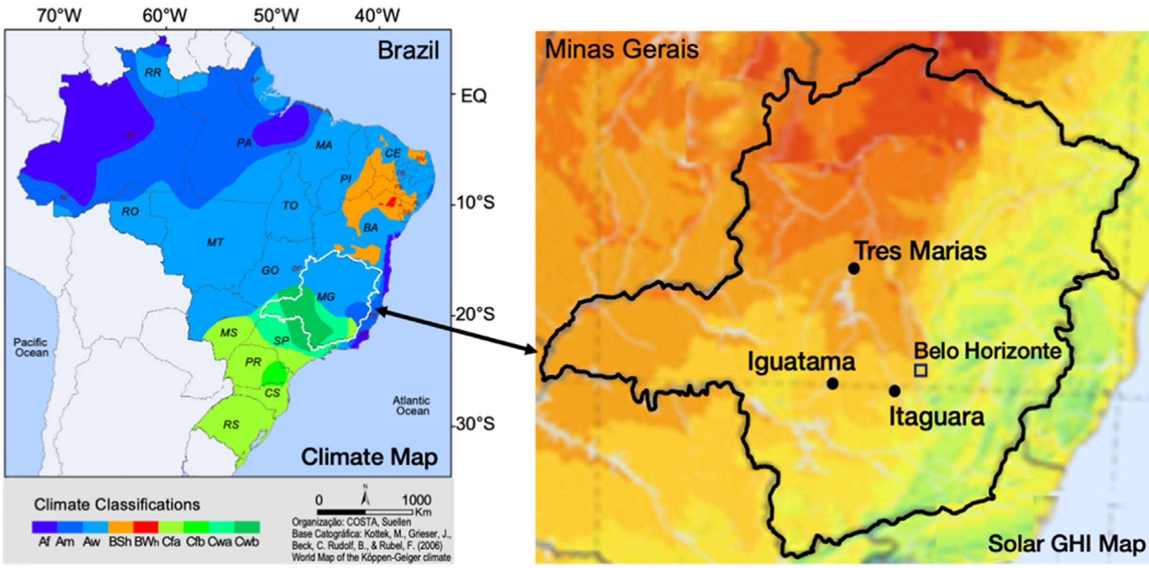

Fig. 4. Climate zone map of Brazil with solar global horizontal irradiance (GHI) map identifying survey sites, with State capital city, Belo Horizonte, provided for reference.

tropical locations. Specifically, the bifacial gain for modules and systems is assessed, evaluating the effects of albedo, site maintenance, climate/environmental conditions, thermal behavior, and back-surface shading. The special cases of tracking versus non-tracking systems are evaluated showing specific attention needs to the albedo changes and rear module shading constraints. These studies are performed on real power plants having different operating conditions. The methodology includes careful I-V characterization of modules and strings, corresponding thermal imaging/mapping, accurate albedo measurements, and correlation with the meteorological site conditions [51,52]. Although we do not identify module manufacturers in this paper, we have examined modules from 6 sources, and all have met the stated specifications [50]. This case study reports the important evaluation of the quality of the both the bifacial PV products being used and their installations in the emerging Brazil PV power plant markets.

2 Basic parameters and definitions

In this section, the key performance, installation and configuration parameters, and measurement definitions are summarized. Though these are common to the bifacial technology, they are included here to provide a common understanding of the methodology and the underlying principles of this bifacial technology case study.

2.1 Albedo

Albedo is defined as the ratio between the irradiance reflected by the ground to the global horizontal irradiance [51–54]. This ratio is a dimensionless parameter that can vary from “1”, in which the ground would behave as a perfect reflecting plane, to “0”, in which case the ground would behave as a perfect absorbing plane [52].

Albedo is usually measured with albedometers or contra-facing horizontal irradiance sensors (e.g., pyranometers or reference solar cells), one facing the sky and the other facing the ground. The albedo value is obtained by dividing the irradiance measured by the ground-facing instrument by the irradiance measured by the sky-facing device. Albedometers are normally installed one to two meters above ground surface [53].

The albedo is influenced by the color and properties of the light-reflecting surfaces present at the rear of a module. Surfaces that are smooth and light in color tend to have higher albedo values, which can effectively enhance the energy generation from the rear side of the module. Typical albedos are in the range of 0.1 to 0.5 for most power plant installations that have local soil, vegetation, or stone-prepared ground coverage [53,54].

2.2 Ground Coverage Ratio (GCR)

The GCR is the ratio of the photovoltaic array area to the total ground area. In the case of an array organized in rows of modules, the GCR is determined by dividing the length (L) of one row by the distance (P) between the bottom of that row and the bottom of its adjacent row (Fig. 5).

An array with a low ground coverage ratio, approaching zero, has rows that are more widely spaced compared to an array with a high ground coverage ratio, nearing one. As the GCR decreases (pitch increases), the area responsible for reflecting light onto the rear side of the modules increases (Fig. 5). Thus, as the GCR increases, the bifacial gain decreases.

