

Article

High-Reflectivity Ground Covers for Energy Yield Enhancement in Single-Axis Tracked Bifacial Photovoltaic Systems: Field Evidence from Brazil

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Abstract

Artificial high-reflectivity ground covers are a potential strategy to increase rear-side irradiance and energy yield in bifacial photovoltaic systems, especially in utility-scale plants with single-axis trackers. This paper reports field evidence from a pilot plant in southern Brazil (27.4° S, 48.4° W), where four reflective covers—a white film, a pearl-white film, a black-and-pearl film, and a white geomembrane—were evaluated against a gray gravel reference. The study combines albedo and spectral characterization, rear-to-front irradiation ratios, energy-yield comparisons, soiling assessment, thermal analysis, and operational observations. Broadband albedo increased from 25% for gray gravel to 53–58% for the reflective films and 72% for the geomembrane. Reflective films increased the rear-to-front irradiation ratio to around 20% and delivered energy gains close to 9%, while the geomembrane achieved the highest irradiance enhancement and gains exceeding 10%. Inverter current limitations led to clipping, indicating that measured gains may underestimate the full energy potential of the reflective covers. Estimated thermal losses were insignificant compared with measured gains, while soiling and fixation methods affected long-term feasibility. The results confirm the technical potential of reflective covers, while showing that utility-scale deployment must consider not only optical performance, but also optical stability, electrical limitations, cleaning and anchoring requirements, drainage adaptations, operation and maintenance practices, and cost constraints.

Keywords: bifacial photovoltaics; albedo; reflective ground covers; geomembrane; single-axis tracker; PV performance; soiling; utility-scale PV



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1. Introduction

Photovoltaic (PV) generation has become one of the main options for expanding electricity supply with low operational greenhouse gas emissions and the lowest levelized cost of energy. Its growth has been enabled by rapid reductions in PV module cost, improvements in efficiency, and manufacturing scale, which have progressively increased the competitiveness of solar electricity in different markets [1]. In countries such as Brazil, where abundant solar resource led to rapid growth in installed PV capacity [2,3], further performance improvements are particularly relevant because even modest percentage gains can translate into large cumulative energy gains over the lifetime of utility-scale PV assets.

Among the most important changes in PV plant design over the last decade has been the consolidation of bifacial modules and single-axis trackers [4–6]. Bifacial modules

generate electricity from irradiance incident on both the front and rear surfaces, while trackers increase the collection of direct irradiance by following the apparent motion of the sun. The combination is especially attractive for utility-scale plants because it can improve energy production per installed watt and reduce the levelized cost of electricity, with bifacial single-axis tracking systems shown to achieve the lowest levelized cost of electricity over more than 90% of the investigated land area in a global techno-economic assessment [7].

The relevance of rear-side irradiance is expected to increase further as the PV industry transitions from *p*-type PERC products to higher-efficiency *n*-type technologies, especially TOPCon and heterojunction modules [8]; as bifacial tandem perovskite-silicon PV evolves from pre-commercial to large-scale deployment, additional performance aspects related to subcell current mismatch will bring more complexity to the handling of the effects albedo. Technology roadmaps indicate that these module families tend to have higher bifaciality factors and lower temperature coefficients than conventional PERC modules [9]. As module bifaciality increases, the rear-side response becomes more effective in converting additional reflected irradiance into electrical output, thereby enhancing the incremental gain provided by reflective covers.

In conventional PV power plants, the ground surface is usually selected or modified according to civil works, vegetation management, access, erosion control, and drainage. In large-scale bifacial PV power plants, however, deliberately increasing ground albedo can increase rear-side irradiance and potentially improve annual energy yield. Artificial high-reflectivity covers such as polymeric films, white membranes, and geomembranes are therefore gaining attention as an approach to enhance bifacial performance without increasing the installed DC capacity or the occupied area. This paper uses the term high-reflectivity ground covers to refer to these artificial reflective surfaces.

The potential benefit of this strategy is conceptually simple but technically complex. Increasing albedo does not automatically lead to a proportional increase in delivered energy. Rear irradiance depends on the view factors between modules, sky, ground, and neighboring rows; on tracker position and backtracking; on the direct and diffuse components of irradiance; and on the spatial distribution of light on the rear side of the module. Additional rear-side irradiance will also influence mismatch, inverter clipping, module temperature, soiling, and maintenance practices. Therefore, field evidence is essential to understand the net gain that can be achieved under realistic operation.

This article reports experimental results from two annual monitoring cycles at the Fotovoltaica/UFSC pilot plant in Florianópolis, southern Brazil (27.4° S, 48.4° W), evaluating the effects of different ground-cover albedos on both irradiance and PV performance. Irradiance effects were characterized at a dedicated albedo measurement station, while the corresponding energy-yield response was measured directly in bifacial PV arrays mounted on single-axis trackers. Preliminary results from the first monitoring cycle, focused on two reflective films, were previously reported in Braga et al. [10] and Azevedo et al. [11]. The present article builds on those preliminary studies by integrating the first-cycle findings with a second annual monitoring cycle, including optimized reflective covers, and by providing a broader assessment of albedo, spectral response, energy yield, soiling, thermal behavior, electrical limitations, and practical installation aspects. The objective is to quantify how different reflective ground covers modified albedo, rear-to-front irradiation ratio, and energy yield in bifacial PV systems with single-axis tracking, while also documenting the observed influence of soiling, temperature, and installation methods. The manuscript is deliberately focused on the field results and on the reflective-cover literature that supports their interpretation.

Accordingly, the novelty and contribution of this work lie in providing independent, year-scale field evidence for engineered high-reflectivity ground covers in single-axis tracked bifacial PV systems under Brazilian operating conditions. The study complements previous simulation-based assessments and field studies carried out in other climatic and system-design contexts, including higher-latitude sites, by combining albedo and spectral characterization with direct PV energy-yield measurements and operational observations over two full-year cycles. Beyond quantifying optical and energy gains, the work discusses practical implementation aspects that may affect utility-scale deployment, including inverter current limitations and power clipping, soiling, thermal effects, anchoring, drainage, and maintenance. In this way, the study contributes to a more complete assessment of reflective covers as a performance-enhancement strategy for bifacial PV plants.

2. Literature Background: Reflective Ground Covers for Bifacial PV

The energy gain of a bifacial PV system can be interpreted at different levels. The optical gain is associated with the additional irradiance reaching the rear surface. The module-level gain includes the bifaciality factor and conversion response of the rear side. The system-level gain includes thermal behavior, mismatch, DC and AC losses, inverter clipping, and the characteristics of the power conversion system [6,12]. This distinction is central for reflective ground covers because their primary action is optical, but the result of interest for plant owners is the net electrical energy delivered by the system.

Rear-side irradiance is generally more spatially non-uniform than front-side irradiance because it is largely composed of sky-diffuse and ground-reflected contributions, whose distribution depends strongly on view factors, tracker position, torque-tube shading, row-to-row shading, module height, ground coverage ratio, and the spatial distribution and optical properties of the reflective surface. This non-uniformity can produce electrical mismatch between cells or substrings and reduce the fraction of the optical gain that is converted into useful power [13–15]. For this reason, measurements and simulations of bifacial systems often require more detailed geometric descriptions than those used for conventional monofacial systems [16–19].

Experimental evidence has shown that increasing ground reflectance can substantially improve PV performance. Chudinzow et al. simulated and assessed bifacial power-plant yield over different ground conditions and reported the strong dependence of bifacial yield on surface reflectivity [20]. In the Brazilian context, Braga et al. evaluated ground-surface effects in two PV plants in the Minas Gerais State in Central Brazil with different configurations [21]. IV measurements showed a 3.5% gain for a polymeric reflective cover with albedo of approximately 0.50 in a monofacial single-axis tracking plant, while white gravel and a white organic cover produced 8 to 11 times higher bifacial gains than natural soil in a fixed bifacial plant. However, the study was based on IV power measurements rather than energy-yield analysis and did not include an economic assessment.

Riedel-Lyngskaer et al. evaluated pilot bifacial systems in a pilot plant in Denmark and found that highly reflective ground materials increased yield for both fixed-tilt and single-axis tracking configurations [22]. However, their economic analysis showed that the value of the additional energy was strongly dependent on material cost and durability, with a small economic margin that did not justify the investment under the uncertainty of the solution performance over time.

Simulation-based and industry studies have also investigated the layout and economic relevance of reflective materials in bifacial PV plants. Rhazi et al. simulated more than 150 reflective-material configurations in France and showed that yield gains increased with the covered area, but not linearly, highlighting the importance of optimizing reflector layout [23]. Their LCOE analysis indicated that materials requiring replacement

during the lifetime of the PV plant were generally not economically attractive. In contrast, for a roofing membrane assumed to have a 25-year lifetime and a cost of 11.5 €/m², some layouts led to modest LCOE reductions [23]. A technical analysis by 7X Energy for two utility-scale projects in Texas (US) reached similar conclusions: a white woven polypropylene ground cover produced modeled annual production gains of 3.4–4.3%, but the base-case NPV remained negative, with feasibility depending on site-specific albedo, GCR, vegetation-management savings, installation labor, material lifetime, and power price [24]. The same study also showed that increased inverter AC clipping reduced the usable benefit of the albedo enhancement, motivating a redesign with a lower DC/AC ratio [24]. Alam et al. reported LCOE reductions with increasing ground albedo, from 72.8 to 70.3 £/MWh for the UK [25]. However, the albedo-enhancement cost was not separately quantified, and material durability or long-term reflectance degradation were not explicitly assessed. More recently, Lewis et al. estimated breakeven installed costs of approximately 1.50–6.00 USD/m² for reflective geomembrane configurations in the US, further emphasizing that the attractiveness of high-reflectivity covers depends on additional energy yield, material layout, installation cost, and long-term reflectance stability [26].

Recent material-screening studies conducted in the US have also shown that high-albedo ground treatments should be evaluated not only by reflectance, but also by cost and durability. Honda and Chatripally [27] assessed six candidate materials for bifacial PV ground treatment, with measured average albedos ranging from 0.52 for polyethylene to 0.67 for EPDM [27]. They also performed accelerated weathering and tensile testing and introduced an albedo-adjusted cost metric, which ranged from 2.31 USD/m² for polyethylene to 67.47 USD/m² for EPDM. These results reinforce that the material with the highest reflectance is not necessarily the most attractive option when cost is considered [27].

