Experimental Performance of Bifacial Photovoltaic Modules Under Standard Test Conditions: Evaluation of Bifaciality and Rear Irradiance Gain

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Abstract

Bifacial photovoltaic systems have gained prominence in Brazil due to their higher efficiency and ability to harness reflected solar radiation. Unlike monofacial modules, they generate energy from both the front and rear sides. This study carried out the experimental characterization of ten bifacial monocrystalline silicon modules under standard test conditions (STC), evaluating electrical parameters such as voltage, current, and maximum power. Electroluminescence (EL) tests were performed to identify microcracks and cell defects. The I-V and P-V curves were obtained for both sides, allowing the calculation of the bifaciality factor and the additional power gain (BiFi). The results showed an average bifaciality factor of 70%, consistent with the manufacturer's data. It was observed that the performance of the rear side depends on the incident irradiance and installation conditions. The modules demonstrated structural integrity and compliance with regulatory standard IEC 60904-1-2. The study reinforces the importance of independent testing to ensure technical reliability. The rear-side gain was quantified under different irradiance levels, highlighting the additional energy potential. The experimental characterization contributes to the design of more efficient and reliable bifacial photovoltaic systems.

Keywords: Bifacial module, Bifaciality, Electroluminescence, Maximum Power, Photovoltaic

1. Introduction

Photovoltaic systems have been expanding rapidly in Brazil, consolidating themselves as one of the country's main sources of electricity generation. In this context, advances in bifacial photovoltaic module technology emerge as a promising strategy to increase the efficiency and energy density of these systems (Mozetic et al., 2023). Unlike monofacial modules, bifacial modules can convert not only the irradiance incident on the front face into electrical energy but also the reflected radiation captured by the rear face (Prates et al., 2024).

To fully understand and incorporate the benefits of bifaciality into engineering projects, it is essential to perform an experimental characterization of the electrical performance of both module faces under controlled conditions. This analysis allows for the validation of specifications provided by manufacturers and supports more precise design decisions in real-world application scenarios, where factors such as albedo, orientation, and shading can significantly impact system performance. Under standard test conditions, bifacial modules can generate 30% more energy than conventional modules by making use of their rear surface. In their work, (Cuevas et al., 1982) showed that it is possible to obtain an increase of up to 50% in electric power generation by simultaneously collecting direct radiation and the albedo from the roof and nearby surroundings of a module using a concentrator device that enhances the albedo. Consequently, it was established that bifacial solar cells can increase the power density of photovoltaic modules compared to monofacial cells, while reducing area-related costs for photovoltaic systems. The additional energy generated by the rear irradiance can range between 5% and 90% of the energy generated by front illumination alone. This percentage depends not only on the module properties and the rear side conversion efficiency, but also strongly on the module's location, orientation, and immediate surroundings (Libal and Kopecek, 2018).

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However, it is important to highlight that these gains are obtained under ideal laboratory conditions, with an AM 1.5 G spectrum and a complete absence of rear-side shading, including minimized cable routing and structures to prevent obstructions. In practice, the actual gains are significantly smaller. Field tests have shown typical gains of only 3% to 4% compared to monofacial modules (De Bona et al., 2022), which is well below what is suggested by manufacturers in a controlled environment. Another relevant aspect is albedo, which represents the ratio between reflected irradiance and incident irradiance on a surface. White surfaces can have an albedo of up to 50%, while common surfaces, such as crushed stone or dry soil, exhibit values around 20%. In principle, it would be reasonable to expect a proportional increase in bifacial gain with the use of more reflective surfaces. However, studies have demonstrated that this additional gain is, at most, 2%, even with the use of high-albedo materials (Formagini et al., 2024).

The objective of this study is, therefore, to present an experimental evaluation of the performance of a bifacial photovoltaic module under standard test conditions, as defined by IEC 60904-1-2, and to discuss the importance of independent testing to validate the information provided by manufacturers. This issue becomes even more relevant given the growing concern that modules submitted for certification do not always accurately represent those marketed on a large scale, reinforcing the need to ensure traceability and reliability throughout the qualification process.

