Performance and Energy Gains of Bifacial PV Technologies Across Different Albedo Conditions

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Abstract

This study evaluates the energy gains of single-axis-tracker bifacial systems across different albedo levels. Results show that high-albedo surfaces can yield up to more than 9% additional annual energy compared to the reference natural ground. The study was carried out in two phases: the first tested modules with p-type PERC cells, while the second phase, reflecting a market update, focused on n-type technology now mainstream for their higher bifaciality, lower degradation and reduced temperature losses. A comparison between p-type and n-type systems under identical albedo conditions validated the benefits of n-type cells. The methodology included data of front and rear irradiance, module operating temperature and power output, and calculating key energy indicators, such as yield. The results confirm the impact of albedo on bifacial gain and highlight the technical benefits of optimizing ground reflectivity for large-scale solar PV plant performance.

Keywords: Bifacial Modules, Energy Gain, Albedo, Single-Axis-Tracking.

1. Introduction

According to the latest renewable energy statistics report, published in 2024 by the International Renewable Energy Agency (IRENA), the total installed renewable energy capacity worldwide grew by approximately 227% between 2014 and 2023. Of this total in 2023, solar photovoltaic energy accounted for about 36.5%. In the same year, photovoltaic generation represented 5.5% of global electricity production (BAMISILE et al., 2025), still a modest share, but a significant increase compared to 2022, when it accounted for 3.6% (BAMISILE et al., 2025). The solar market is expected to continue its rapid expansion through 2050, when solar energy could account for approximately 25% of the global electricity mix. (POURASL; BARENJI; KHOJASTEHNEZHAD, 2023) In addition, the upcoming COP30, to be held in Brazil in November 2025, highlights the renewed global focus on environmental issues, placing carbon emission reduction at the center of the debate on energy transition.

In this context, solar energy stands out as a key green technology. Photovoltaic modules, once considered small, inefficient, and costly, have evolved substantially, becoming both more efficient and economically accessible. Over the years, different technologies have emerged, dominated the market for a certain period, and were subsequently replaced by more efficient and cost-effective alternatives. (STEFANI et al., 2023). Currently, according to the report published by Fraunhofer ISE in 2025, the market is dominated by silicon wafer–based technologies, which account for 98% of global production. Among these, n-type cells are particularly prominent, representing 70% of the market according to the ITRPV, as demonstrated in Figure 1.

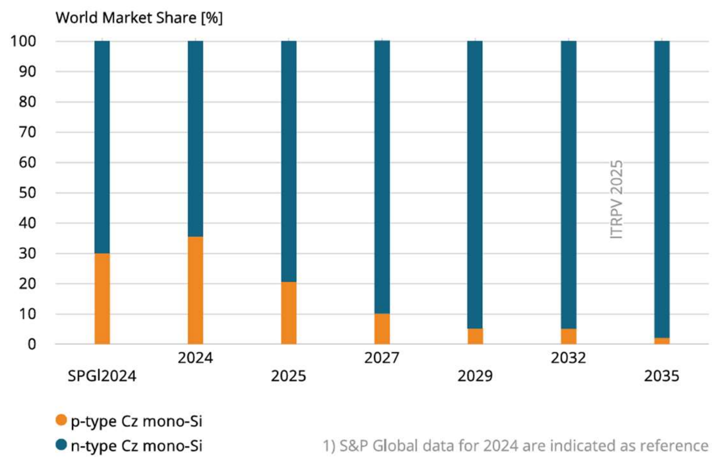

Figure 1 –Market for different wafer types S&P Global (SPGI) data are indicated for 2024 - Source: (ITRPV, 2025).