In parallel with the peer-reviewed literature, technical press reports indicate growing commercial interest in reflective membranes and geomembranes for bifacial PV applications. Articles published by industry news outlets have reported emerging commercial interest in reflective geomembranes and related ground-cover materials for bifacial PV projects, including manufacturer- or developer-provided estimates of yield gains, LCOE reductions, additional CAPEX, and payback periods [28–30]. Reported field applications indicate a wide range of yield gains, from approximately 5% to 20%, reflecting differences in system configuration, tracker geometry, baseline albedo, cover layout, and local operating conditions. However, the same reports also highlight uncertainties related to incomplete cost accounting and potential annual reflectivity losses caused by weathering and dust accumulation. More recently, a specialized PV industry news outlet reported the development of one of the reflective membranes evaluated in the present study by a Brazilian manufacturer, including its application in a bifacial PV plant in the Minas Gerais state region, with a reported 7% gain measured at the inverter output [31]. These technical reports do not replace independently validated scientific studies, but they show that reflective covers are already being considered in commercial, demonstration and showcase projects and reinforce the need for field-based assessments of energy gain, durability, soiling, and practical feasibility.

Besides broadband albedo, the spectral distribution of the reflected irradiance can influence PV performance. Different surfaces with similar broadband albedo may reflect differently across the spectral response range of silicon modules. Riedel-Lyngskaer et al. and Tonita et al. showed that spectral albedo can affect bifacial PV system output measurements and system model predictions, particularly when reference sensors and PV modules respond differently to the reflected spectrum [32,33]. In the Brazilian context, Braga et al. further demonstrated that local spectral irradiance distributions can deviate substantially from standard reference spectra, reinforcing the need to consider spectral

effects in PV performance assessments [34,35]. Therefore, field characterization of artificial ground covers should, whenever possible, include both broadband albedo and PV-weighted measurements.

Operational exposure is another key issue. The reflectivity of artificial covers may decrease because of soiling, weathering, surface degradation, biological growth, or damage during maintenance. The effect can be stronger in locations with dust sources, nearby construction, dry periods, or insufficient natural cleaning. Studies of bifacial PV on reflective surfaces have noted that maintaining the optical properties of the ground material is essential for the long-term value of the solution [22,33]. Thermal effects must also be considered because additional reflected irradiance absorbed by the modules can increase operating temperature and partially offset energy gains [36,37].

Finally, utility-scale deployment requires practical feasibility beyond optical performance. Reflective covers must remain stable under wind, allow access for operation and maintenance, avoid creating new soiling traps, and be compatible with drainage and environmental requirements. Large PV plants can alter runoff and surface conditions [38], and additional impermeable or low-permeability covers may further affect hydrology and erosion. The present work therefore evaluates not only measured yield gains, but also the practical issues observed during the field campaign.

3. Materials and Methods

3.1. Pilot Plant and Albedo Characterization

The experimental campaign was carried out at the Solar Energy Research Laboratory Fotovoltaica/UFSC PV pilot plant in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br). The site includes bifacial PV systems mounted on horizontal single-axis trackers (SATs) and a dedicated albedo station adjacent to the tracker field, as shown in Figure 1. The experimental design compared systems installed over high-reflectivity ground covers with a reference system installed over gray gravel, whose measured albedo is within the 20–30% range typically associated with common ground conditions in Brazilian utility-scale PV plants. The comparison was performed under the same local meteorological conditions and using the measured energy output of each tracked PV system.

The photovoltaic system measurements were carried out using the instrumentation installed on the tracker systems, including sensors for module temperature, rear-side irradiance, and front-side plane-of-array irradiance, as shown in Figure 2 and described in Table 1.

Table 1. Instrumentation used for photovoltaic system measurements at the single-axis tracker bifacial PV pilot plant. Selected sensors are shown in Figure 2.

Measurement	Instrument	Specification
Front- and Rear-Side Global POA Irradiance	EKO MS-80S	Classe A Pyranometer;
Front- and Rear-Side POA Irradiance	IMT Si-mV-85-PT100	Classe A Reference Cell
PV Module Temperature	PT1000	Classe A
Electrical Parameters	Huawei SUN2000	String Inverters
Meteorological Variables	Fotovoltaica/UFSC Weather Station	Various Sensors

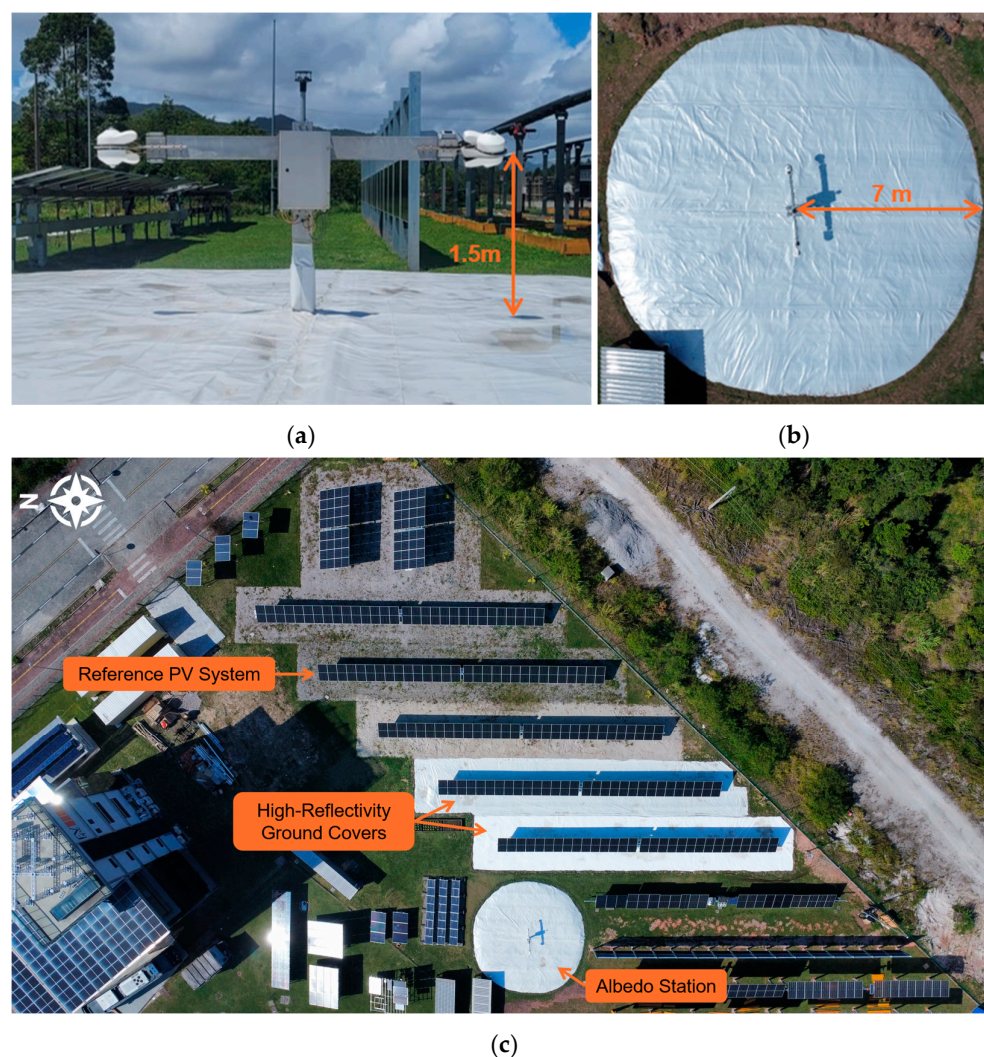


Figure 1. Experimental infrastructure at the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltica.ufsc.br): dedicated albedo station showing (a) the sensor setup and (b) the material surface under evaluation; and (c) bifacial SAT PV pilot plant, indicating the reference system, the systems with high-reflectivity ground covers, and the albedo station. The albedo station is located adjacent to the single-axis solar trackers used for the energy-yield validation of the experiment.

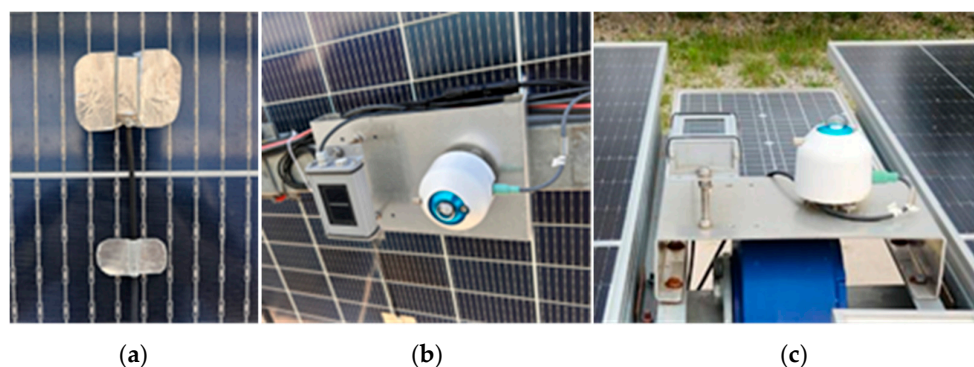


Figure 2. Sensors used to measure (a) module operating temperature, (b) rear-side irradiance, and (c) front-side plane-of-array irradiance at the single-axis tracker bifacial photovoltaic pilot plant. Sensors are described in Table 1.

Two experimental cycles were carried out. The first cycle covered April 2024 to March 2025 and evaluated a white film and a pearl-white film, while the second cycle covered

May 2025 to April 2026 and evaluated a black-and-pearl film and a white geomembrane. In both cycles, energy-yield gains were calculated relative to the gray gravel reference operating under the same time window and filtering criteria as the corresponding high-reflectivity-cover system. Although the two cycles were carried out in different calendar periods, each cycle covered a full 12-month period. The use of annual monitoring periods strengthens the representativeness of the reported gains by capturing seasonal variations in solar geometry, incidence angles, irradiance conditions, temperature, and rainfall. At the same time, the relative comparison with the gray gravel reference reduces the influence of meteorological variability within each performance comparison. Since the two cycles were carried out in different calendar periods, the absolute yield values obtained in different cycles are not directly compared in this study. Cross-cycle comparisons are restricted to relative gains and should be interpreted with caution, since monitoring periods may differ in soiling exposure, diffuse irradiance fraction, rainfall distribution, surface moisture, and material aging.