2. Methodology

2.1. Module characterizations

Ten bifacial monocrystalline silicon photovoltaic modules with half-cell technology, identified as MB01 to MB10, were analyzed. Each module has a maximum power output of approximately 645 W under Standard Test Conditions (STC), with an average conversion efficiency of 20.8%. The main electrical parameters measured under these conditions are open-circuit voltage (Voc) of 44.8 V, short-circuit current (Isc) of 18.35 A, voltage at the maximum power point (Vmp) of 37.7 V, and current at the maximum power point (Imp) of 17.11 A. The modules have a nominal bifaciality factor of 70%, indicating good capability to harness the radiation incident on the rear side. The physical dimensions of each module are 2384 mm in length and 1303 mm in width, resulting in a total area of 3.10 m². The modules support a maximum system operating voltage of 1500 V and a maximum fuse current of 35 A. The thermal coefficients associated with electrical performance are −0.26%/°C for voltage and +0.05%/°C for current, demonstrating adequate thermal stability under ambient temperature variations.

2.2 Experimental Procedure

The modules were submitted to laboratory tests for electrical and visual characterization, including electroluminescence (EL) analyses and current-voltage (I-V) curve measurements under STC. These procedures aimed to evaluate the electrical performance, verify response uniformity, and identify potential defects in the photovoltaic cells, ensuring the modules' compliance with the requirements of standard IEC 61215.

The electroluminescence test was performed with the objective of identifying microcracks, interconnection failures, and other structural defects in the cells. The direct current (DC) source was configured to operate at 47 V and 11 A, with a maximum power limited to 500 W. Images were captured with a Nikon EOS RP camera equipped with a lens and an optical filter operating in the spectral range of 900 to 1200 nm, allowing the detection of the luminescence signal emitted by the silicon. For a complete characterization, the test was carried out on both the front and rear faces of the modules, enabling the analysis of structural integrity on both surfaces.

The I-V curves were obtained separately for each side of the modules using a HighLight 3 Class A+A+A+ solar simulator, in accordance with the requirements of IEC 60904-9. The front-side tests were conducted under STC conditions, irradiance of 1000 W/m², temperature of 25 °C, and AM 1.5 spectrum. The modules were positioned on the simulator plane with a tilt of less than ±5° relative to the horizontal plane, ensuring simultaneous illumination of both the module and the reference device, as shown in Figure 1. During the test, the simulator connectors and the temperature sensor were attached to the module terminals, and the ambient temperature was stabilized at 25 °C. The rear side was covered with a non-irradiant background to avoid additional reflections. Subsequently, measurements were performed in accordance with IEC 60904-1-2, simulating different rear-side irradiance levels (0, 50, 100, 150, and 200 W/m²) to evaluate the bifacial behavior of the modules.

Figure 1: Representation of the module installation in the solar simulator.

2.3 Calculating Bifaciality

The bifaciality factor is the ratio between the electrical characteristics of the rear side and those of the front side, and it is used to evaluate the rear side's contribution to the overall device performance. To determine this factor, the main I-V characteristics of both sides are measured under Standard Test Conditions (STC): irradiance of 1000 W/m², temperature of 25 °C, and reference solar spectrum AM1.5G, in accordance with IEC 60904-3, using a non-illuminated background to isolate the electrical response of each side. To assess the bifaciality of the tested module, the primary I-V characteristics of both sides, front and rear, must be measured under STC, using the previously defined non-irradiated background.

The bifaciality of the short-circuit current, φ_{ISC} is the ratio between the short-circuit current generated exclusively by the rear side of the bifacial device (I_{SCr}) and that generated by the front side (I_{SCf}). Both currents are measured under STC (1000 W/m², 25 °C, with the reference solar spectral irradiance distribution IEC 60904-3 AM1.5G), as expressed in Eq. 1.

$$\varphi_{I_{SC}} = \frac{I_{SCr}}{I_{SCf}} \qquad \text{(eq. 1)}$$

In addition to the current bifaciality factor, other bifaciality factors can be calculated. The open-circuit voltage bifaciality is determined by Eq. 2.

$$\varphi_{V_{OC}} = \frac{V_{OC_r}}{V_{OC_f}} \qquad \text{(eq. 2)}$$

where (Voc_r) represents the open-circuit voltage measured when the device is illuminated only at the rear, and (Voc_f) corresponds to the open-circuit voltage when the device is illuminated only at the front, both under STC.

