THE ROLE OF HIGH-ALBEDO GROUND COVER MATERIALS IN IMPROVING BIFACIAL PV PERFORMANCE: A CASE STUDY IN BRAZIL

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Abstract

This study evaluates the energy gains associated with the use of high-albedo artificial ground covers in bifacial PV plants with single-axis trackers. The application of such films in PV plants offers several benefits, including soiling mitigation and vegetation control. However, they also increase surface impermeabilization, which may have drainage and environmental consequences. This study focuses specifically on evaluating the associated energy benefits. Two white film materials were characterized at an albedo station, then tested at a pilot plant in Florianópolis, Brazil (27°S, 48°W). Both solutions showed a spectrally sensitive albedo measured with reference cells of 58%. Energy gains of 9.5% and 8.9% were observed compared to a reference system (26% albedo), despite a 2.6°C rise in module temperature, causing an estimated additional thermal loss of 0.8%. Energy losses due to albedo reduction from soiling ranged from 1.5–2.1% on clear days, reaching 3.4% on cloudy days. Among installation methods, trench anchoring proved most durable, while alternatives using sand weights showed reduced durability and caused sand spillage, leading to soiling on the reflective films. The findings support the viability of high albedo covers as a strategy for enhancing bifacial PV performance. Future studies shall focus on durability and techno-economic viability of these films.

Keywords: Bifacial PV, Ground Cover, White Film, Albedo Enhancement, PV Performance Optimization.

1. Introduction

Bifacial photovoltaic (PV) modules, particularly when paired with single-axis trackers, have shown substantial energy yield improvements and reductions in the levelized cost of electricity (Rodríguez-Gallegos et al., 2020). These gains depend heavily on site-specific variables such as ground albedo, installation height, row spacing, and local climate (IEA PVPS, 2021). Bifacial PV modules accounted for 60% of global PV module production in 2024 (VDMA, 2025), driven largely by their increasing use in large-scale power plants with tracking systems.

In this context, high-albedo artificial ground covers have emerged as a promising strategy to enhance rear-side irradiance and improve bifacial system performance (pv magazine, 2023a, 2023b). Beyond performance enhancement, they help suppress vegetation and mitigate soiling. Accurately modeling rear irradiance for such surfaces remains a challenge, as it depends on both the spectral and angular characteristics of reflected light as well as changing environmental conditions (Campos et al., 2025). Although increased rear irradiance can raise module temperatures — particularly in hot climates (Oliveira et al., 2025, 2024) — the resulting temperature losses are largely offset by the substantial energy gains from the additional irradiation. It is important to note that their presence can alter soil permeability, creating engineering, environmental, and regulatory challenges that have not yet been fully addressed.

Furthermore, as the industry transitions to n-type bifacial cells (VDMA, 2025) — which feature higher bifaciality and reduced thermal losses — the benefits of optimizing rear-side irradiation become more relevant. Reflective ground covers materials may play a key role in maximizing the potential of this next-generation technology.

This paper presents the results of a study conducted in Florianópolis, Brazil, to evaluate the real-world

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performance of different artificial high-albedo ground covers. The study aims to quantify the associated energy gains, analyze the impact on module operating temperature, and assess the maintenance requirements of such materials. The findings offer insights into the practical viability of these solutions for enhancing performance in large-scale bifacial PV systems.

2. Experimental Setup

The study was carried out at a bifacial single-axis tracker pilot plant in Florianópolis, Brazil (27°S, 48°W), equipped with state-of-the-art bifacial PV modules and monitoring systems to assess the impact of varying ground albedo conditions on bifacial photovoltaic performance (Formagini et al., 2024; Silva et al., 2024). The experimental plant consists of five identical tracked systems, three of which are evaluated here: two covered with reflective films (white and pearl-white) and a reference system installed on gray gravel.

Initially, the pilot PV plant employed bifacial modules with p-type monocrystalline silicon PERC cells, featuring an individual nominal power of 645Wp. Four months into the analysis period, the project transitioned to n-type modules, following the prevailing industry trend. The current modules have an individual capacity of 575 Wp, reflecting their smaller format—a decision primarily motivated by glass breakage issues encountered with the previous modules (Azevedo et al., 2024; Braga et al., 2023). These new modules feature M10 cells, a smaller form factor compared to the G12 cells used in the first phase. The new n-type wafer-based cells offer several advantages over the previous p-type PERC technology, including higher efficiency, lower degradation rates, reduced temperature-related losses, and superior bifaciality of approximately 80%, compared to 70% for the p-type modules.