During the experimental campaign, the PV modules installed in the pilot plant were replaced. The initial configuration used *p*-type monocrystalline silicon PERC bifacial modules, while the current configuration uses *n*-type monocrystalline silicon bifacial modules. The main characteristics of both module types are summarized in Table 2.

Table 2. Main characteristics of the initial and current PV modules used in the bifacial single-axis tracker pilot plant.

Parameter	Initial PV Modules	Current PV Modules
Cell Technology	Bifacial mono-Si <i>p</i> -type PERC	Bifacial mono-Si <i>n</i> -type
Nominal Power	645 Wp	575 Wp
Wafer Size	G12	M10
Bifaciality Factor	~70%	~80%
Power Temperature Coefficient	−0.34%/°C	−0.30%/°C
Efficiency	20.8%	22.3%
Initial Degradation	2%	1%
Annual Degradation	0.45%/year	0.40%/year

Before the reflective covers were evaluated, baseline periods were carried out for both module configurations. During these periods, black tarps were installed below all evaluated trackers to homogenize the ground reflectivity and impose a uniform low-albedo condition, as shown in Figure 3. The purpose of this procedure was to verify the relative consistency among the identical PV systems before attributing performance differences to the ground covers.

Albedo was characterized by broadband radiometric measurements and by silicon reference cells, complemented by spectral reflectance measurements. The instrumentation used at the dedicated albedo station is shown in Figure 4 and described in Table 3. Broadband albedo represents the ratio between reflected and incident solar irradiance integrated over the sensor response. Reference-cell albedo provides a PV-weighted estimate that is closer to the spectral response of crystalline silicon modules. Spectral measurements were used to compare the wavelength-dependent reflectance of natural surfaces and artificial covers within the relevant range for silicon PV conversion.

The characterization periods for the four ground covers and the reference surface are reported in Table 4. All materials were monitored for at least two months, but the periods were not identical because the materials were installed and evaluated sequentially during the experimental campaign. However, since the albedo measurements were performed on horizontal, unshaded surfaces, they were less affected by tracker geometry, module shading, and operational conditions than the rear-side irradiance and energy-yield

indicators measured at the PV systems. Moreover, the adopted monitoring periods were substantially longer than the spot field measurements commonly used for solar-reflectance characterization of horizontal surfaces, such as those described in ASTM E1918 [39]. As discussed in Section 4.1, the evaluated surfaces presented well-defined albedo levels and trends, while the longer time series provided additional information on temporal stability, soiling, and cleaning effects.



Figure 3. Pilot plant during the baseline period, with black tarps installed below the identical PV systems to homogenize the ground reflectivity and impose a uniform low-albedo condition before the evaluation of the reflective covers.

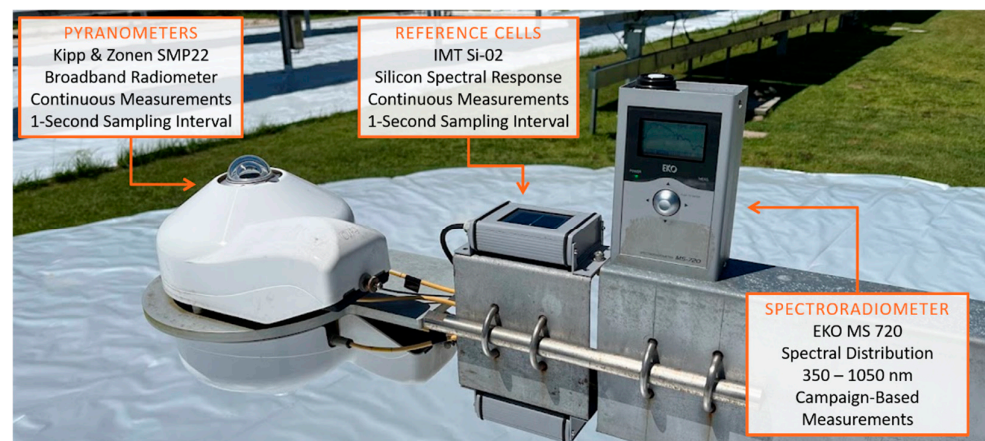


Figure 4. Instrumentation used for albedo characterization at the dedicated albedo station of the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br).

3.2. Characterization and Performance Indicators

For the characterization of the materials installed at the albedo station, the broadband albedo, (α), was calculated as the ratio between the reflected irradiance measured by the downward-facing pyranometer ($G_{\text{reflected}}$) and the incident global irradiance measured by the upward-facing pyranometer (G_{incident}), as shown in Equation (1). Similarly, the silicon-response-weighted albedo (α_{Si}) was obtained from the pair of silicon reference cells ($G_{\text{reflected,Si}}$ and $G_{\text{incident,Si}}$), as shown in Equation (2). The spectral reflectance ($\alpha(\lambda)$) was defined as the wavelength-dependent ratio between the reflected and incident spectral irradiance, as shown in Equation (3).

$$\alpha = \frac{G_{\text{reflected}}}{G_{\text{incident}}} \quad (1)$$

$$\alpha_{\text{Si}} = \frac{G_{\text{reflected,Si}}}{G_{\text{incident,Si}}} \quad (2)$$

$$\alpha(\lambda) = \frac{E_{\text{reflected}}(\lambda)}{E_{\text{incident}}(\lambda)} \quad (3)$$

Table 3. Description of the instrumentation used at the albedo station of the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br).

Measurement	Instrument	Specification	Time Resolution/ Measurement Range	Application
Incident Global Irradiance	Kipp & Zonen SMP22	Class A Pyranometer	1 s	Broadband Albedo Calculation
Reflected Global Irradiance	Kipp & Zonen SMP22	Class A Pyranometer	1 s	Broadband Albedo Calculation
Incident Irradiance	IMT Si-mV-85-PT100	Class A Reference Cell	1 s	Silicon-Response Albedo
Reflected Irradiance	IMT Si-mV-85-PT100	Class A Reference Cell	1 s	Silicon-Response Albedo
Incident and Reflected Spectral Irradiance	EKO MS-720	Portable Spectroradiometer	350–1050 nm	Spectral Reflectance

Table 4. Results of natural-surface and high-reflectivity cover characterization at the albedo station.

Material	Reference-Cell Albedo	Broadband Albedo	Evaluation Period
Gray Gravel	24%	25%	22 Oct 2022–8 Jan 2024
Pearl-White Film	58%	54%	1 Mar 2024–6 May 2024
White Film	58%	53%	8 May 2024–17 Dec 2024
White Geomembrane	76%	72%	19 Dec 2024–24 Apr 2025
Black-and-Pearl Film	63%	58%	1 May 2025–30 Apr 2026

For the PV systems, the main bifacial optical indicator was the rear-to-front irradiation ratio, ($R_{\text{rear/front}}$), defined as the ratio between the irradiation incident on the rear plane of array (H_{rear}) and the irradiation incident on the front plane of array (H_{front}) over the selected analysis period, as shown in Equation (4).

$$R_{\text{rear/front}} = \frac{H_{\text{rear}}}{H_{\text{front}}} \quad (4)$$

Energy performance was evaluated using the specific yield of each tracker system, (Y), calculated as the ratio between the energy generated during the selected period (E) and the installed front-side nominal power (P_{STC}), as shown in Equation (5). The energy gain of each reflective-cover system (G_{cover}) relative to the gray gravel reference was calculated using the specific yield obtained under the same time window and filtering criteria (Y_{cover} and Y_{ref}), as per Equation (6).

$$Y = \frac{E}{P_{\text{STC}}} \quad (5)$$

$$G_{\text{cover}} = \left(\frac{Y_{\text{cover}}}{Y_{\text{ref}}} - 1 \right) \quad (6)$$

For the first cycle, the analysis included both monthly results and an annual synthesis. For the second cycle, monthly and daily results were evaluated to observe cleaning events and the stability of the gains. The analysis was restricted to the 9:00–15:00 time interval to reduce the influence of external and non-uniform shading on the comparison between

systems. As a result, the absolute specific-yield values reported in this work should not be interpreted as full-day yields for the site, but as consistent comparative indicators for the evaluated systems.

Measurement uncertainty was considered when interpreting the albedo, irradiance, and energy-yield indicators. According to the manufacturer specifications, the Kipp & Zonen SMP22 Class A pyranometers used for broadband irradiance measurements have an expected uncertainty below 1% for daily totals and approximately 2% for hourly totals under typical operating conditions. The IMT Si-mV-85-PT100 Class A reference cells have a calibration uncertainty of 1.2% and a measurement uncertainty of $\pm 0.3 \text{ W/m}^2 \pm 1.6\%$ of the measured value. Electrical monitoring data, obtained from the Huawei SUN2000 string inverter, have an uncertainty of 0.5%, according to the manufacturer. Because the main comparisons in this work are relative comparisons between systems operating under the same time window and filtering criteria, systematic effects common to the compared systems are expected to be partially reduced. The robustness of the measured gains was therefore assessed by comparing the magnitude and temporal consistency of the observed differences with the magnitude of the expected measurement uncertainty.

3.3. Soiling, Thermal and Installation Assessment

Soiling was evaluated through cleaning events and performance comparisons before and after cleaning. In the first 12-month cycle, construction activities adjacent to the pilot plant led to substantial deposition of particles on the reflective films, which provided a specific opportunity to quantify the loss associated with soiling under intense accumulation. In the second 12-month cycle, cleaning events were also documented, but the absence of nearby construction allowed a more representative assessment of normal exposure at the site.

The thermal behavior of the systems was assessed using irradiance-weighted module temperature. This metric gives greater weight to temperatures measured during high-irradiance periods, when energy production is more relevant. Estimated additional thermal losses were calculated from the measured temperature differences and the module temperature coefficient. Because the reported energy gains are based on measured energy generation, the thermal penalty is already embedded in the net energy results; the separate thermal analysis was used to interpret the physical mechanisms.

Practical installation aspects were documented during the campaign. Different fixation methods were tested for the reflective films, including metallic staples, raffia bags filled with sand, PVC tubes filled with sand, and trench anchoring. The assessment was qualitative but operationally important because anchoring, wind stability, durability, dirt accumulation, drainage, and maintainability can determine whether a high-albedo cover is feasible in a utility-scale plant.