2.3 Module mounting height

The measure of the distance between the bottom of the lowest part of the module and the ground surface (Fig. 6). This is a key factor that significantly influences bifacial gain.

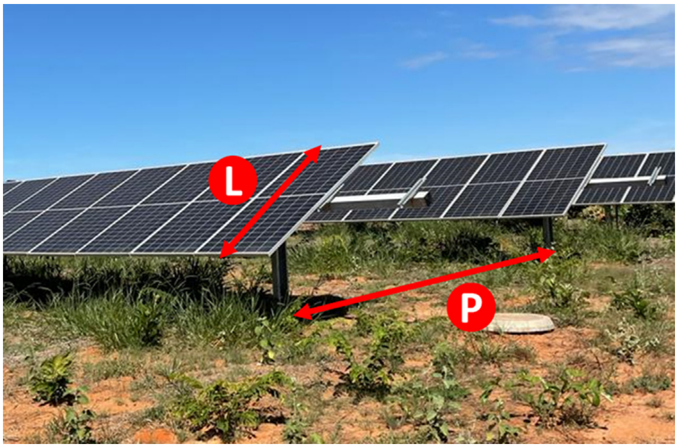

Fig. 5. Pitch (P) and length (L) designations for determining the GCR.

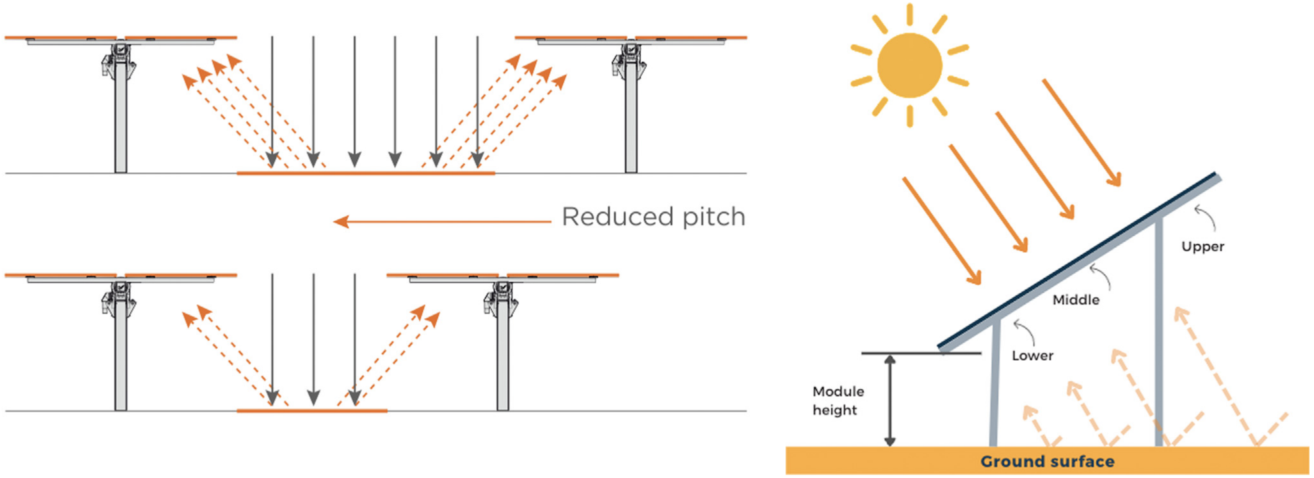

Fig. 6. Key installation geometries: Left – Graphical representation illustrating the relationship between the pitch and the variation in reflected irradiation [8]; Right – Elevation and relation to reflected radiation.

The elevation of the module can impact the irradiance on the rear side in different ways. To optimize the reflectance of solar rays and achieve increased bifacial gain, it is essential to ensure adequate space between the module and the ground. Modules positioned at higher locations on the mounting system (or the upper side of the modules) can capture a greater amount of diffuse irradiance compared to those located closer to the ground. Additionally, modules installed at higher positions typically operate at lower temperatures, resulting in a potential increase in energy production.

2.4 Bifaciality factor

This is a measure of how much energy the rear of the panel will produce compared to the front of the panel. This is usually reported under standard test condtions. At present, in bifacial modules, bifaciality factors normally range between 70% and 95%. The bifaciality factors are reported on the manufacturers' data sheets.

2.5 Bifacial gain

The bifacial gain is the power produced by the rear side of the bifacial module as a fraction of that produced by the front side. This parameter is a primarily a function of the bifaciality factor, the albedo, and the physical installation factors (GCR, mounting height). This gain is usually between 3% to 10% for typical installations.