To calibrate the experimental setup, a low-reflectivity black tarp was used to cover all ground types for 14 days encompassing various sky conditions. The results for this period were used to establish a baseline for understanding intrinsic differences between the PV systems, independent of albedo variations. The images shown on Fig 1 and Fig 2 provide visual references of the pilot plant and its configuration during the baseline and normal operation period, respectively.

Fig 1: Image of the pilot plant used for the energy evaluation of the reflective ground covers during the baseline period.

Fig 2: Image of the pilot plant used for the energy evaluation of the reflective ground covers during the normal operation period.

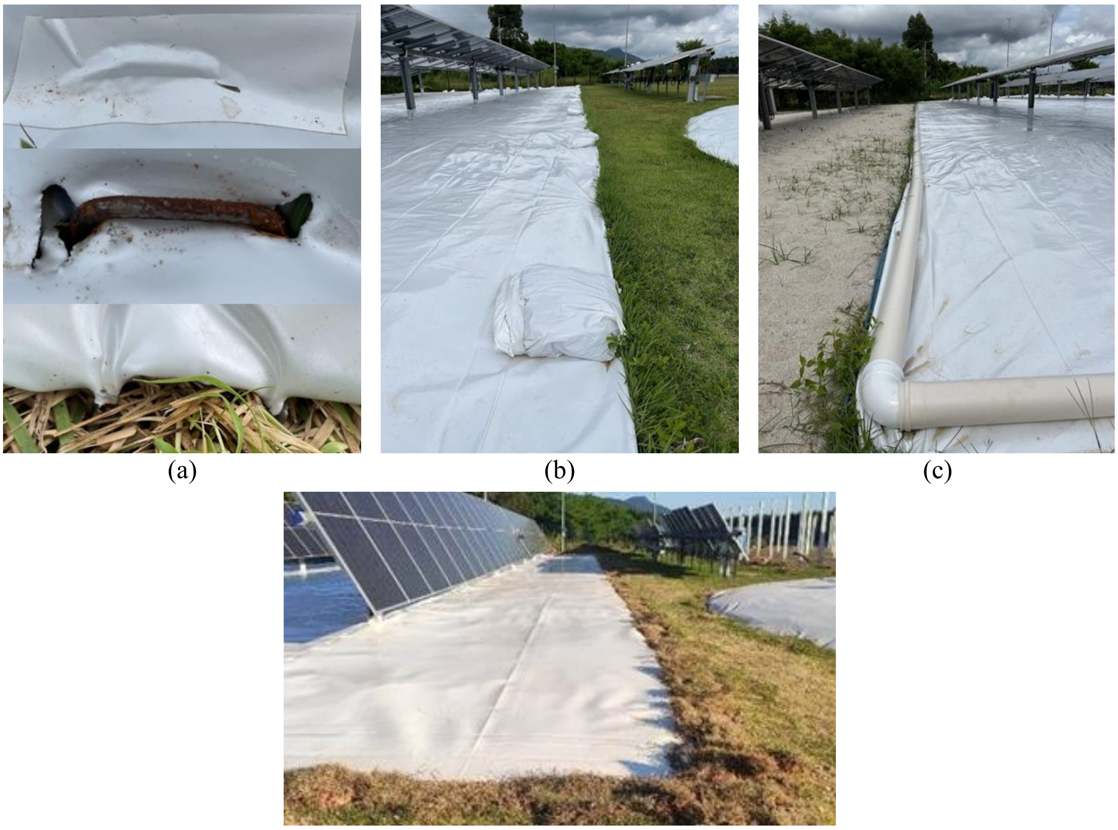
The PV systems were continuously monitored for a full year using high-precision sensors. Front and rear plane-of-array irradiance were measured for each individual system with spectrally-flat pyranometers (Class A EKO MS-80S) and reference cells (Class A IMT Si-mV-85-PT100), selected for their spectral and optical sensitivity, as their response closely resembles that of bifacial PV modules (Fig 3). Module temperature for each system was recorded with Class A PT1000 thermistors, and electrical data were acquired at 1-minute intervals from Huawei SUN2000 string inverters. Environmental variables were also monitored using the extensive instrumentation available at the Fotovoltaica/UFSC weather station (Mantelli Neto et al., 2019).

Fig 3: Sensors used for measuring plane-of-array rear irradiance: Class A EKO MS-80S pyranometer (left) and Class A IMT Si-mV-85-PT100 reference cell (right).