4. Results and Discussions

4.1. Albedo and Spectral Characterization of the Materials

The measured albedo values confirmed that the artificial covers substantially increased the reflectivity of the ground surface relative to gray gravel. The gray gravel reference presented 24% reference-cell albedo and 25% broadband albedo. The white and pearlescent white films presented reference-cell albedo of 58% and broadband albedo of 53% and 54%, respectively. The black-and-pearl film reached 63% reference-cell albedo and 58% broadband albedo. The white geomembrane presented the highest reflectance, with 76% reference-cell albedo and 72% broadband albedo (Table 4).

The differences observed between the natural reference surface and the artificial high-reflectivity covers were substantially larger than the expected measurement uncertainty of

the instrumentation, making this distinction robust. Smaller differences among reflective films should nevertheless be interpreted with caution, considering the combined influence of measurement uncertainty, exposure period, and soiling conditions.

Because the materials were not characterized simultaneously, the absolute albedo values reported in Table 4 should be interpreted as representative of their respective exposure intervals. Nevertheless, the measured albedo levels were generally stable and showed well-defined differences among the evaluated surfaces. As discussed later in this section, the main sources of temporal variation were soiling accumulation on the artificial covers and surface moisture effects on the natural reference surface.

The difference between broadband and reference-cell albedo highlights the importance of sensor spectral response. Reference cells weigh the reflected irradiance in a way that is closer to the response of silicon PV modules, while broadband pyranometers integrate a wider spectral range. For bifacial performance modeling, these two measurements should not be mixed without care. A model may either use PV-weighted albedo directly or apply a spectral correction, but applying both approaches simultaneously could double-count the same effect.

The spectral measurements showed that the artificial covers had higher reflectance than the natural surfaces over a large portion of the crystalline-silicon response range (Figure 5). The geomembrane and the reflective films maintained elevated reflectance across the visible and near-infrared intervals, while the natural reference surfaces were considerably less reflective. The increased noise observed near the lower and upper wavelength limits is attributed to the reduced sensitivity of the measurement equipment close to the boundaries of its operating range. The shape of the curves is relevant because the contribution of rear-side irradiance to photocurrent generation depends on both the intensity of the reflected radiation and the PV device's quantum efficiency at each wavelength.

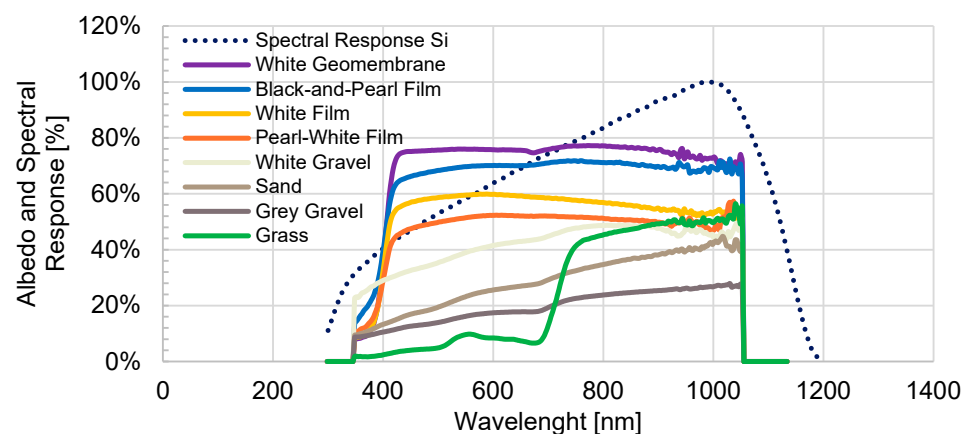


Figure 5. Measured spectral reflectance of the high-reflectivity ground covers and natural reference surfaces (solid lines) measured at the Solar Energy Research Laboratory Fotovoltaica/UFSC albedo station in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br). The spectral response of a silicon PV device is also presented as a reference (dotted line).

Measurements on representative clear and cloudy days indicated that the relative ranking of the materials' reflectance was preserved under different sky conditions, although the absolute reflectance level varied between measurements (Figure 6). These differences should be interpreted cautiously because spectral acquisitions are instantaneous and sensitive to short-term irradiance variability, especially under overcast conditions, whereas daily albedo measurements integrate the surface response over a full day and across different incidence angles.

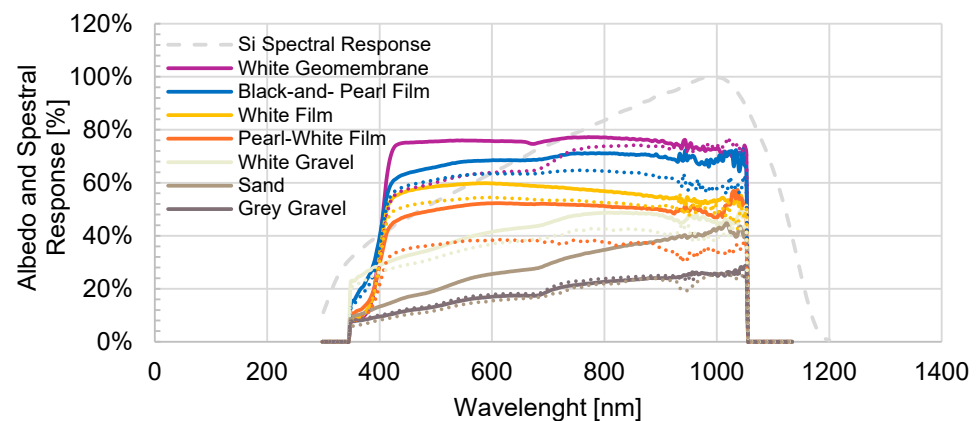


Figure 6. Spectral reflectance of the evaluated materials on representative clear-sky (solid lines) and cloudy days (dotted lines) measured at the Solar Energy Research Laboratory Fotovoltaica/UFSC albedo station in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br). The spectral response of a silicon PV device is also presented as a reference (dashed line).

The temporal analysis showed that gray gravel maintained a relatively stable albedo over a long monitoring period (Figure 7a), with variations mainly associated with sky conditions and possibly influenced by rainfall events and changes in surface moisture. In contrast, the white film exhibited a gradual reduction in albedo during outdoor exposure (Figure 7b), with partial recovery after cleaning events. These results indicate that the optical durability of reflective covers should be assessed through long-term outdoor monitoring or accelerated degradation tests. Lewis et al., for example, evaluated the reflective geomembrane used in their study after accelerated aging tests based on the IEC TS 62788-7-2 standard [40] procedures and reported no significant loss of reflectance, suggesting that some materials retain their optical performance during their service life [26]. Nevertheless, field- and material-specific factors such as soiling, abrasion, biological growth, maintenance activities, and drainage conditions must still be considered when extrapolating accelerated-test results to long-term utility-scale operation.

The relationship between albedo and clear-sky index (k_c) presented in Figure 8 reinforces this conclusion. The gray gravel reference showed a clearer reduction in measured albedo under cloudier conditions (low k_c), while the artificial covers were less sensitive to the sky index (Figure 8). This behavior suggests that reflective covers may not only increase average albedo but also reduce the variability of rear-side irradiance contributions under changing sky conditions.

4.2. System-Level Reflective Cover Performance and Electrical Limitations

The annual energy-yield analysis was carried out separately for the two experimental cycles and then consolidated. In both cycles, the systems installed over reflective covers were compared with the gray gravel reference operating under the same local meteorological conditions and data-filtering criteria. The main performance indicators were the rear-to-front irradiation ratio ($R_{\text{rear/front}}$, Equation (4)), and the annual energy gain relative to the reference system (Equation (6)).

The first annual cycle compared the white and pearl-white films with the gray gravel reference. As shown in Figure 9a, the module update described in Section 3.1, which was implemented to follow current industry trends, occurred during the first experimental cycle and was followed by a baseline period. This baseline period was used for system verification and was excluded from the annual energy-gain calculations. Both events are identified in Figure 9a because they affected system operation and comparability during the corresponding months. Despite these operational interruptions, the reflective films

consistently increased the rear-side irradiance contribution and produced positive energy gains relative to the reference surface. The cleaning event carried out in November 2024 was followed by an increase in measured gains, which may be associated with both the removal of accumulated soiling and seasonal variations in irradiance conditions. Soiling effects are further discussed in Section 4.3.

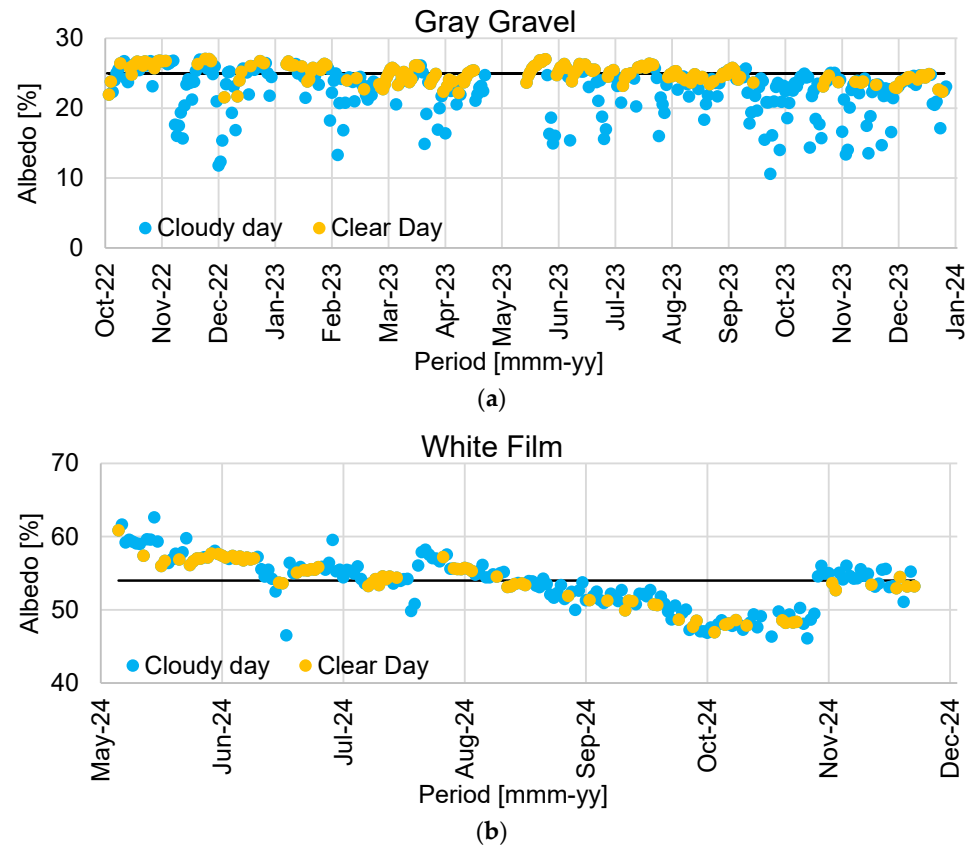


Figure 7. Temporal evolution of daily average broadband albedo for the longest monitoring periods, measured at the Solar Energy Research Laboratory Fotovoltaica/UFSC albedo station in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br): (a) gray gravel, used as the natural reference surface; and (b) white film, used as an artificial high-reflectivity cover. Clear-sky days ($k_c > 0.8$) are highlighted in yellow, and cloudy days ($k_c \leq 0.8$) in blue. The solid black lines indicate the overall albedo for the measurement period.