3 Methodology

For each power plant, the survey starts with a site inspection following the NREL spreadsheet method [55]. This documents the condition of the arrays and modules (wiring, damage, soiling, shading, etc.), the physical parameters defined in the previous section, and the maintenance and condition of the site. Specifically, the GCR, module height, and pitch were analyzed to ensure optimum installations. The tests and measurements include recording of the electrical characteristics (under standard IEC conditions

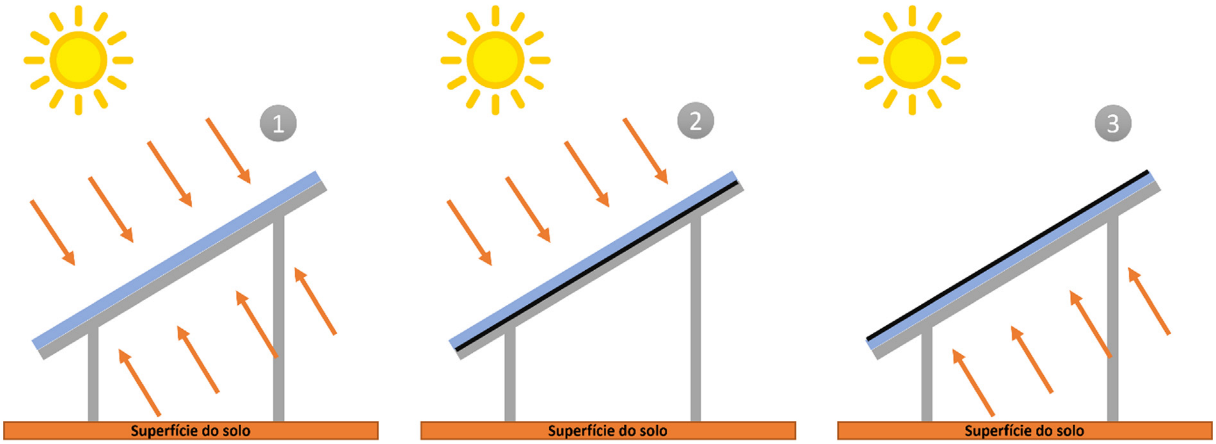

Fig. 7. I-V characteristics were obtained for three different test configurations.

[1,48,50]), thermography, and evaluation of the important albedo characteristics for the site. Individual modules and strings are assessed and compared with manufacturer's specifications and acceptance tests. All modules and strings were cleaned before performing the measurements.

Electrical characterization: The electrical parameters obtained from the photovoltaic module are current, voltage, and nominal power, and the entire I-V characteristic is recorded. A Daystar DS-1000 I-V curve tracer was utilized for these procedures. The analysis of this characteristic verifies the modules' performance and identifies any potential issues. The curve tracer logs the short-circuit current, open-circuit voltage, and maximum power (voltage and current at this point) of the module. The nominal module temperature is monitored using thermocouple sensors.

Solar irradiance and albedo: For the measurement of global and reflected solar radiation, and the solar albedo, a Hukesflux Class-A Digital Albedometer, model SRA30-D1, was used. This albedometer is composed of two SR30 Spectrally Flat Class A pyranometers. In this configuration, one pyranometer is up-facing, measuring the global solar radiation in the plane of the module, and the other is downfacing, measuring the solar irradiance reflected by the specific ground cover.

Climate conditions and temperature: A meteorological station manufactured by LUFFT, model WS600-UMB, was utilized to measure the ambient temperature in the vicinity to the module. The nominal module temperature is recorded using thermocouple sensors interfaced with the electronic equipment.

Thermography: Infrared images of the photovoltaic module surfaces were areal mapped in order to evaluate possible operating problems (e.g., hot spots due to defects, shading etc.). A Fluke Ti450 infrared camera was used for these procedures. This equipment has high sensitivity, enabling the visualization of even small temperature differences in the module. The camera displays this information through a color palette presented on its touchscreen interface.

Bifacial characterization: The evaluation of the energy production difference between the "front" and "rear" cells of the modules involved conducting three electrical test configurations (Fig. 7):

- I-V characteristics of the complete module.
- I-V characteristics of the front side of the module, with the rear side covered.
- I-V characteristics of the rear side of the module, with the front side covered.

The tests provide the values of the main measured electrical parameters and I-V curves for the three test configurations: the complete module, the covered rear side, and the covered front side.

Ground Cover: Solar power plants located in the state of Minas Gerais primarily are located on natural ground cover, either red or brownish soils and soils with non-uniform vegetation. Some bifacial power plants have been groomed with crushed light-colored stone to enhance the amount of reflected irradiation and, consequently, boost energy production. In one case, a proprietary white organic sheet was investigated for potential dual used (i.e., to increase albedo and to mitigate vegetation growth). These "landscaping" features are illustrated in Figure 8.