Albedo characterization of the three materials was carried out using a dedicated monitoring station at the Fotovoltaica/UFSC solar research laboratory, specifically designed to provide continuous, high-resolution measurements of ground reflectivity. Details of the station and the albedo measurements are presented in a separate study at this same conference. The measured albedo values were 25% for gray gravel, 54% for the white film, and 55% for the pearl-white film.

Concurrently with the white films' energy performance analysis, a white geomembrane was characterized at the albedo station. This material exhibited a better performance, showcasing superior gains in reflectivity compared to the films, with 74% albedo. Although further studies on the energy gains of this material installed on the trackers are necessary, it appears to be a superior alternative for PV applications due to its high albedo, greater robustness, and longer warranty period. Given that photovoltaic modules typically carry a 30-year warranty, materials offering greater durability are highly preferable to such projects.

For the installation of the films, initially three methods were tested for the reflective materials: metal clamps, raffia bags filled with sand, and PVC pipes filled with sand, as seen in Fig 4. The films were later secured using trench anchoring, with its edges buried in the soil — a technique that proved more stable and durable under environmental stress (Fig 4d). The robustness of each installation method was assessed through periodic inspections and documentation of failures such as corrosion, physical wear, and displacement due to strong winds.



(a) (b) (c)

(d)

Fig 4: Installation methods tested for the high-reflective films: (a) metal clamps, (b) raffia bags filled with sand, (c) PVC pipes filled with sand, and (d) trench anchoring.

Given that periodic cleaning of the films proved unrepresentative of real-world operation and maintenance conditions in utility-scale PV plants, the study adopted a monitoring strategy to track the evolution of soiling. Regular aerial drone imaging was employed to visually document the accumulation of soiling on the reflective films, with images consistently captured around the same time of day to facilitate correlation with PV system performance. *Ad hoc* cleanings were carried out to quantify reflectivity losses from soiling by comparing daily energy gains—referenced to the gray gravel system—immediately before and after cleaning, under both cloudy and clear conditions. To minimize uncertainties, only days with similar irradiance levels and close proximity to the cleaning event were considered.

3. Results and Discussion

1.1. Installation Method

During the evaluation period, the raffia bags and PVC pipes used for anchoring experienced physical degradation, with cracks developing in the tubes and wear on the bags. Nevertheless, this damage did not compromise the films' attachment to the trackers, meaning their primary function was maintained. However, this degradation contributed to the accumulation of soiling on the films, thereby impacting their performance. Further details can be seen in Fig 5.

(a) (b)

Fig 5: Issues found with the installation methods used for the reflective films: (a) wear and tear of raffia bags and (b) cracks on the PVC pipes. These issues resulted in sand spillage and losses on the films' reflectivity.

The U-clamp fixation method demonstrated low reliability in the medium to long term. After only a few months of environmental exposure, the clamps exhibited significant corrosion and deformation. The tape used to increase fixation robustness proved incompatible with outdoor use, degrading rapidly after UV exposure. Furthermore, a high-wind event resulted in the partial displacement of the film at the albedo station, underscoring the insufficiency of this fixation method under adverse weather conditions. These observed issues are presented in Fig 6.

The final configuration, which employed trench anchoring (Fig 4d), proved to be the most effective, with no issues reported to date.

(a) (b) (c)

Fig 6: Issues found with the installation methods used for the reflective films: (a) degradation of adhesive tape and tear of film at the point of fastening (b) corrosion of clamps used for fastening the films to the ground, and (c) film that came detached due to strong winds.

1.2. Soiling Losses

The analysis of performance losses due to soiling accumulation on the reflective films yielded quantifiable losses, as summarized in Tab 1. Fig. 7 shows the status of soiling accumulation on the films right before the cleaning event. The results indicated losses ranging from 1.5% to 2.1% on clear-sky days and reaching 3.4% during periods of higher cloud cover, with an average loss of 2.6% between the two systems and conditions analyzed. Based on the interval between cleaning events, the average monthly progression of soiling losses can be estimated at -0.65% month. It is important to emphasize that these results are directly related to the specific climatic and environmental conditions of the evaluated photovoltaic system, as well as the season and site characteristics. Therefore, their extrapolation to other locations is limited.

Although quantifiable, the soiling losses found in this study are not representative of large-scale application of these films in PV power plants. Soiling losses are expected to be inversely proportional to the ground coverage ratio of high-reflectivity films, since these films help reduce dust generation and accumulation. In other words, in sites where a large portion of the ground is covered by reflective films, soil exposure is minimized, which limits both the production and transport of dust onto the films themselves.