The second evaluation cycle assessed two improved ground covers with higher albedo, the black-and-pearl film and the white geomembrane, whose monthly energy gains are shown in Figure 9b. Cleaning events were carried out more frequently during this cycle than during the first. However, the results show limited correlation with these cleaning events, except for the October 2025 cleaning, after which a clearer increase was observed. To further investigate the short-term variability of the gains, daily energy gains are presented in Figure 10, with days classified according to sky condition: clear days in yellow, partially cloudy days in orange, and overcast days in red.

The results from Figure 10 show that energy gains tended to increase under cloudier conditions. This behavior indicates that, during sunnier days, especially in summer months (December to February) with higher solar resource, the performance of high-reflectivity covers was more frequently constrained by electrical limitations of the system, reducing the fraction of the additional rear-side irradiance converted into useful energy. In contrast, under cloudier conditions, the system operated farther from inverter limits, allowing a larger fraction of the optical gain to be converted into electrical output. This same effect is also evident in the monthly results of both evaluation cycles shown in Figure 9, where

lower energy gains are consistently observed during summer months despite the higher solar resource available. No systematic response to the cleaning events was observed in the daily energy-gain series, suggesting that soiling had a limited and context-dependent effect during the second cycle; this aspect is discussed in more detail in Section 4.3.

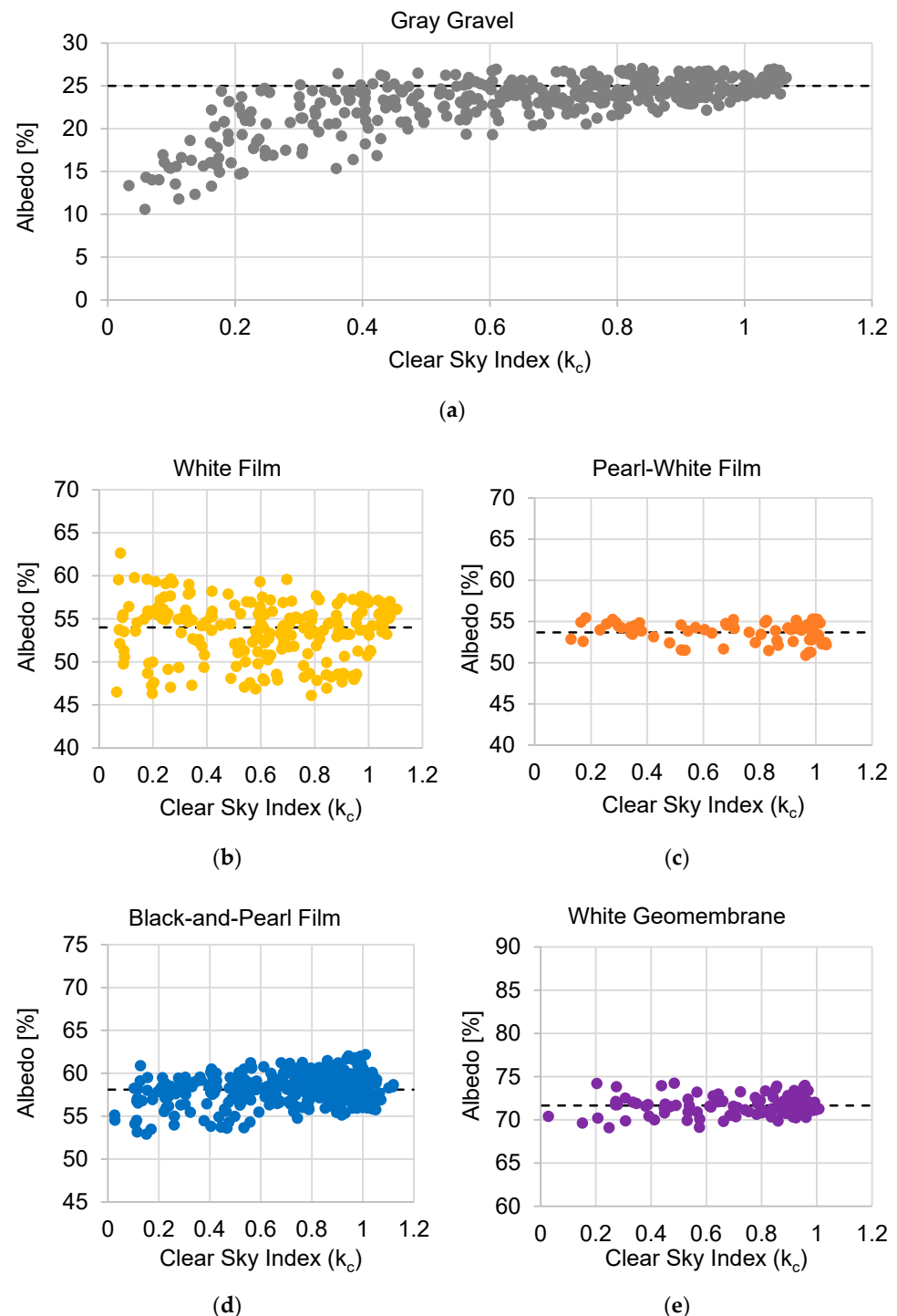


Figure 8. Daily average broadband albedo as a function of the clear-sky index (k_c), measured at the Solar Energy Research Laboratory Fotovoltaica/UFSC albedo station in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br): (a) gray gravel, (b) white film, (c) pearl-white film, (d) black-and-pearl film, and (e) white geomembrane. The dashed lines indicate the overall albedo for the evaluation period.

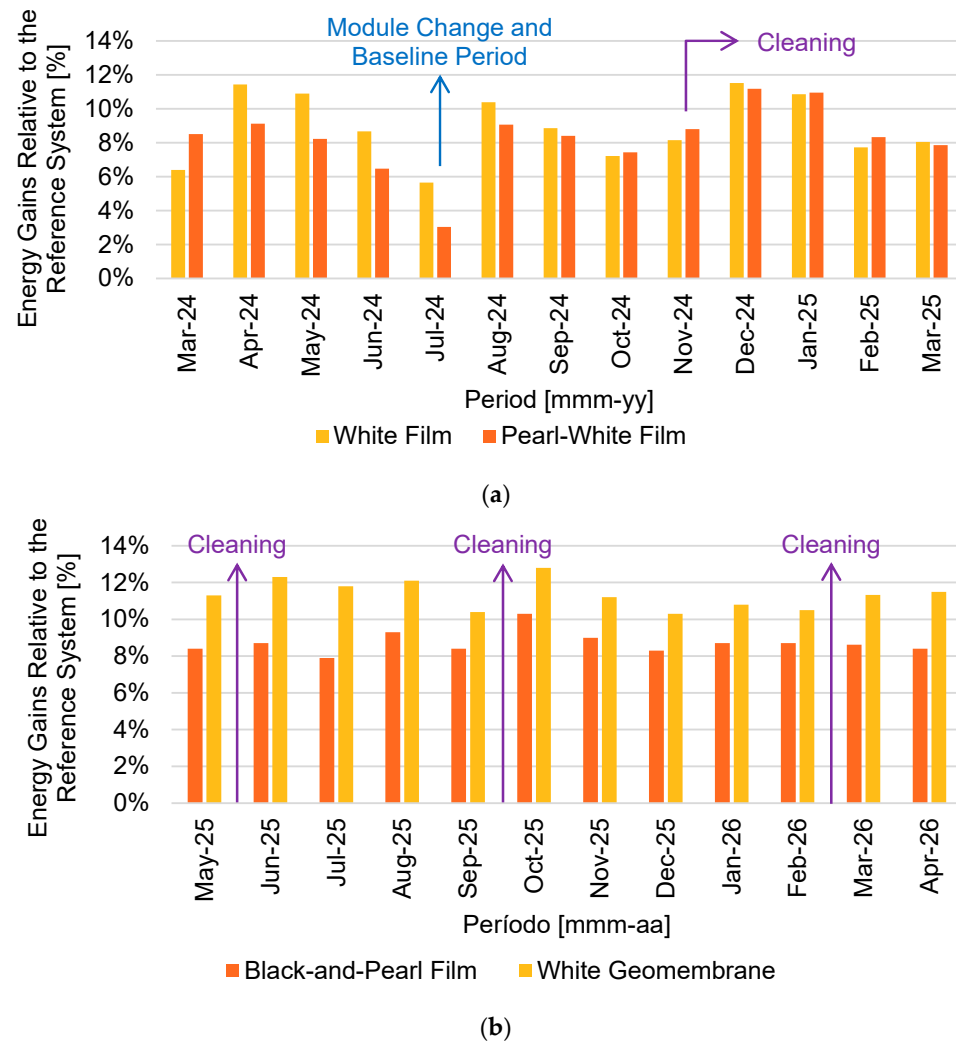


Figure 9. Monthly energy gains relative to the gray gravel reference during the experimental campaign, measured at the Solar Energy Research Laboratory Fotovoltaica/UFSC albedo station in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br): (a) pearl-white and white films in the first 12-month experimental cycle; and (b) black-and-pearl film and white geomembrane in the second 12-month experimental cycle.