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Figure 2 presents the historical evolution of solar cell efficiencies at the laboratory scale. Among these emerging technologies, perovskite and tandem cells stand out, offering significant potential for efficiency gains. While commercial crystalline silicon modules (particularly n-type) achieve efficiencies between 22% and 25.7%, perovskite–silicon tandem cells have reached record efficiencies of 34.9% under laboratory conditions (FRAUNHOFER ISE, 2025). However, as relatively recent technologies, they still face challenges related to stability, accelerated degradation, high production costs and limited scalability. Figure 3 clearly illustrates this technological immaturity, showing the significantly larger gap between cell (small area) and module (large area) efficiencies for tandem and perovskite technologies compared to established crystalline silicon, reflecting the challenges in transferring these technologies from laboratory to industrial scale.

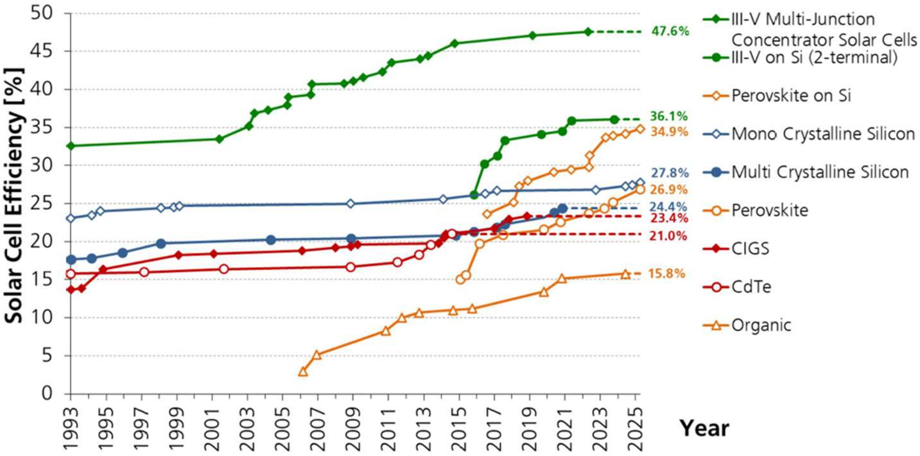

Figure 2: Development of Laboratory Solar Cell Efficiencies (1993–2025). Source: Fraunhofer ISE, Photovoltaics Report, slide 30, updated 29 May 2025.

In contrast, one of the most relevant short-term market shifts is the wide-scale adoption of bifacial modules, which can harvest irradiance from both the front and rear sides. Although the bifacial concept is long-established, its recent economic viability and manufacturing maturity have led to widespread market penetration. The conversion of the additional rear irradiance substantially improves energy generation and contributes to a significant reduction in the levelized cost of this renewable energy source (Rodríguez-Gallegos et al., 2020).

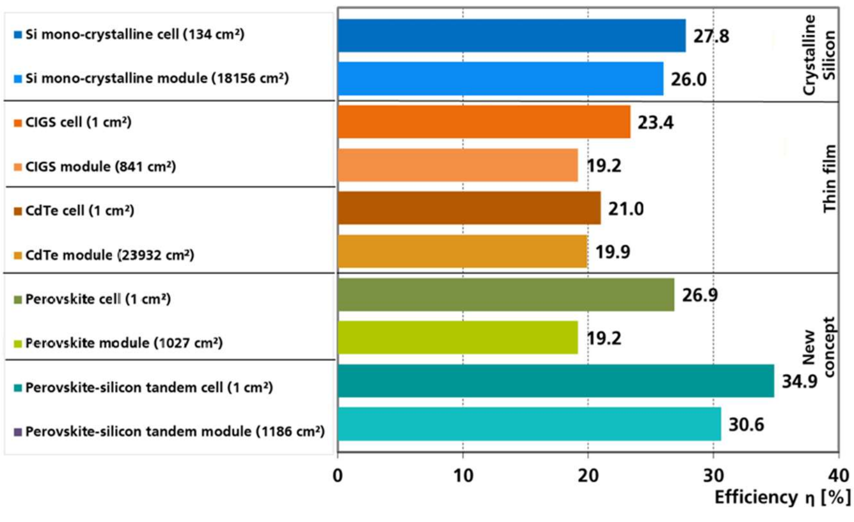

Figure 3: Efficiency Comparison of Technologies. Source: Fraunhofer ISE, Photovoltaics Report, slide 31, updated 29 May 2025.