Fig 7: Accumulation of soiling on the reflective films right before the *ad hoc* cleaning event, used to quantify the associated energy losses presented in Tab. 1.

Tab 1: Summary of albedo soiling loss and degradation rate for the evaluated reflected films, based on the soiling accumulation presented in Fig. 7.

Parameter	White Film	Pearl-White Film	Average
Soiling Loss on Clear Day	-2.07%	-1.51%	-1.79%
Soiling Loss on Cloudy Day	-3.40%	-3.40%	-3.40%
Average Soiling Loss	-2.74%	-2.45%	-2.60%
Time Between Cleanings	4 months	4 months	4 months
Average Progression	-0.68%/month	-0.61%/month	-0.65%/month

1.3. Temperature Effects

An anticipated operation temperature rise was confirmed and is directly attributable to the enhanced ground reflectivity provided by the films, which intensifies the total solar irradiance capture by the bifacial modules. Fig 8 and Fig 9 illustrates the operating temperature profiles of the three analyzed systems during a cloudy day and a clear day. Notably, the thermal response profile across all systems remains consistent in both scenarios, although the absolute temperatures naturally fluctuate with the intensity of the incident radiation. On sunny days, the difference between systems becomes more pronounced, with a greater increase in temperature observed for those installed over the high-reflectivity films.

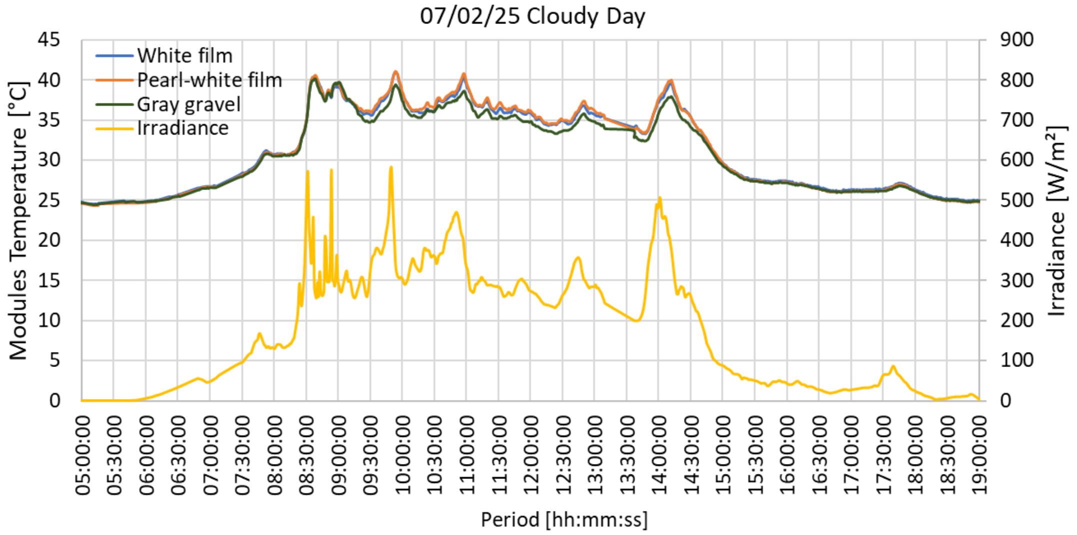


Fig 8: Operating temperature of the three systems under analysis for a cloudy day. Global horizontal irradiance is also shown as a reference.