The combined results from both evaluation cycles are summarized in Table 5. For the reflective films, increasing broadband albedo from 25% for gray gravel to 53–58% raised the rear-to-front irradiation ratio from 7.6% to approximately 20–21% and produced average annual energy gains of 8.8–9.5%. In the first cycle, the pearl-white and white films increased $R_{\text{rear/front}}$ to 20.4% and 21.1%, with corresponding energy gains of 8.9% and 9.5%, respectively. In the second cycle, the black-and-pearl film increased $R_{\text{rear/front}}$ to 19.8% and produced an energy gain of 8.8%, while the white geomembrane achieved the highest performance, with broadband albedo of 72%, $R_{\text{rear/front}}$ of 23.1%, and an average annual energy gain of 11.3%. These results confirm previous findings that artificial increases in ground albedo can substantially enhance bifacial PV performance [22,26,28–31], while providing additional field evidence for engineered ground covers under Brazilian operating conditions.

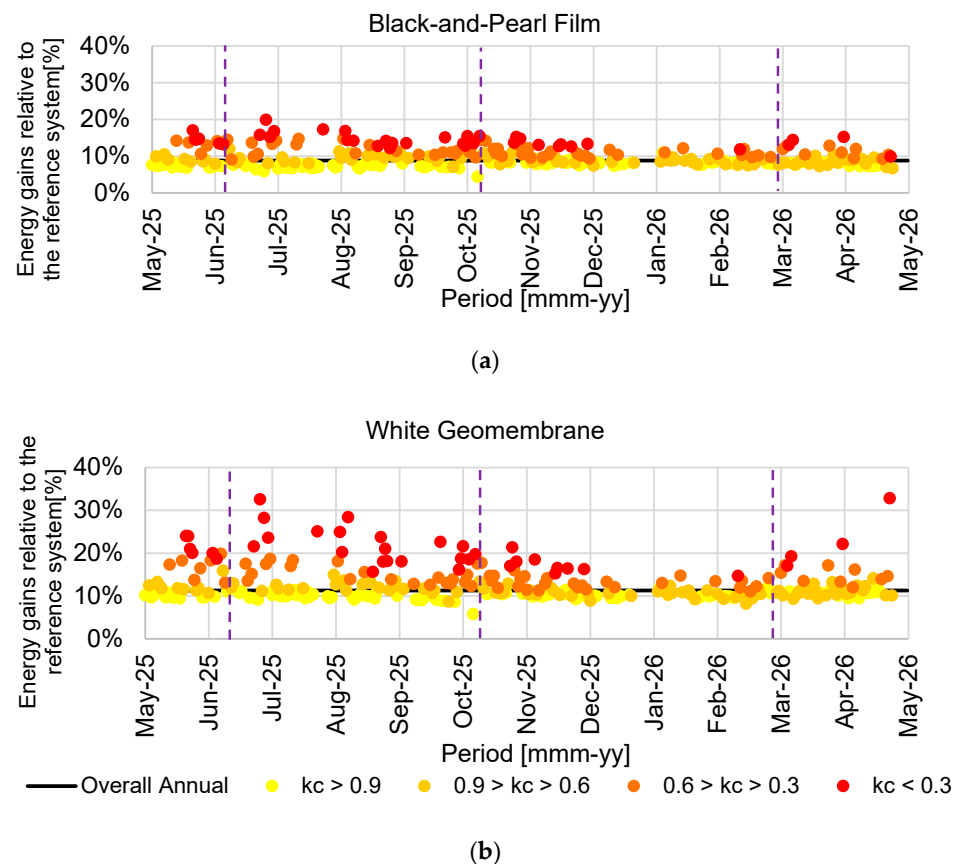


Figure 10. Daily energy gains relative to the gray gravel reference during the second 12-month experimental cycle, measured at the Solar Energy Research Laboratory Fotovoltaica/UFSC albedo station in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br): (a) black-and-pearl film; and (b) geomembrane. Purple vertical dashed lines indicate cleaning events; black horizontal solid lines indicate the mean gain over the analyzed period.

Table 5. Summary of results from the two experimental cycles.

Cycle	Surface/Ground Cover	Albedo	$R_{\text{rear/front}}$	Annual Energy Gain
1	Gray Gravel	25%	7.6%	-
1	White Film	53%	21.1%	9.5%
1	Pearl-White Film	54%	20.4%	8.9%
2	Gray Gravel	25%	7.6%	-
2	Black-and-Pearl Film	58%	19.8%	8.8%
2	White Geomembrane	72%	23.1%	11.3%

The annual energy gains measured for the reflective covers were substantially larger than the uncertainty associated with the inverter electrical measurements. The observed gains were more than one order of magnitude higher than the 0.5% uncertainty specified for the inverter measurements and were consistently observed over monthly and annual aggregation periods. Therefore, although their exact magnitude may be affected by measurement uncertainty and operational variability, the positive effect of the high-reflectivity covers is robust relative to the expected measurement uncertainty.

The relationship between albedo and energy gain was therefore not linear. Although the geomembrane had substantially higher albedo than the black-and-pearl film, the additional energy gain was more modest than the albedo difference alone would suggest. This indicates that the net energy benefit is also influenced by system geometry, rear-side irradiance distribution, thermal behavior, and electrical conversion limits. This effect

is also suggested by the results in Figures 9 and 10, where lower gains were observed during summer months and clear days, when the systems operated more frequently close to inverter limits and part of the additional rear-side contribution was likely affected by clipping. Similar system-level limitations associated with the conversion of additional irradiance from reflective covers were also reported by Lewis et al. [26].

The reduction in energy gains during periods with higher solar resource suggests that clipping and other inverter-related constraints affected the conversion of the additional rear-side irradiance. To quantify this effect, the occurrence of inverter power clipping and input-current clipping was evaluated during the second experimental cycle for the geomembrane, black-and-pearl film, and gray gravel reference systems. The annual results are summarized in Table 6.

Table 6. Annual occurrence of inverter power clipping and input-current clipping during the second experimental cycle for the geomembrane, black-and-pearl film, and gray gravel reference systems. Percentages are expressed relative to the total operating time considered in the analysis.

Description	Geomembrane	Black and Pearl Film	Gray Gravel
Total Operating Time	3962 h 11 h/day	3962 h 11 h/day	3962 h 11 h/day
Power Clipping	50 h 1.3%	39 h 1.0%	15 h 0.4%
Current Clipping	13 h 0.3%	10 h 0.3%	3 h 0.1%

As shown in Table 6, power clipping occurred more frequently in the systems installed over high-reflectivity covers than in the gray gravel reference system. Power clipping occurred for 1.3%, 1.0%, and 0.5% of the operating time in the geomembrane, black-and-pearl film, and gray gravel systems, respectively. Input-current clipping was less frequent, but followed the same trend, occurring for 0.3% of the operational time in the geomembrane and the black-and-pearl film systems, and 0.1% in the gray gravel reference system. Although these percentages are small when expressed relative to the annual operating time, clipping events occur during high-irradiance periods, when the systems would otherwise be expected to generate more energy and when the instantaneous contribution of the reflective covers could be highest. In the present dataset, most current-clipping events occurred during periods in which the inverter power limit was also reached; therefore, current clipping should be interpreted as a subset of the power-clipping periods rather than as an additional independent limitation time.

The monthly distribution of clipping events is presented in Table 7. The results show that inverter-related limitations were concentrated mainly between October and March, with the highest frequencies during the summer months. This seasonal behavior is consistent with the lower relative gains observed during high-resource periods in Figures 9 and 10. The geomembrane system showed the highest clipping frequency, followed by the black-and-pearl film and the gray gravel reference, indicating that the additional rear-side irradiance provided by the high-reflectivity covers increased the occurrence of inverter-related limitations. Although the annual duration of clipping was relatively small, these events occurred precisely during periods of high irradiance, when the instantaneous optical gain from the reflective covers could be highest.

Table 7. Monthly occurrence of inverter power clipping and input-current clipping during the second experimental cycle. Values are expressed as a percentage of operating time in each month. Clipping intensity is indicated by a red color gradient, ranging from white (no clipping) to red (highest clipping levels).

Period	Power Clipping			Current Clipping		
	Geo-Membrane	Black and Pearl Film	Gray Gravel	Geo-Membrane	Black and Pearl Film	Gray Gravel
May 2025	0%	0%	0%	0%	0%	0%
June 2025	0%	0%	0%	0%	0%	0%
July 2025	0%	0%	0%	0%	0%	0%
August 2025	1%	0%	0%	0%	0%	0%
September 2025	1%	1%	0%	0%	0%	0%
October 2025	3%	2%	1%	1%	0%	0%
November 2025	3%	3%	1%	1%	1%	0%
December 2025	4%	3%	1%	2%	2%	0%
January 2026	5%	4%	2%	2%	1%	1%
February 2026	3%	3%	1%	1%	1%	0%
March 2026	2%	1%	0%	1%	0%	0%
April 2026	0%	0%	0%	0%	0%	0%

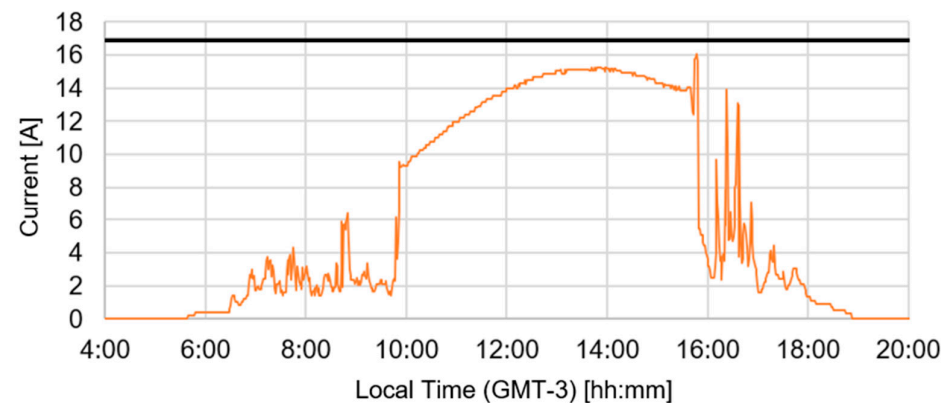
To further illustrate the input-current limitation mechanism, selected inverter input-current profiles during operation with the white geomembrane are shown in Figure 11. No current limitation is observed on a clear day, as shown in Figure 11a, when the additional rear-side irradiance could be converted into electrical energy without exceeding the inverter input-current limit. In contrast, during days with frequent cloud-edge effects, shown in Figure 11b, the measured current repeatedly reached the current limit. This behavior is related to short duration overirradiance events, which occur only under specific atmospheric conditions, particularly when cloud edges temporarily enhance the irradiance incident on the array. Such events have been reported in PV systems and can be especially relevant in high-irradiance climates and in the specific location of the study [41–44]. In the present case, the increased rear-side contribution from the high-reflectivity ground cover further amplified the current generated by the modules during these transient events.