Similarly, the maximum power bifaciality is calculated using Eq. 3.

$$\varphi_{Pmax} = \frac{Pmax_r}{Pmax_f} \qquad \text{(eq. 3)}$$

To determine a bifacial photovoltaic module's energy gain due to radiation incident on the rear side, a solar simulator with adjustable irradiance levels is used. In this methodology, irradiance levels are configured to simulate the contribution of irradiance on the rear side, even though radiation is emitted only on the front side of the module. In other words, we consider the sum of the incident irradiance on the front face and the irradiance that would reach the rear face, the latter being weighted by the bifaciality factor of the module. Thus, the equivalent irradiance level applied to the front face is determined by:

2.4 Rear Irradiance Gain Calculation

The gain in power driven by rear irradiance, known as bifacial gain or BiFi, aims to verify whether the gain in efficiency caused by the rear side of the module follows a linear trend with irradiance. It is obtained from the slope of a linear adjustment of the maximum power (Pmax) as a function of the equivalent irradiance, found previously. Once the value of the module's bifaciality factor has been determined, the procedure for calculating BiFi, which is the power gain driven by radiation on the rear side of the module, is performed, as detailed below.

The power gain performance driven by rear irradiance, BiFi, is the slope derived from the linear fit of the data series P_{max} versus G_r. This fit is performed using the least squares method and must be forced to cross the P_{max} axis at P_{maxSTC} and its non-linearity must be considered in the uncertainty estimate.

In addition to BiFi, two specific values of P_{max} should be reported, $P_{maxBiFi100}$ and $P_{maxBiFi200}$, for $G_{r_1} = 100\ W/m^2$ and $G_{r_2} = 200\ W/m^2$, respectively. $P_{maxBiFi100}$ e $P_{maxBiFi200}$ should be obtained by linear interpolation of the data series P_{max} versus G_r according to eq. 6 and eq. 7, respectively.

$$P_{maxBiFi100} = P_{maxSTC} + BiFi \cdot 100 \qquad \text{(eq. 6)}$$

$$P_{maxBiFi200} = P_{maxSTC} + BiFi \cdot 200 \qquad \text{(eq. 7)}$$

3. Results and Discussion

Electroluminescence (EL) testing was conducted on both the front and rear surfaces of the bifacial modules. The acquired images, exemplified by Figure 2 for module MB06, revealed no microcracks, inactive regions, or other defects. All modules exhibited uniform luminescence, with the absence of dark spots or non-emissive areas that could negatively impact the modules’ electrical performance or energy yield.

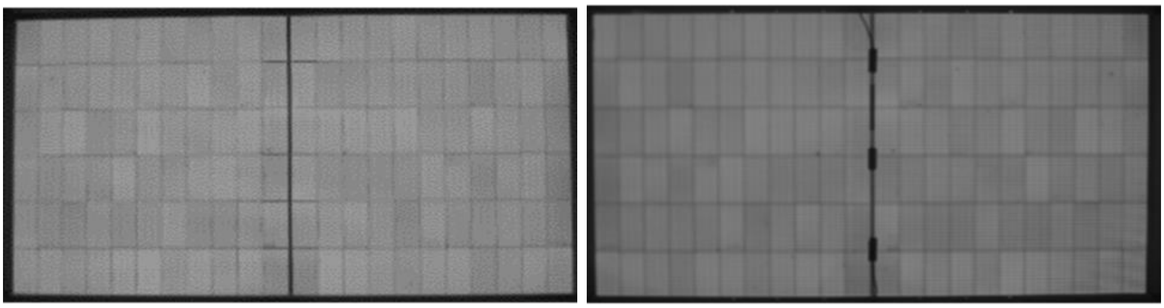

Figure 2: Results of the electroluminescence camera test.

The characteristic curves I-V and P-V under Standard Test Conditions were also measured for the front side of all analyzed modules. The results of the measurements under standardized conditions on the front side of the modules are presented in Table 1. For comparison purposes, Table 1 also shows a comparison between the measured values and those declared by the manufacturer. As a result, the modules exhibited values higher than those stated on their labels, with the exception of module MB10, which showed a power slightly below the manufacturer’s rating. However, this value falls within the measurement uncertainties of the solar simulator. The measurement uncertainty associated with the determination of maximum power in the tests conducted on the modules is ±2.23%.

Table 1: Results of the measurement under standardized conditions for the modules.

Module	MB01	MB02	MB03	MB04	MB05	MB06	MB07	MB08	MB09	MB10
Power (W)	647,7	655,0	648,7	645,1	645,6	649,6	645,4	645,2	648,0	640,2
Ref.	0,42%	1,56%	0,58%	0,03%	0,10%	0,72%	0,06%	0,04%	0,48%	-0,74%

Table 2 presents the electrical characteristics of the analyzed modules in comparison with the information provided by the manufacturer. From the table analysis, it can be observed that the tested modules have Voc, Isc, Vmpp, and Impp values close to those specified in their datasheets. The characteristic curves (I–V and P–V) under Standard Test Conditions (STC) for the front side of the analyzed modules are illustrated in Figure 3.