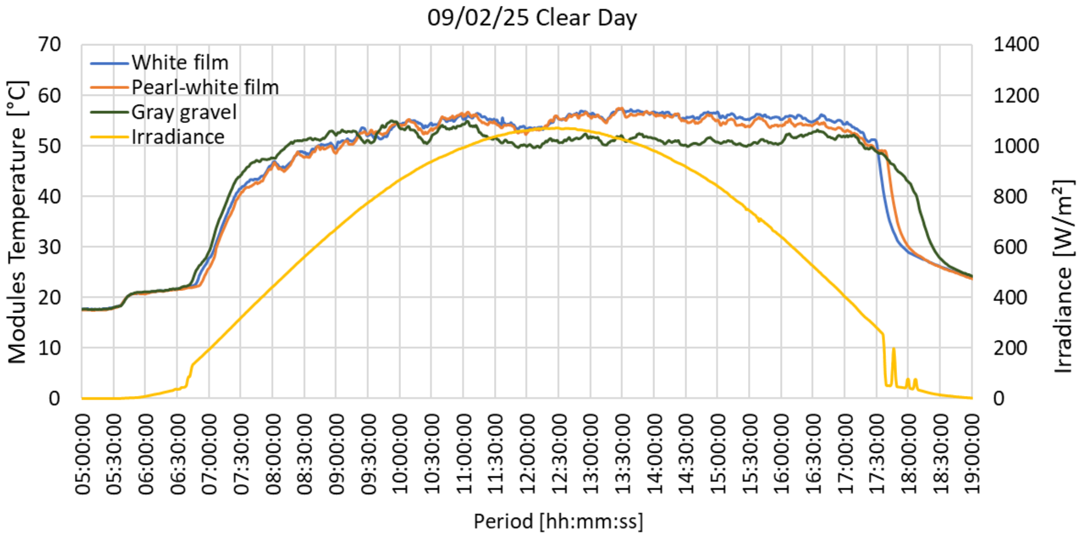


Fig 9: Operating temperature of the three systems under analysis for a clear day. Global horizontal irradiance is also shown as a reference.

This consistent thermal behavior suggests and confirms the core hypothesis that the increased ground reflectivity fundamentally influences the systems' thermal dynamics, leading to a generalized temperature elevation. It is important to highlight, however, that the thermal losses associated with this higher operating temperature are already accounted for in the energy gain analysis. Again, the results demonstrate that the energy gains realized through enhanced reflectivity substantially outweigh the efficiency losses linked to the corresponding rise in module operating temperature.

In addition to the analysis on specific days, a more comprehensive assessment was carried out using data from the entire monitoring period. In this analysis, the average temperature weighted by irradiance was adopted as a metric for comparison between the systems, shown in Fig 10. The application of irradiance weighting is essential for this analysis, as it gives greater importance to temperature data recorded during periods of peak solar irradiance and, consequently, higher energy generation. This methodological approach provides a more representative estimate of the thermal efficiency losses directly attributable to the module temperature increase.

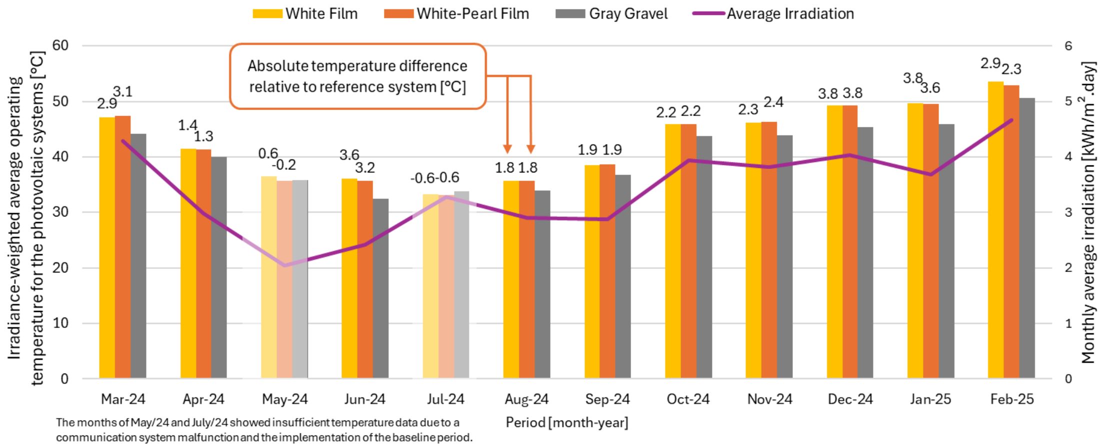


Fig 10: Monthly irradiance-weighted operating temperature for the reference (gray bars), white film (yellow bars) and pearl-white film (orange bars) systems. Data labels on top of the bars represent the absolute temperature difference between the respective system and the reference for a given month. Average daily irradiation is also shown as a reference (purple line).

The installation of the white and pearl-white films induced a consistent elevation in the operating temperature of the photovoltaic modules. During the summer months, when solar radiation levels and ambient temperatures were the highest, the films resulted in peak monthly temperature differences of up to 3.8°C compared to the reference system with gray gravel. As previously established, this thermal effect is directly associated with the increased ground reflectivity provided by the films.