In 2024 alone, global PV installations exceeded 700 GW, bringing the total installed capacity to more than 2.5 TW (VDMA, 2025). As shown in Figure 4, the market share of bifacial modules has grown rapidly, reaching over 60% of new installations in 2024 (VDMA, 2025), demonstrating that what was once a niche technology is now the market standard. In this context, the present study focuses on the performance of bifacial photovoltaic systems under different ground reflectivity conditions. By analyzing rear-side irradiance capture and the influence of various soil types, the results point to practical strategies for increasing energy production, highlighting the potential of bifacial plants.

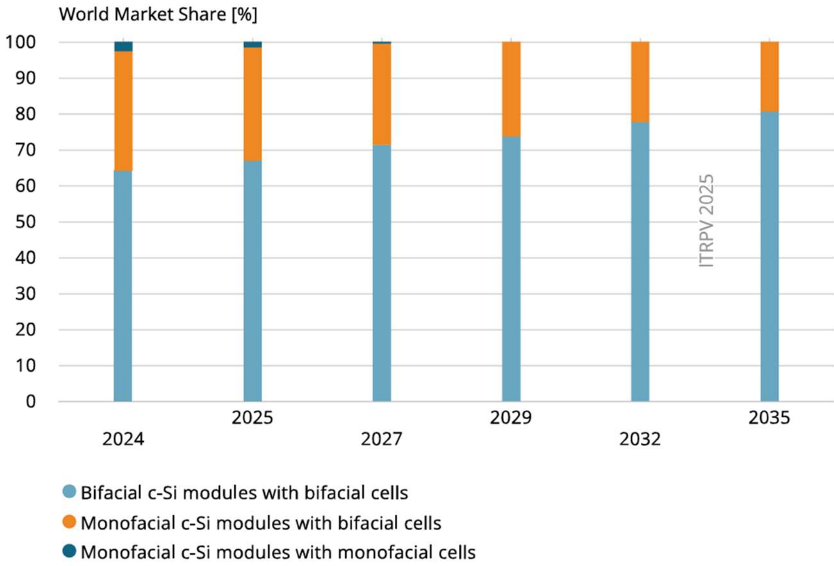

Figure 4: Market share of bifacial - Source: (ITRPV, 2025).

2. Methodology

The experimental setup consisted of a pilot plant with bifacial modules mounted on single-axis trackers, exposed to different types of ground, allowing analysis of performance variations caused by albedo (Figure 5). Sensors installed along the trackers measured module temperature and plane-of-array (POA) irradiance on both the front and rear sides. Measurements were conducted using PT1000 Class A thermistors, reference cells (IMT Si) and Class A pyranometers (EKO MS-80S), ensuring high accuracy in characterizing both incident and reflected irradiance, as well as operating temperature.

Electrical data were recorded directly by the inverters on both the direct current (DC) and alternating current (AC) sides. Data was sampled at second-level intervals and stored as one-minute averages, which were subsequently used in the analyses presented in this study.

Figure 5: Aerial images of the PV pilot plant used for evaluation of bifacial systems in phase 1.

The initial evaluation employed modules with monocrystalline silicon PERC cells (p-type), installed over four types of ground arranged along an east–west albedo gradient: grey gravel (0.26), sand (0.41), kaolin (0.43) and white gravel (0.52). The surface with the lowest albedo, grey gravel, was used as a reference to compare the energy gains of the other surfaces, since its albedo value is similar to those used in energy forecasts for large scale PV power plants in Brazil.

Following market trends toward higher-efficiency technologies, the system was later upgraded with n-type cell-based modules. These modules feature higher bifaciality, lower temperature coefficients, and reduced degradation rates, attributes increasingly valued in utility-scale projects. With higher efficiency and bifaciality ratio, the n-type modules were installed over modified ground surfaces (Figure 6): white gravel was replaced by a highly reflective white film (albedo 0.53) and kaolin by a pearl-white film (albedo 0.54). To enable direct comparison of p-type and n-type modules under equivalent conditions, a subset of p-type modules was also installed over the grey gravel reference ground. Table 1 provides detailed information on the modules installed in each phase.