4 Results

Three distinct cases are investigated for the effects of the important parameters on the bifacial technology performance under the Brazil operating conditions. These also illustrate the issues in reporting performances for these technologies. Through the evaluation of a bifacial module's performance using real ground coverings with various materials found in the soils of Minas Gerais (albedo), it became possible to compare the results obtained for the bifacial modules in different regions (Fig. 4). The first case (Iguatama) is representative of the normal surveys for the PV power plants. The second case, Três Marias, provides a special study to evaluate the gain in using bifacial modules

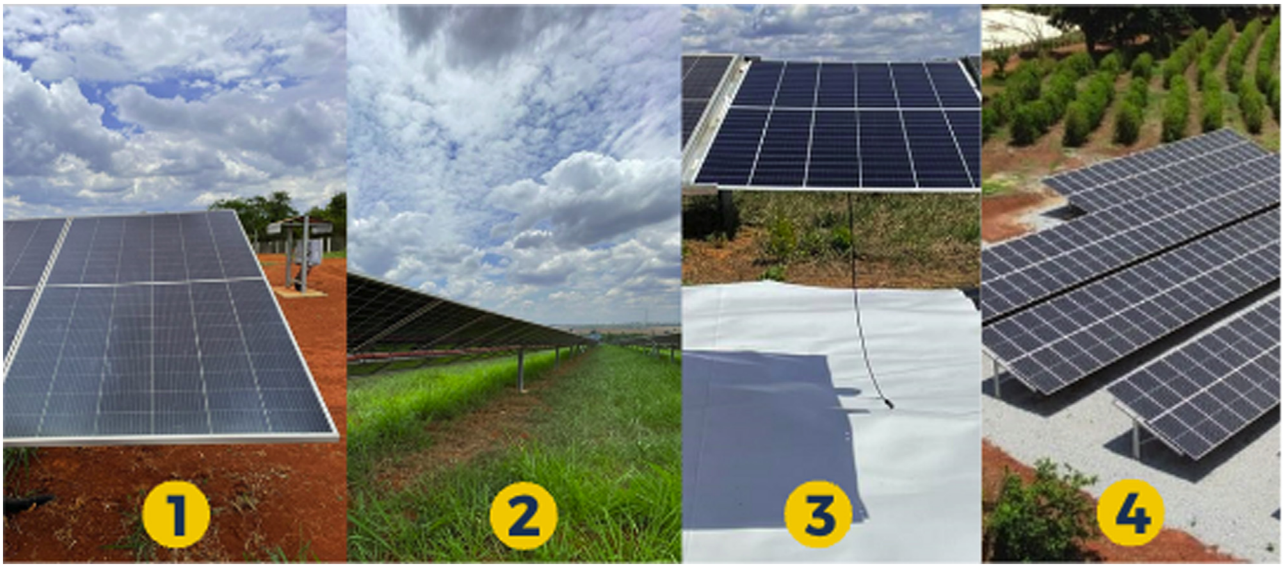

Fig. 8. Various types of ground cover for systems in Minas Gerais with different albedos (1) red soil, (2) green natural vegetation, (3) experimental organic sheet, (4) crushed white stone.

over the existing conventional panels—as well as an evaluation of a potential organic ground covering to increase albedo and limit vegetation growth. Itaguara is a non-tracking plant and represents the third case having side-by-side comparisons of the effects of different ground covers on the performance. The typical electrical characterizations are summarized and compared in Table 1. The physical power plants configurations in this study were evaluated, and all meet the requirements for the GCR and the height to deliver the optimum power from the installation.

4.1 Iguatama solar plant

This first case considers an in-depth evaluation of a bifacial, East-West oriented solar tracking system. The Iguatama Solar Plant is located in West-Central Minas Gerais (Fig. 4), with coordinates (20.174°S, 45.7082°W). This plant was installed in 2022 with capacity of 2.5 MW (with a twin 2.5 MW system located adjacently). This installation has a non-uniform ground cover of red soil and vegetation (Fig. 9) that is typical of most current bifacial systems in the State of Minas Gerais.

The albedo was measured at various points along rows of modules at locations not shaded, with a surface/vegetation representative of the ground. The average albedo value found under these conditions was approximately 0.11. This albedo is expected for this ground cover, but improvement in the reflection by maintenance of the site could improve this parameter and the resulting system performance.

The photovoltaic generator is composed of glass-glass bifacial modules with monocrystalline cells and a nominal power of 590-Wp. The module has a bifaciality factor of $70\% \pm 5\%$. To evaluate the energy production difference between the "front" and "rear" cells of the module, electrical tests were conducted in three different configurations. All the I-V characteristics obtained were normalized to standard test conditions (STC), with an irradiance of $1000\,\mathrm{W/m^2}$ and a cell temperature of 25 °C. Modules and strings were measured to evaluate quality. All met the manufacturer's specifications. One module result is presented here to illustrate typical performance.

Following the methodology (Sect. 3), the operating I-V characteristics of the complete (both sides) module were recorded, (i.e., neither of the sides of the bifacial module was covered) and normalized to STC as presented in Figure 10a. The results are summarized in Table 1 for these bifacial 490 Wp modules.

Subsequently, the I-V characteristics were also acquired for the front side of the module and the rear side separately (Figs. 10b and c). That is with the rear and front covered as shown in Figure 11 to acquire each result independently, with typical I-V parameters are included in Table 1

From these measurements (Fig. 10), a bifacial gain of 6.2% is calculated. From the independent measurement of the front only and back only module sides exposed to the same standard irradiance, the bifaciality factor was within the manufacturer's specification.