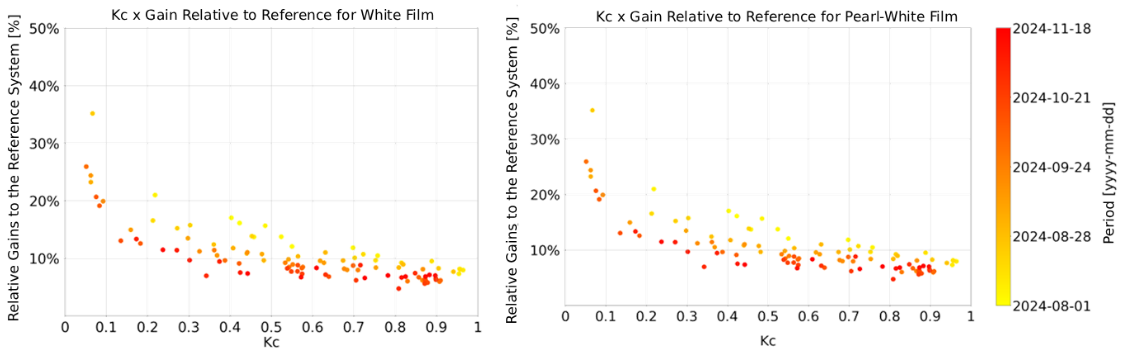
Additionally, the results show that the reference system recorded 42.1°C annual irradiance-weighted operating temperature, whereas both film systems registered an average of 44.7°C, reflecting an overall temperature increase of 2.6°C. Considering the modules' temperature loss coefficient of −0.3%/°C (a value tending to decrease with technological evolution), this 2.6°C increase represents an estimated additional thermal efficiency loss of only 0.8%.

1.4. Clearness Conditions

The clear sky index (k_c) was employed as an indicator of cloud cover, where higher values correspond to sunny days and lower values indicate overcast conditions. As showed in Fig 11, the correlation analysis between this index and the energy gain of the systems over the reflective films, relative to the reference system, demonstrates that for lower k_c values (more clouds), the energy gain is more pronounced.

This behavior can be attributed to the increased contribution of diffuse irradiance under overcast sky conditions, which enhances light reflection from the white film surface, thus favoring energy capture on the posterior face of the bifacial modules mounted on the single-axis trackers.

In addition to the cloud cover effect, the temporal analysis of this correlation reveals a gradual reduction in energy gain over the monitored period (evident by a curve of lower gains corresponding to more recent data points). This trend directly reflects the impact that the accumulation of soiling on the film surfaces had on their reflectivity and energy gains, progressively reducing the efficacy of both films. This analysis is crucial as it allows us to visually distinguish the separate impacts of cloudiness and soiling on film performance. As previously observed, film performance is favored on days with higher cloudiness (low k_c), but it is also compromised by accumulated soiling. Thus, in purely monthly analyses, it becomes difficult to discern variations in gains due to soiling or to cloud cover levels. These correlation graphs allow us to visually distinguish these two distinct effects.



(a) (b)

Fig 11: Correlation between daily clear-sky index (k_c) and relative energy gain, compared to the reference system, for the system installed over the reflective white film (a) and the pearl-whithe reflective film (b). Points are colored according to measurements date.

1.5. Energy Gains

Tab 2 summarizes the global energy results obtained during the evaluation period. During the baseline period — when all systems were installed over uniform ground cover — the white and pearl-white systems showed relative energy gains of 2.6% and 0.2%, respectively, compared to the reference system over gray gravel. These results emphasize the importance of the calibration step, which allowed for the identification of intrinsic performance differences, such as edge effects or minor electrical mismatches, that are independent of ground albedo.

As demonstrated in Tab 2, the systems with white and pearl-white films received between 20.4% and 21.1% additional rear-side irradiation (H_{rear}/H_{front}), compared to just 7.6% for the reference system, highlighting the impact of enhanced albedo in boosting rear-side irradiation. This increased rear-irradiance contributed to relative energy gains of 9.5% and 8.9%, respectively, for the white and pearl-white systems, when compared to the reference system installed over gray gravel. These values were calculated by excluding the baseline period, isolating the effect of the reflective materials. Based on both the baseline and these results, it can be concluded that there are no significant differences between the two films, as confirmed by the albedo station data, which resulted in very similar albedo results for both films. Therefore, the observed differences in energy gains are likely experimental artifacts.