Additionally, since the analyzed modules are bifacial, the characteristic curves under STC for the rear side were also obtained. The results of the electrical characteristics are presented in Table 3. Analysis of the table shows that the measured values are in good agreement with those reported in the datasheets. The I–V and P–V curves for the rear side of the modules are illustrated in Figure 4.

Table 2: Results of the electrical characteristics of the front face of the modules compared to the manufacturer's declared values.

Characteristics	Power [W]	Vmpp [V]	Impp [A]	Voc [V]	Isc [A]
Manufacturer	**645,0**	**37,7**	**17,1**	**44,8**	**18,4**
Average	647,1	37,9	17,1	44,8	17,9
MB645-01	647,7	38,0	17,1	45,0	17,8
MB645-02	655,0	37,5	17,5	44,8	18,1
MB645-03	648,7	38,1	17,0	44,8	18,0
MB645-04	645,2	38,1	16,9	44,7	17,9
MB645-05	645,6	38,2	16,9	44,9	17,8
MB645-06	649,6	37,6	17,3	44,8	18,0
MB645-07	645,4	37,6	17,2	44,7	17,9
MB645-08	645,3	38,0	17,0	44,7	17,9
MB645-09	648,1	37,9	17,1	44,8	17,9
MB645-10	640,3	38,1	16,8	44,6	17,7

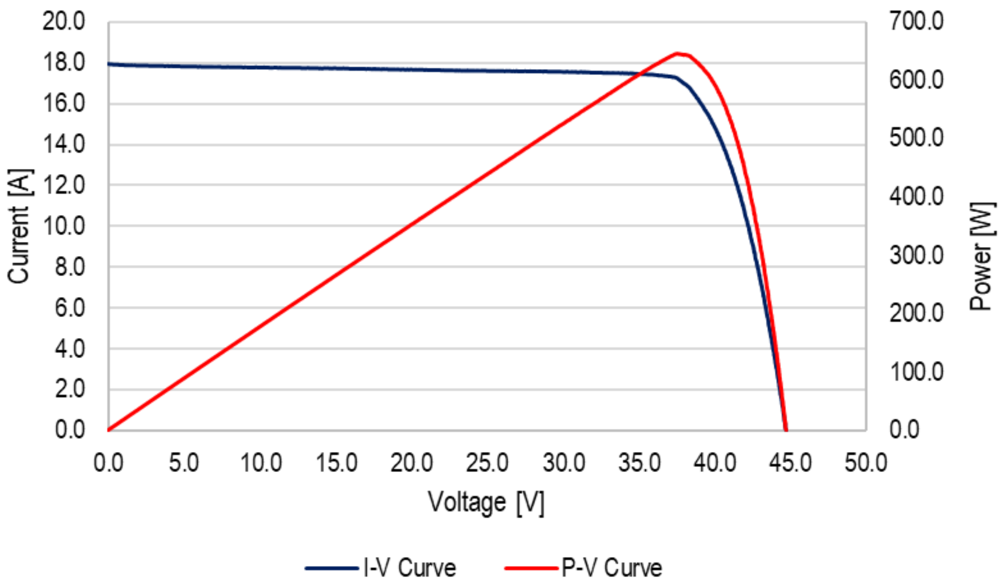

Figure 3: Result of the I-V characteristic test on the front face of the modules.

Table 3: Results of the electrical characteristics of the rear face of the modules compared to the manufacturer's declared values.

Characteristics	Power [W]	Vmpp [V]	Impp [A]	Voc [V]	Isc [A]
Manufacturer	**451,5**	**37,7**	**11,9**	**44,8**	**12,8**
Average	450,5	38,6	11,6	44,1	12,7
MB645-01	446,4	38,9	11,4	44,5	12,4
MB645-02	455,9	38,6	11,7	44,2	12,9
MB645-03	454,6	38,6	11,7	44,1	12,7
MB645-04	446,0	38,9	11,4	44,1	12,7
MB645-05	452,9	38,6	11,7	44,1	12,7
MB645-06	449,8	38,7	11,6	44,1	12,7
MB645-07	451,7	38,6	11,6	44,0	12,8
MB645-08	447,9	38,4	11,6	44,0	12,7
MB645-09	452,0	38,4	11,7	44,0	12,9
MB645-10	447,5	38,6	11,5	44,0	12,6

By observing Figures 3 and 4, it can be seen that the modules exhibit a drop in the I-V curve, resembling the characteristic curve of a module with partially shaded cells. This behavior is due to the presence of the bypass diode boxes located at the center of the module, which, because of their size, partially cover some of the cells. Another observation that can be inferred from Figure 4 is the shape of the P-V curve, which appears more triangular compared to the P–V curve of the front side. A possible explanation for this behavior is the difference in the depletion layer formed by the PN junction on the rear side of the module.