The change in the shape of the characteristics (Fig. 10c) obtained for the rear side of the module is likely due to some non-uniform and lower level of illumination of the back module area—and seems to be consistent for the entire installation. As a result, the fill factor for the rear side was lower than the entire module I-V characteristics: 69.4% vs 75.4%, respectively. For the configuration of this solar tracking system, the torque tube provided a source of shading on the rear side of the module. This was responsible for the rear cell characteristics and the reduction in bifacial gain.

The torque tube of the tracking system structure had a distance of approximately 8 cm from the rear face of the photovoltaic modules. A thermographic inspection was conducted on the module rows using the Fluke Ti450 infrared camera. The average cell temperature was found

Table 1. Summary of I-V parameters for typical modules for Iguatama, Três Marias, and Itaguara power plants highlighting albedos and bifacial gains.

	Average Albedo	Area (m^2)	Voc (V)	Isc (A)	FF	Vmax (V)	Imax (A)	Pmax (Wp)	Efficiency (%)	Bifacial Gain
Iguatama Bifacial (tracking) (Rating 590 Wp; 20.8% efficiency; bifaciality factor: 70% ± 5%)										
Total Module	–	2.83	44.56	18.65	0.754	35.73	17.53	626.3	22.1	6.2%
Front	–	2.83	42.95	16.58	0.775	35.09	15.73	551.9	19.5	–
Rear *(normal reddish ground/vegetation cover)*	0.11	2.83	38.96	0.86	0.694	35.96	0.65	23.2	–	–
Três Marias (tracking) (Rating 395 Wp – Monofacial; 405 Wp; 20% – Bifacial, bifaciality factor 75%)										
A. Monofacial	N/A	2.01	43.18	9.61	0.73	33.6	8.95	300.7	19.4	NA
B. Bifacial (normal reddish ground with vegetation cover)	0.20	2.01	43.69	11.47	0.75	34.61	10.86	375.9	18.7	7.0%
C. Bifacial (white organic sheet)	0.55	2.01	43.17	11.93	0.76	33.78	11.52	389.2	19.4	7.3%
Itaguara Bifacial (non-tracking) (Rating: 590 Wp; 649 Wp with 10% rear power gain)										
A. Bifacial (combination brownish ground and vegetation cover)										
Total Module	0.03-0.05	2.83	42.60	17.87	0.76	34.2	16.85	576.3	20.4	0.5%
Front	–	2.83	42.71	17.74	0.76	34.33	16.71	573.6	20.3	–
B. Bifacial (crushed white stones)										
Total Module	0.40	2.83	42.34	18.03	0.76	34.71	17.14	594.9	21.0	3.7%
Front	–	2.83	42.71	17.74	0.76	34.33	16.71	573.6	20.3	–
C. Bifacial (white organic sheet)										
Total Module	0.50	2.83	42.91	18.15	0.78	34.88	17.29	603.1	21.3	5.1%
Front	–	2.83	42.71	17.74	0.76	34.33	16.71	573.6	20.3	–

Fig. 9. Details of the ground conditions at the Iguatama Solar Power Plant.

to be 52 °C. Additionally, it was observed that throughout all the rows of modules, the solar cells located at the middle height of the modules exhibited up to 30 °C higher T than the module's average temperature, as shown in Figure 12. Further studies are being conducted to establish a relationship between cell heating and shading caused by the mounting structure and how this can be mitigated. Module center bowing was observed that could be the result of this temperature non-uniformity. The concern is that over time, this temperature difference could be a root cause for module and system degradation. However, currently all PV modules (and strings) do meet the manufacturer's and standard commissioning specifications.

4.2 Três marias solar plant

The location of Três Marias is shown in Figure 4 (18.2053°S, 45.2275°W), located near the San Francisco River, Northwest of the Minas Gerais Capital. This single-axis tracking power plant is one that currently uses ***monofacial***, monocrystalline PV panels. These 395-Wp monofacial modules did meet the manufacturer's specifications and the strings met the Brazil requirements [49].

However, the objective of this present study was to evaluate the production gain of the solar power plant if fitted with bifacial modules. Because the site operator was implementing additional plants for the area, the analysis of what the bifacial gain would provide with the natural ground covering—and possibly the option of installing a proprietary white polymeric layer under the module rows. The site's natural ground cover is red soil (high iron content) and non-uniform vegetation (Figs. 11 and 13). The purpose of installing the white polymeric layer is to create a surface that significantly increases the radiation reflected by the ground as well as reducing the impact of vegetation growth near the modules. This would prevent shading issues at specific times of the day that are encountered at the site—and reduce maintenance costs.

An albedometer was installed in an unshaded area with a surface/vegetation representative of the ground (Fig. 13). Albedo values were observed to be 0.20 during the period close to solar noon. For the bifacial gain estimation of a module, I-V characteristics were acquired for reference our bifacial reference modules (brought to the site specifically for this portion of the site survey), with a power rating of 405 Wp. This module is a glass-glass configuration without metal frames and has a bifaciality factor of 70 ± 5%. Again, all I-V characteristics were normalized to standard test conditions (STC), with an irradiance of 1000 W/m^2 and cell temperature of 25 °C.