Tab 2: Evaluation results for the white films and reference system: albedo characterization, rear-to-front irradiation ratio, energy yield, and energy gains compared to the reference system for the monitoring

Parameters	Reference Gray Gravel	Pearl-White Film	White Film
Measured Albedo	25%	54%	55%
H_{rear}/H_{front}	7.6%	20.4%	21.1%
Energy Yield	3.17 kWh/kWp.day	3.44 kWh/kWp.day	3.46 kWh/kWp.day
Energy Gain	-	8.9%	9.5%
Baseline Energy Gain	-	0.2%	2.6%

For the productivity, the overall performance monitoring over the 12-month period, as presented in Fig 12, showed that the monthly yield for the systems fluctuated between 2 kWh/kWp.day and 5 kWh/kWp.day over the project analysis period, caused by seasonal variations of solar resource availability and system performance. The systems installed with the reflective films consistently demonstrated superior productivity compared to the gray gravel reference system, a performance attributed directly to the sustained higher albedo values exhibited by the films throughout the evaluation. Furthermore, the rear-to-front irradiation ratio (H_{rear}/H_{front}) serves as a key indicator of the magnitude of solar resource capture by the module's posterior surface relative to the frontal irradiance. During normal operating periods, this critical ratio exhibited a typical fluctuation between 15% to 25%. This foundational data confirms that the films successfully enhanced solar resource capture, leading to tangible increases in energy yield. Higher rear-irradiation ratios were observed during December 2024 and January 2025, exceeding 30%. However, these values resulted from failures in the tracking systems, which caused the modules to face the wrong direction during certain periods of the day, leading to increased rear-side irradiance capture. Although this might initially appear beneficial, the overall system efficiency was compromised, since the front side of the modules is more efficient and should receive the highest possible irradiance.

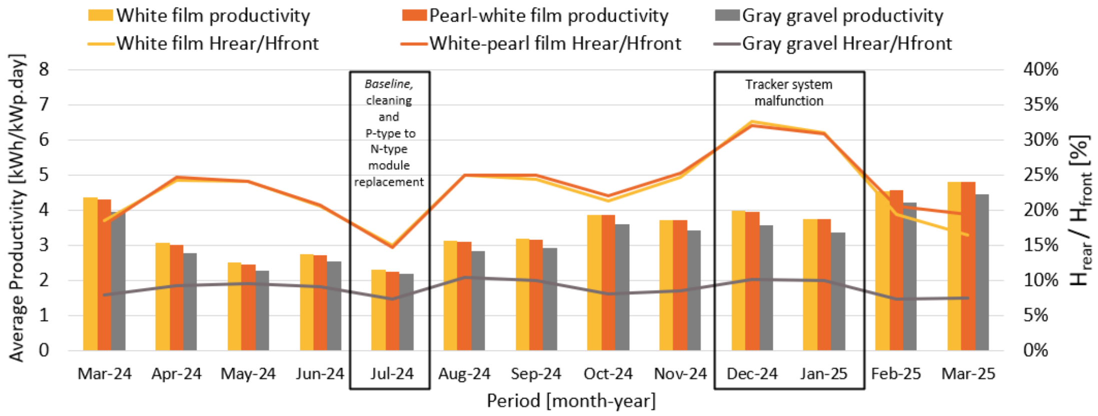


Fig 12: Average monthly energy yield for the reference system (gray bars), white film system (yellow bars), and pearl-white film system (orange bars). Rear irradiation ratios are shown as lines in corresponding colors for the respective systems.

The detailed quantification of the performance difference between the films is illustrated in Fig 13, which shows the relative energy gains achieved by the white and pearl-white films with respect to the reference system. Over the monitoring period, both reflective ground covers consistently yielded significant energy gains, with monthly values ranging approximately from 2.8% (considering the baseline period, with no substantial relative gains between the systems) up to 11.5% (during the tracker system malfunction). These results confirm the effectiveness of high-albedo surfaces in significantly increasing the total energy production of bifacial photovoltaic systems.