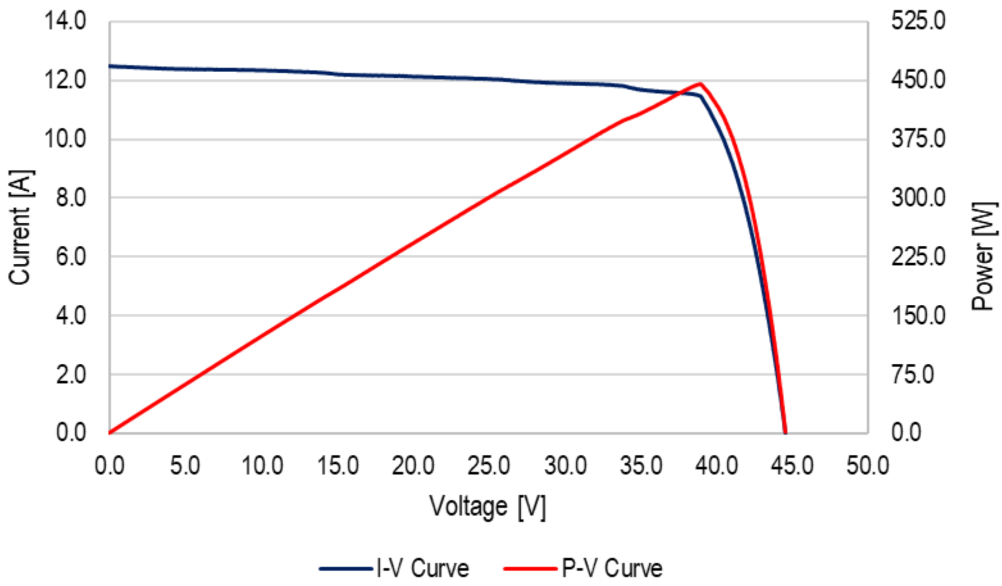

Figure 4: Result of the I-V characteristic test on the front face of the modules.

Table 4 presents the results for maximum power (φPmax), short-circuit current (φIsc), and open-circuit voltage (φVoc). According to IEC 60904-1-2, the bifaciality factor is considered the lowest value among these parameters; in this case, the lowest average factor obtained was 69.6%, a value consistent with the 70% reported by the manufacturer.

Table 4: Measurement result of bifaciality factors of modules

φ	BiFi (%)	Avg (%)	MB1 (%)	MB2 (%)	MB3 (%)	MB4 (%)	MB5 (%)	MB6 (%)	MB7 (%)	MB8 (%)	MB9 (%)	MB10 (%)
φ_{Pma}	70.0	69.6	68.9	69.6	70.1	69.1	70.2	69.3	70.0	69.4	69.7	69.9
φ_{Voc}	100.0	98.6	99.1	98.7	98.7	98.8	98.4	98.6	98.5	98.6	98.3	98.7
φ_{Isc}	70.0	71.3	69.9	71.4	71.2	71.2	71.7	70.7	72.2	71.4	72.3	71.2

After determining a bifaciality factor of 70%, the BiFi was calculated, representing the power gain due to irradiance on the rear side of the module. Specific irradiance levels were applied, combining 1000 W/m² on the front side with increasing values on the rear side. Table 5 presents the results of the measurements under these conditions, including the average BiFi value obtained.

Table 5: Results of maximum power measurements for different irradiance intensities.