For the natural soil/vegetation albedo condition, the module reached the maximum power (P_{MAX}) of 375.9 Wp (Fig. 14a), with the associated parameters summarized in Table 1. The evaluation of the front and rear module surfaces, as described for Três Marias, yielded a bifacial gain slightly higher (~7%) than Iguatama due to the higher albedo.

Subsequently, a white polymeric layer was installed beneath the module row to quantify the maximization of radiation reflected by the ground, as shown in Figure 13b. In this condition, it was observed that the albedo reached values close to 0.50 at the time of measuring the I-V curve of the module, representing a positive variation of over two times compared to the natural soil.

After the installation of the white polymeric layer on the ground, the module reached the maximum power (P_{MAX}) of 389.2 Wp. The I-V characteristics are presented in Figure 14b and with parameters summarized in Table 1.

Despite the albedo increase of over two times, it was found that the gain in electrical parameters was smaller. The nominal power of the module with the white polymeric covering increased by 3.5% over the normal ground covering case. It is concluded that the gain in the photovoltaic generator's power does not justify the investment in acquiring an extensive area of white polymeric layer. Additionally, it was observed that a

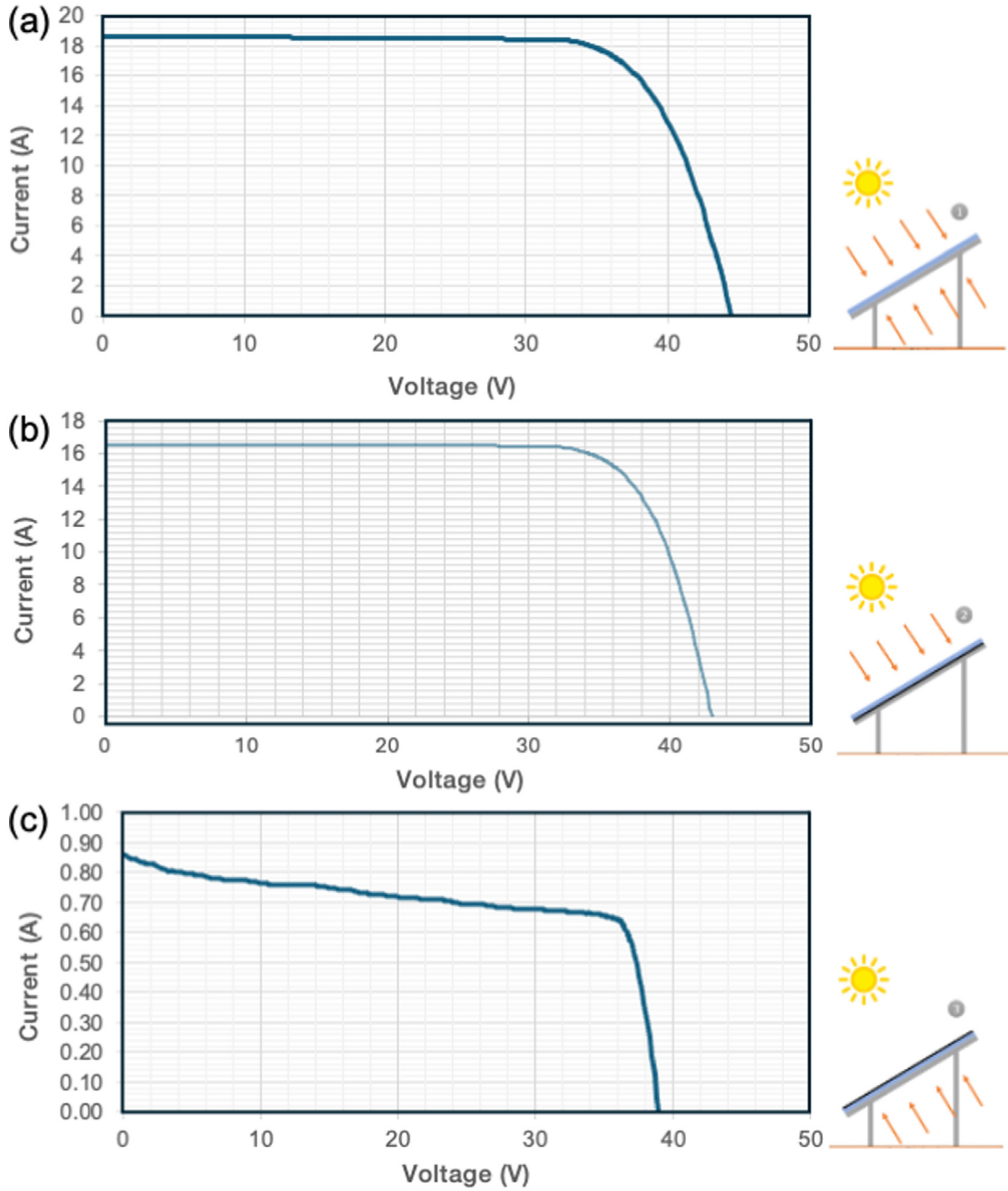

Fig. 10. I-V characteristics of bifacial module (Iguatama): (a) Complete (operating with front and rear sides); (b) Front side only; (c) Rear side only.

significant amount of dust and dirt accumulates on the white layer when installed on several days on under the modules, reducing its ability to reflect sunlight over time. The growth in vegetation at the site was rapid. And the application of the polymeric layer beneath the module rows would be control this. But the cost savings in maintenance would have to be more closely analyzed to justify this materials use.