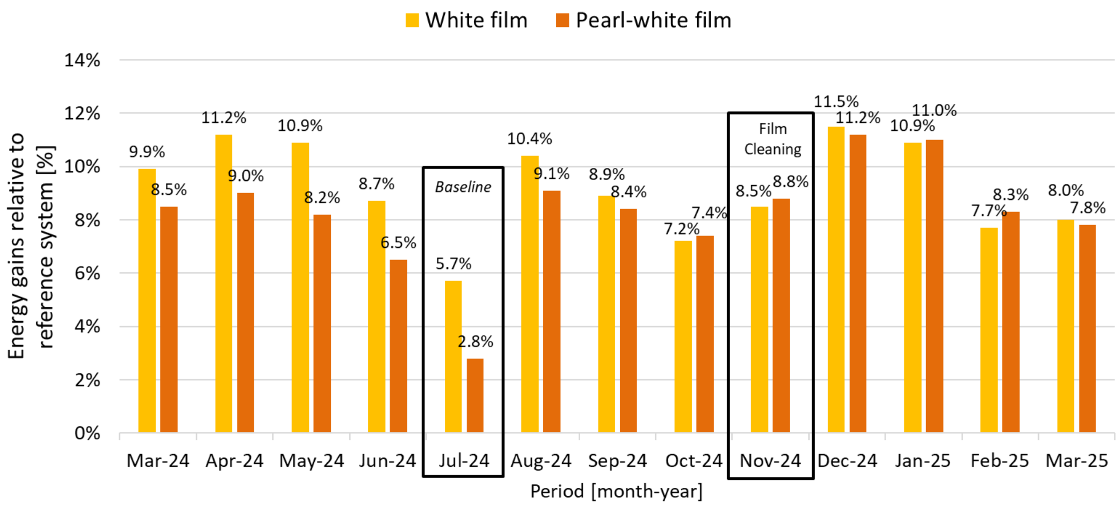


Fig 13: Relative energy gains between the film systems and the reference system with gray gravel soil.

The performance analysis was temporally segmented by several key events. An expected decline in system productivity was observed during the baseline period in July 2024, resulting from the deliberate modification of the ground surfaces, specifically the covering of the underlying soil beneath all systems with a black tarp for the baseline period. Furthermore, the systems exhibit significant seasonality in productivity, primarily influenced by the cyclical variation in available solar resources, which peak during the summer months and decrease substantially in winter. Crucially, the ratio of rear-side irradiance gain also fluctuates in correlation with the prevailing cloud cover throughout the year. As previously established, bifacial gains are augmented on cloudier days. Consequently, months characterized by higher cloud coverage yield a greater proportional contribution from the rear face to total energy generation.

Finally, the data collected between December 2024 and January 2025 must be contextualized by a tracking system malfunction that occurred in December. This technical issue demonstrably impacted both the overall productivity and the established relationship between the rear and front irradiation during this two-month period. However, since all systems were uniformly affected during this period, the relative energy gain compared to the reference system remains representative of the ground cover performance.

4. Final Remarks

This study confirms that the strategic application of high-reflectivity ground covers is an effective measure to significantly enhance the energy output of bifacial photovoltaic systems. The observed relative energy gains are primarily attributed to the improved albedo conditions, which resulted in a substantial increase in rear-side irradiance capture. The overall thermal results confirmed the observed causal relationship: the energy gains provided by the increased rear-side irradiance vastly outweigh the associated thermal losses, resulting in consistently positive net energy gains, despite the modest rise in module operating temperature.

The quantitative results are intrinsically linked to the specific climatic and environmental conditions of the evaluated system, limiting the extrapolation of these figures to other locations. Therefore, the appropriate application of advanced simulation tools is strongly recommended to enable a more accurate, site-specific evaluation that properly adjusts the findings to local climatic conditions.

The optimization of film cleaning routines is critical, although soiling losses are expected to be inversely proportional to the level of ground coverage achieved and are expected to be much lower than the ones presented for this pilot study. The viability and optimization of film cleaning routines must be assessed individually, considering the local progression of soiling losses and the associated cleaning costs. It is highly recommended to explore the possibility of integrating film cleaning with the existing scheduled maintenance and cleaning protocols for the photovoltaic modules of the plant. Additionally, the operational challenge of water scarcity in many regions of Brazil where PV plants are located necessitates evaluating water-minimizing alternatives, such as dry-cleaning techniques, and integrating cleaning with existing scheduled maintenance protocols.

Building on these findings, further investigation is underway. Early results from a white geomembrane exhibiting 74% albedo are promising, projecting an energy yield increase to exceed the 10% threshold. These findings reinforce the technical value of deploying reflective materials as an effective strategy for optimizing bifacial photovoltaic performance. For large-scale deployment, a comprehensive cost-benefit analysis is paramount to fully assess the financial viability of these applications. Future work must address non-energy benefits (such as vegetation suppression and reduce PV module soiling) and critical issues like long-term material durability and the potential environmental and drainage impacts due to surface impermeabilization.

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