Therefore, in addition to conventional inverter power clipping, reflective covers may introduce or intensify input-current limitation when the electrical design is not able to accommodate the increased rear-side current. This indicates that part of the optical gain may not be converted into useful energy under specific high-irradiance and cloud-edge conditions. The clipping frequencies presented in Tables 6 and 7 support the interpretation that the annual energy gains reported here were more limited during high-irradiance periods, when the instantaneous optical contribution of the reflective covers was expected to be highest.

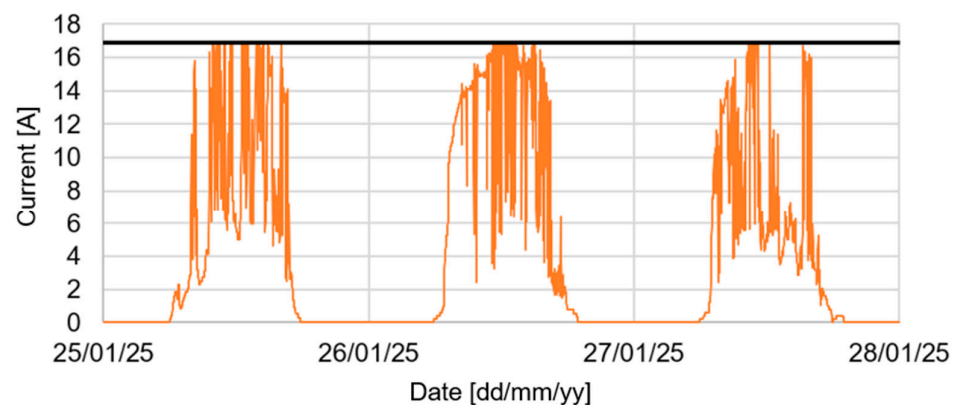
It is important to note that the pilot systems evaluated in this study have a low inverter loading ratio of approximately 0.86, calculated from the installed DC capacity of 17.25 kWp and the inverter nominal power of 20 kW. Therefore, the clipping frequencies observed here should be interpreted as a conservative indication of this limitation. In conventional utility-scale PV systems, which are often designed with higher inverter loading ratios, commonly around 1.2–1.3 in Brazil, the same increase in rear-side irradiance could lead to more frequent or more severe clipping if not considered during system design.

The input-current limit is also relevant. The inverter used in the pilot system is limited to 18 A, highlighting the importance of compatibility between inverters and newer high-

current PV modules. Even in a low-ILR system, high module current combined with enhanced rear-side irradiance can bring the string operating current close to the inverter input limit, particularly during cloud-edge events.



(a)



(b)

Figure 11. Examples of inverter input-current profiles (orange solid lines) during operation with high-reflectivity covers (geomembrane), measured at the Solar Energy Research Laboratory Foto-voltaica/UFSC albedo station in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltica.ufsc.br): (a) clear day without current-limit exceedance (20 December 2025); and (b) consecutive summer days with frequent cloud-edge effects and inverter input-current limitation. The solid black lines indicate the inverter current limit.

Overall, these results indicate that reflective-cover applications may require different electrical design choices from systems installed over natural or lower-albedo surfaces, including the optimization of inverter current limits and inverter loading ratio. These aspects are particularly important for retrofitting existing plants, where the original electrical design may not be able to fully convert the additional rear-side irradiance into useful energy.

4.3. Soiling Effects

Soiling was one of the main operational factors observed during the field campaign. During the first cycle, construction activities east of the trackers created a substantial source of particle deposition. The spatial pattern shown in Figure 12, with less intense accumulation farther from the construction area, supports the relationship between the nearby works and the soiling observed on the reflective covers. Before cleaning, both the white and pearl-white films exhibited visible particle accumulation. Energy measurements before and after a cleaning event showed that the resulting soiling losses were measurable

and depended on sky conditions. For the white film, the estimated loss was 2.1% on a sunny day and 3.4% on a cloudy day, while the corresponding values for the pearl-white film were 1.5% and 3.4%, respectively. Overall, the average soiling loss was estimated at 2.6%, corresponding to an average progression of approximately 0.65% per month during this construction-affected period (Table 8).



Figure 12. Pilot solar PV plant at the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltica.ufsc.br), and the albedo station, during the first experimental cycle before cleaning the covers, showing considerable soiling accumulation on the white and pearl-white reflective films due to adjacent construction activities, visible in the lower part of the image.

Table 8. Estimated soiling losses and average monthly progression for the white and pearl-white reflective covers during the first evaluation cycle, which was affected by construction activities adjacent to the pilot plant (Figure 12).

Indicator	White Film	Pearl-White Film	Average
Soiling loss on a sunny day	−2.1%	−1.5%	−1.8%
Soiling loss on a cloudy day	−3.4%	−3.4%	−3.4%
Average soiling loss	−2.7%	−2.5%	−2.6%
Average loss progression	−0.68%/month	−0.61%/month	−0.65%/month

The second 12-month cycle allowed a complementary assessment under less disturbed conditions because there were no adjacent construction activities. The cleaning events of 10 June 2025, 8 October 2025, and 26 February 2026 were documented with aerial images of the black-and-pearl film and geomembrane before and after cleaning (Figure 13). The visual inspection confirmed that soiling still occurred, but the accumulation was less severe than during the first cycle.

The energy-gain analyses previously presented in Figures 9 and 10 provide context for interpreting soiling effects during the second cycle. In particular, Figure 10 shows the daily energy gains, with cleaning events marked by vertical dashed lines. The gains fluctuated substantially from day to day, especially under cloudier conditions, partly because electrical

limitations affected the conversion of the additional rear-side irradiance. This variability makes it difficult to isolate cleaning effects from meteorological conditions using daily energy data alone.

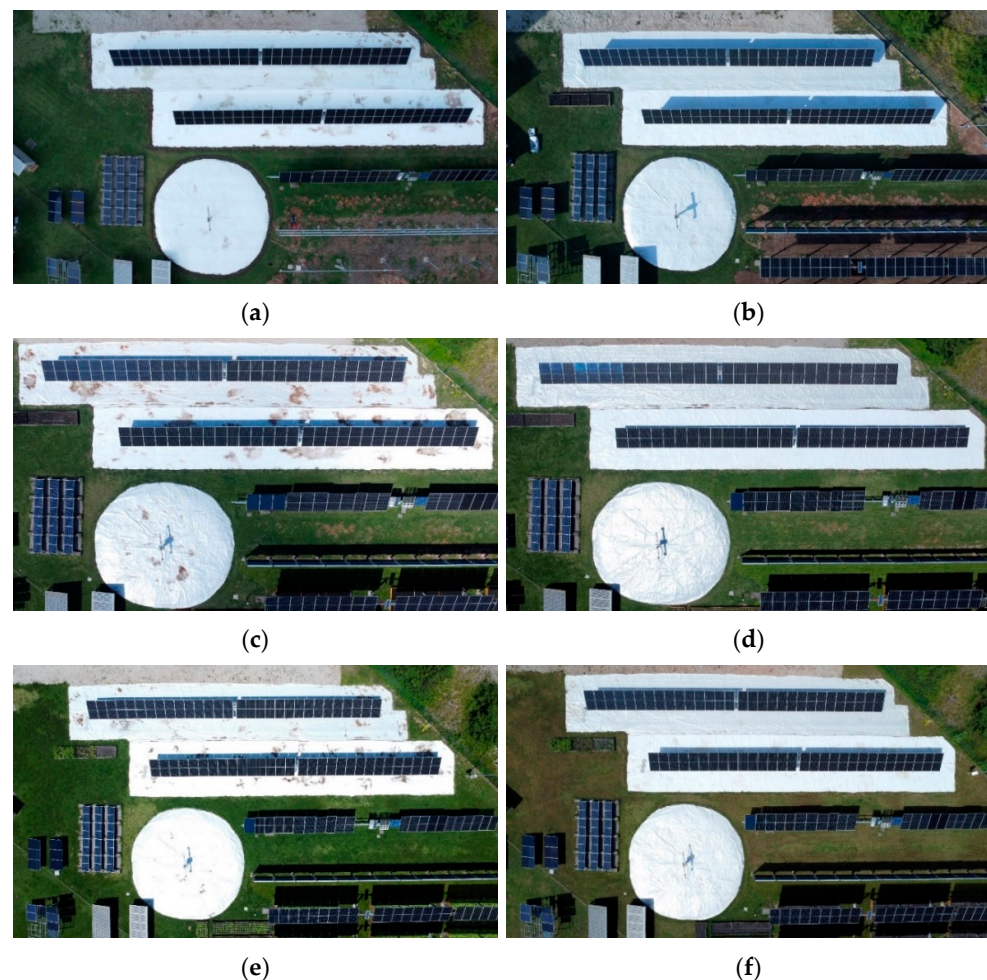


Figure 13. Aerial images of the PV systems at the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br) with high albedo ground covers before (left) and after (right) cleaning events during the second 12-month experimental cycle for the black-and-pearl film and white geomembrane: (a,b) cleaning of 10 Jun 2025; (c,d) cleaning of 8 Oct 2025; and (e,f) cleaning of 26 Feb 2026.

Therefore, a complementary analysis based on incident irradiation gain (Figure 14) was carried out to reduce the influence of system electrical limitations on the results. This analysis showed a weaker correlation with cloudiness and no systematic response to cleaning events, indicating that soiling had a limited impact on cover performance during the second experimental cycle. These findings suggest that the higher soiling losses observed in the first cycle were likely associated with specific exposure conditions, particularly construction activities near the pilot plant, while under more representative operating conditions the impact of dirt accumulation may be lower and more dependent on local environmental and maintenance factors.

Therefore, the results from the two cycles indicate that soiling should be treated as a relevant operational variable, but one that is strongly dependent on the deployment context. For utility-scale techno-economic analyses, it is important to consider sensitivity scenarios for different soiling-loss rates and cleaning frequencies, rather than directly extrapolating a single value obtained from the pilot plant. This approach makes it possible to represent both situations with higher particle deposition, such as construction periods, exposed soil,

or intense vehicle traffic around the plant, and more stable operating conditions, in which the impact of soiling on the covers may be reduced.