Irradiance (W/m²)	Ref.	MB1	MB2	MB3	MB4	MB5	MB6	MB7	MB8	MB9	MB10
1000	645	647.7	655.0	648.7	645.2	645.6	649.6	645.4	645.3	648.1	640.3
1035	660.8	670.3	677.5	670.2	662.0	667.3	671.8	667.0	663.4	666.3	657.6
1070	676.6	693.4	701.7	693.2	689.7	683.8	692.9	684.5	687.2	687.9	682.8
1105	692.4	715.5	726.6	717.8	710.7	712.8	712.6	710.1	708.8	711.7	705.5
1140	708.2	735.8	744.7	736.8	731.4	728.4	738.2	732.1	728.4	735.7	728.2

Additionally, calculations were performed to determine the theoretical maximum power when the module is exposed to 1000 W/m² on the front side and 100 W/m² and 200 W/m² on the rear side, referred to as PmaxBiFi100 and PmaxBiFi200, respectively. The results of the average module powers, both calculated and measured, are illustrated in Figure 6, and the values are summarized in Table 5.

Table 5: Measurement results for different irradiance levels.

φ	Equivalent irradiance on the rear side [W/m²]	Irradiance on the front side [W/m²]	Pmax [W]	Pmax BiFi [W]	BiFi [W/(W/m²)]
70	0	1000	647.10	-	0.4392
	50	1035	667.33	-	
	100	1070	689.71	691.02	
	150	1105	713.21	-	
	200	1140	733.96	734.94	

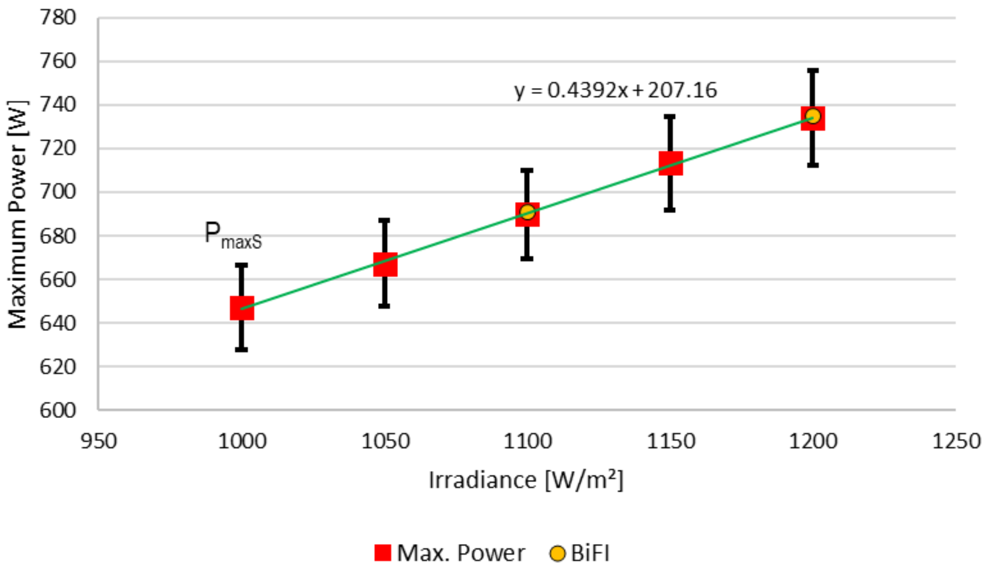

Figure 6: Result of the I-V characteristic test on the front face of the modules.

4. Conclusion

Laboratory tests were conducted to characterize the electrical and visual performance of bifacial monocrystalline silicon photovoltaic modules, including current–voltage measurements, electroluminescence analyses, and determination of the bifaciality factor and additional power gain. These procedures, carried out under controlled temperature and irradiance conditions, aimed to assess the modules' electrical behavior and verify compliance with applicable technical standards.

The EL analyses revealed no microcracks, interconnection failures, or low-luminescence regions, indicating good structural and electrical integrity. I-V measurements confirmed that the maximum power values under Standard Test Conditions were consistent with the manufacturer's specifications, validating the quality and reliability of the modules. The experimentally determined bifaciality factor agreed with the nominal 70% value reported in the datasheet.

Under laboratory conditions, the rear side demonstrated the ability to generate high power values, highlighting the potential of bifacial technology to increase energy yield. However, in real operating environments, the effective gain is typically lower—around 2% to 4% compared to monofacial modules—due to shading from cables and mounting structures, as well as spectral and angular non-uniformity of the reflected irradiance. Thus, the reduced field performance results from non-ideal installation and irradiation conditions rather than limitations of the technology itself.

The tests confirmed compliance with IEC 60904-1-2 requirements and validated the accuracy of the parameters used for photovoltaic system design, ensuring adequate performance and operational reliability throughout the equipment's lifetime.

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