4.3 Itaguara solar plant

The Itaguara (Fig. 8, with coordinates 20.3923°S, 44.4864°W) solar power plant is a non-tracking (fixed) bifacial plant, with panels at a tilt of 20° oriented towards geographical north. The plant has 152, 590 Wp bifacial-PV modules, totaling 89.7 KWp. In this study, different f albedos were evaluated for each row of installed arrays:

Fig. 11. Procedure for I-V characteristics of the separate front and rear sides of the bifacial module.

Fig. 12. Thermography of PV modules using the Fluke Ti450 infrared camera.

Row 1: the natural soil of the site, Row 2: crushed stone ground, and Row 3: white polymeric surface, shown in Figure 15.

For the natural soil (brownish dirt) albedo condition, the modules reached an average maximum power (P_{MAX}) of 576.3 Wp. The associated I-V parameters are summarized in Table 1. Albedo values were measured to be low, <0.05, due to the low reflectivity of the ground surface, lower than the prevalent reddish soil encountered at most Brazil locations (e.g., Três Marias and Iguatama). Following the procedure described previously, the electrical parameters were determined separately for the front side (e.g., covering the panel back as in Fig. 11) and the rear side of the modules. Considering these measurements and those for the complete module (front and rear cells of the module), a bifacial gain of 0.47% is calculated.

For the natural crushed stone ground condition, the module reached the maximum power (P_{MAX}) of 594.9 Wp, with a higher average albedo (0.4). This is reflected in the higher maximum power current (I_{mp}) of 17.14 A and a maximum power voltage (V_{mp}) of 34.71 V as presented in Table 1. The higher bifacial gain (3.71%) was also aided by enhanced diffuse scattering from the ground cover.

And for the natural white polymeric surface ground condition, the module reached the maximum power (P_{MAX}) of 603.1 Wp, with measured albedos ~0.5. Thus, higher power current (I_{mp}) of 17.29 A and a maximum power voltage (V_{mp}) of 34.88 V were observed (Tab. 1). The results showed a measured bifacial gain of 5.14%–indicative of the much higher reflectivity. However, the polymeric covering cost and surface reflectivity lifetime are issues that would have to be resolved before any large-scale use of this approach.

5 Summary and conclusions

This case study surveyed bifacial module performance and behavior for 3-representative sites in Minas Gerais State. These power plants provided the opportunity to investigate

Fig. 13. Comparison measurement of albedo at Três Marias: Left – Natural ground cover; Right – Organic white sheet covering.

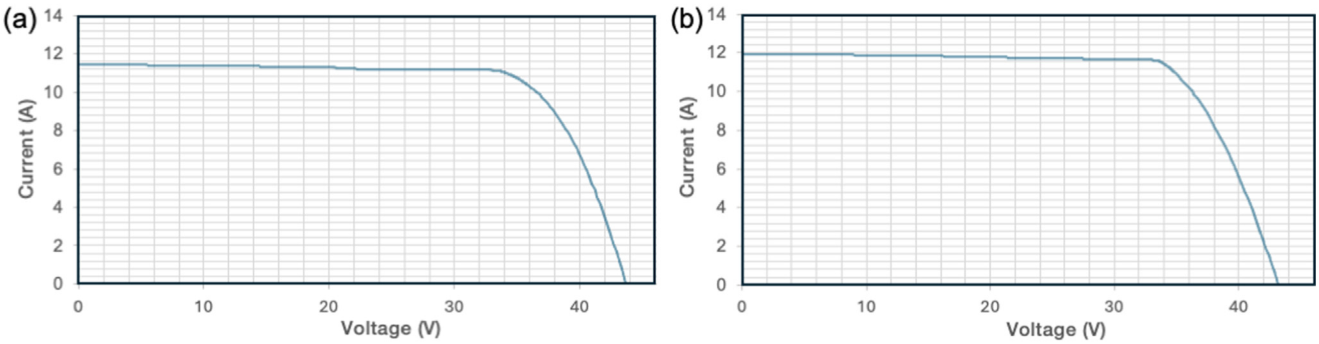

Fig. 14. I-V characteristics of bifacial module (Três Marias): (a) Complete (front and rear) module with natural ground cover (375.9 Wp); (b) Complete with polymeric ground cover sheet (389.2 Wp).

and compare both tracking and non-tracking installations and a variety of ground covering conditions with various albedos. The studies showed:

- Albedo is the primary factor in both the overall performance of bifacial modules and systems. The bifacial gain for the sites was shown to depend directly on the albedo and the condition of the ground cover at the plants. Module performances were shown to correspond to the manufacturers' data sheets indicating the quality of the product, but some concerns were noted in this study for site installation and conditions.
- Iguatama: Though the modules were within the manufacturer's specifications, several issues were reported. First, the center of the modules was shaded by the torque tube of the tracker. This shading resulted in unanticipated heating of the cells in the middle of the modules—as much as 30 °C above the average temperature of the other regions of the module during midday. In turn, this heating caused some bowing in the module due to the glass expansion in these regions. This may be a concern for the long-term reliability of these components.
- Três Marias: This monofacial tracking power plant provided the opportunity to investing the gain in power that the site could experience with bifacial technology. For the ground cover conditions (soil/vegetation), an average bifacial gain of about 7% was measured, with the albedo of 0.20. At the request of the site operator, a proprietary which polymeric ground covering was evaluated—with a good albedo of 0.50. This yielded a gain of 3.5% over the existing soil/vegetation ground condition. This modest power enhancement would probably not be sufficient to invest in this covering for a MW-sized plant. The covering would have a benefit to control the rapid vegetation growth at this site, but would have to be analyzed further for the financial comparison to the normal costs in maintain the site. Additionally, it was observed that the "white" surface did become soiled after a few days—which would require extra maintenance as well.
- Itaguara: This site provided the opportunity to compare common ground covering for a fixed bifacial power plant. Three rows were of the array were prepared with different

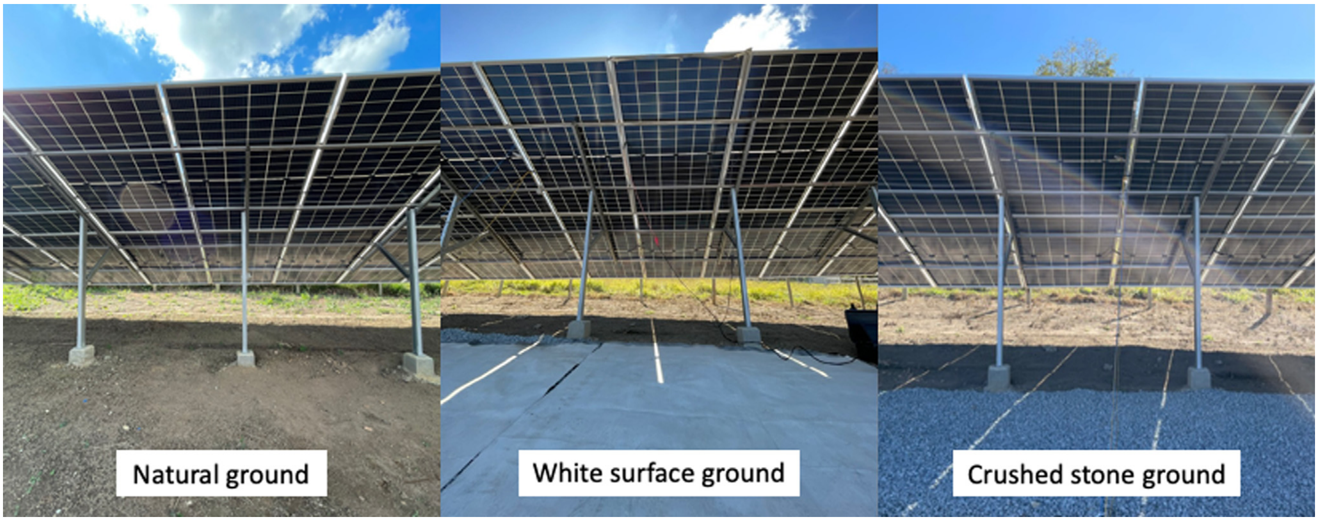

Fig. 15. Study of different ground coverings for effect of albedo on bifacial panel rows at the Itaguara Solar Plant: Natural ground (brownish); Crushed light stone; White polymer surface.

ground coverings: (a) normal soil (brownish); (b) crushed light rocks; and (c) a white organic cover. Of these, the bifacial gain provided by the crushed stones was significantly greater (~8 times) than the natural soil. And the white organic cover, about 11 times greater. However, the ease in application and cost of the crushed stone would probably make this the best choice for bifacial site preparation.

The quality of the modules used at these sites was confirmed, with all measured modules (including those at the monofacial installation in Três Marias) were within manufacturers' specifications. In addition, all strings passed the commissioning specifications. The importance of the albedo for bifacial installations is critical—and the investment in the ground conditions can lead to signficant power enhancements especially with the continuing improvement in bifacial device performance. Certainly with the cost of the bifacial panels now nearly the same as the conventional ones, the use of this technology would certainly be the choice for both tracking and non-tracking power plants.

Conflict of interest

The author(s) declare that they have no conflict of interest.

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Author contribution

All the researchers were worked equally. Each of them helped in the writing of this paper.

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