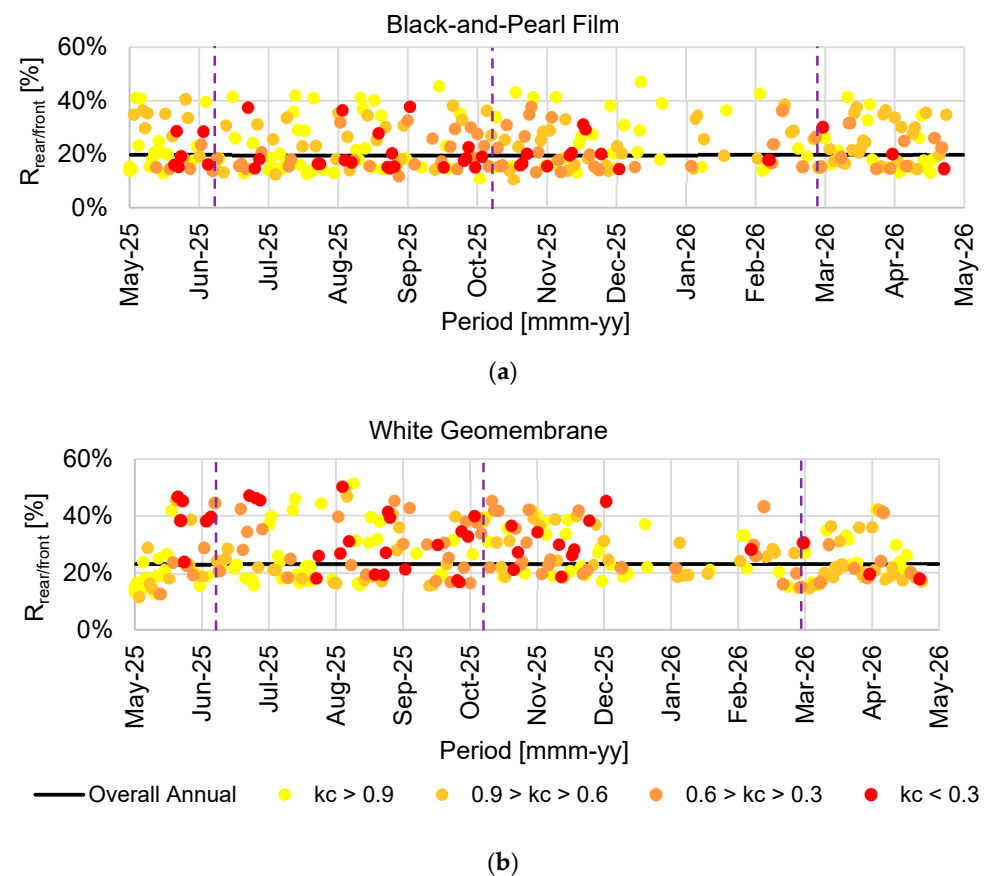


Figure 14. Daily rear-to-front irradiance ratio during the second 12-month experimental cycle, measured at the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil (27.4° S, 48.4° W, www.fotovoltaica.ufsc.br): (a) black-and-pearl film; and (b) geomembrane. Purple vertical dashed lines indicate cleaning events; black horizontal solid lines indicate the mean gain over the analyzed period.

4.4. Thermal Behavior

The thermal behavior of PV systems operating with reflective ground covers was evaluated separately because increasing the irradiance incident on bifacial modules can also increase operating temperature, which may partially offset the electrical benefit of the additional rear-side contribution.

In the first evaluation cycle, the irradiance-weighted average module temperature was 42.1 °C for the gray gravel reference and 44.7 °C for both the white film and pearl-white film systems. The average temperature increase was therefore approximately 2.6 °C, with monthly differences reaching up to 3.8 °C in summer. Using a module temperature coefficient of $-0.3\%/^{\circ}\text{C}$, the annual thermal loss was estimated at about 0.8%, and the maximum monthly effect was around 1.1%.

In the second cycle, which used optimized reflective covers based on the spectral response of silicon modules, the thermal penalty was smaller despite the higher rear-side contribution. The irradiance-weighted average temperature was 33.7 °C for the reference, 34.0 °C for the white geomembrane, and 34.9 °C for the black-and-pearl film. The corresponding temperature increases were 0.3 °C and 1.2 °C, leading to estimated additional thermal losses of approximately 0.1% and 0.4%, respectively.

The results from both experimental cycles indicate that the use of reflective covers produced only small increases in module operating temperature and even smaller temperature-related PV losses. These losses are much lower than the measured energy gains and therefore do not compromise the net benefit of the reflective covers in the evaluated configurations. Their relative importance may become even smaller in future applications, as modern PV cell and module technologies increasingly present lower temperature coefficients of power. It is important to highlight that, because the gains reported in the previous subsections are based on measured energy output, they already include the combined effects of rear-side irradiance, temperature, electrical losses, and real operating conditions. Therefore, the thermal analysis should be interpreted as a supporting diagnostic to quantify one of the mechanisms affecting net performance, rather than as an additional correction to the measured energy gains.

4.5. Practical Installation Aspects

The campaign also provided relevant information on installation and fixation methods. Four alternatives were tested for the reflective films: metallic staples, raffia bags filled with sand and PVC tubes filled with sand for anchoring, and trench anchoring (Figure 15). Each method had different implications for stability, soiling, maintenance, and ease of installation.



Figure 15. Fixation methods evaluated for the reflective films during the experimental campaign: (a) metallic staples; (b) raffia bags filled with sand; (c) PVC tubes filled with sand; and (d) trench anchoring.

The methods based on staples, bags, and tubes presented limitations during field exposure. Metallic staples corroded, sand containers contributed to dirt spreading on the films, PVC tubes also became sources of local soiling, and insufficient fixation allowed film displacement during windy conditions (Figure 16). The trench-anchoring method, in which film edges were buried in the soil, provided better practical stability among the evaluated options. This result shows that utility-scale application depends not only on optical performance but also on robust civil and operational design.



Figure 16. Problems identified in film fixation methods: (a) corrosion of metallic staples; (b) sand spreading from anchoring bags; (c) sand spreading from anchoring tubes; and (d) film detachment during a windy day due to insufficient fixation.

5. Conclusions

This paper presented field results from a Brazilian pilot plant evaluating high-reflectivity ground covers in bifacial PV systems with single-axis tracking. The experimental evidence confirms that reflective covers can substantially increase broadband albedo, rear-to-front irradiation ratio, and measured energy yield relative to a natural reference surface with albedo representative of common ground conditions in Brazilian utility-scale PV plants.

The white and pearl-white films increased broadband albedo to 53–54%, raised the rear-to-front irradiation ratio from 7.6% to approximately 20–21%, and produced annual energy gains of 9.5% and 8.9%, respectively, compared with the gray gravel reference. The further optimized black-and-pearl film increased broadband albedo to 58%, the rear-to-

front irradiation ratio to 19.8%, and the energy yield by 8.8%. The white geomembrane achieved the highest values, with 72% broadband albedo, a rear-to-front irradiation ratio of 23.1%, and an annual energy gain of 11.3%. These results confirm previous findings that artificial increases in ground albedo can enhance bifacial PV performance, while providing field evidence for engineered reflective covers under Brazilian operating conditions.

The results also show that the implementation potential of reflective covers cannot be assessed from albedo alone. The relationship between albedo and energy gain was not linear, indicating the influence of system geometry, rear-side irradiance distribution, thermal behavior, and electrical conversion limits. Inverter-related constraints were particularly relevant during high-irradiance periods, when part of the additional rear-side contribution was affected by clipping. In addition to conventional power clipping, current limitations were observed under specific cloud-edge overirradiance conditions, showing that reflective covers may amplify transient current peaks when the electrical design cannot accommodate the additional rear-side irradiance. Therefore, systems designed to operate with high-reflectivity ground covers may require different electrical design criteria and an optimized inverter loading ratio compared with systems installed over natural or lower-albedo surfaces. This aspect is especially important when retrofitting existing PV plants, where the original DC/AC ratio, string configuration, and inverter current limits were not necessarily selected to accommodate the additional rear-side current produced by reflective covers.

Operational aspects also affected the interpretation and long-term feasibility of the solution. Soiling losses were measurable during the first cycle, which was strongly influenced by construction activities near the pilot plant, but no systematic cleaning response was observed during the second cycle under more representative exposure conditions. This indicates that soiling should be treated as a context-dependent operational variable rather than extrapolated from a single value. Thermal losses were small compared with the measured gains and were already embedded in the net energy results. The optical stability of the covers, especially under long-term outdoor exposure, remains an important factor to be assessed through extended field monitoring or accelerated degradation testing. Practical aspects such as anchoring, wind stability, durability, drainage, maintainability, and compatibility with operation and maintenance routines are also decisive for utility-scale deployment.

Overall, high-reflectivity ground covers represent a promising strategy for enhancing the productivity of bifacial single-axis tracking systems. However, the results reported here are specific to the evaluated site, materials, tracker geometry, module technology, electrical configuration, and local operating conditions. The magnitude of the energy gain and the economic attractiveness of the solution are expected to vary with climate, solar resource, latitude, natural ground albedo, system geometry, electrical limits, soiling conditions, and maintenance practices. Therefore, application in utility-scale PV plants should be supported by integrated techno-economic analysis combining energy gains, cleaning and maintenance needs, anchoring, drainage, environmental compatibility, durability, and cost. The field results reported here provide an experimental basis for validating simulation models for bifacial PV systems operating under high rear-side irradiance conditions and for future techno-economic studies of reflective ground covers in Brazilian PV plants.

The main limitations of the study are the single-site nature and the pilot-plant scale of the experiment, as well as the sequential rather than fully simultaneous evaluation of some materials. Therefore, the results should be interpreted as field evidence from a small-scale pilot installation, rather than as a complete representation of all climatic regions, plant layouts, and utility-scale implementation conditions. Future research should include simultaneous multi-material testing over longer periods and validation in additional climatic

regions, latitudes, and plant layouts. Further work should also use multi-climate field data to validate simulations and develop techno-economic analyses that account for material cost, installation, anchoring, drainage, cleaning, maintenance, and reflectance degradation, as well as inverter loading ratio, and current-limit constraints. Further investigation is also needed to determine whether PV plants designed from the outset for high-reflectivity ground covers require different tracker, electrical, and operation-and-maintenance design criteria than conventional bifacial PV plants.

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