Table 1: Main characteristics of the PV modules installed in the systems evaluated in this study.

Parameters	**Canadian Solar CS7N-645 (Phase 1)**	**JA Solar JAM72D30-550/GB (Phase 2)**	**JA Solar JAM72D40-575/GB (Phase 2)**
Technology	p type PERC	p type	n type
Rated power	645	550	575
Temperature coefficient [%/°C]	-0.35	-0.35	-0.30
Bifaciality factor	0.7	0.7	0.8
Efficiency	20.7%	21.3%	22.3%
Expected first-year degradation	2%	2%	1%
Expected annual degradation	0.45%	0.45%	0.40%

Although the photovoltaic systems were theoretically identical, both evaluation phases began with a calibration stage in which black tarps were used to create uniform low-albedo conditions under each tracker (Figure 7). This approach enabled the quantification of intrinsic performance differences between systems before introducing the effects of ground reflectivity. Ideally, the baseline period should encompass a full seasonal cycle to capture system variations under a wide range of conditions, providing a more representative estimate of intrinsic performance. However, due to operational constraints, this was not feasible. In this study, baseline periods ranged from 10 to 90 days, ensuring exposure to varied atmospheric conditions for robust estimation without compromising the experimental schedule.

Table 2 presents the baseline results from both experimental phases. In Phase 1, operational challenges were encountered, particularly with the kaolin surface, where the fine material contaminated the black tarps during baseline measurements, complicating the quantification of intrinsic differences. Consequently, reliable baseline data for kaolin in Phase 1 could not be established.

Figure 6: Aerial images of the PV pilot plant used for evaluation of bifacial systems in phase 2.

Figure 7: Aerial image of the PV pilot plant used for evaluation of bifacial systems during the baseline period with low-albedo black tarp coverage.

Observing the Phase 2 baseline results, an interesting aspect is noted: The gain difference between almost all systems was below 0.5%, except for the system located at the edge, which showed a difference of 2.49%. While this value is small in absolute terms, it may become significant at utility scale, raising questions about the origin of this behavior.

Table 2: Baseline results from both phases.

Parameters	Gray Gravel	Sand	Kaolin	White Gravel	Pearl-White Film	White Film
PHASE 1						
Energy Gain	0%	-0.5%	-1.7%	0.5%	-	-
PHASE 2						
Energy Gain	0%	-0.18%	-	-	0.12%	2.49%

This effect can be attributed to an edge effect in the experimental setup. The pilot plant was designed with a 7m pitch, slightly larger than the usual pitch for PV plants in Brazil, aiming to minimize the effects of adjacent ground types on individual system energy production. However, the surrounding environment, such as grass or nearby terrain, still influenced the results, particularly for systems at the edges of the array.

The objective of this work is to compare systems under equivalent conditions, evaluating the performance of technologies over different ground types. In this context, baseline correction proved essential, as some systems may initially appear to outperform others due to intrinsic system gains, rather than differences in ground type.

Energy yield (kWh/kWp) was adopted as the primary performance metric, as Phase 2 involved two module types with differing nominal powers. Differences in energy production among ground types, derived from yield, were used to evaluate the relative performance of photovoltaic technologies (p-type and n-type) under reference albedo conditions. Additionally, relationships between albedo, rear-side irradiance factor, module temperature, and yield gain were analyzed, aiming to investigate the influence of optical and thermal ground properties on the performance of each technology.

3. Results

After the reference period, the influence of albedo on the energy performance of bifacial modules became evident. The Rear Irradiation Factor (RIF), defined as the ratio of the sum of rear to front irradiation, revealed a clear correlation between ground reflectivity and the additional fraction of irradiance captured by the modules (Figure 8).

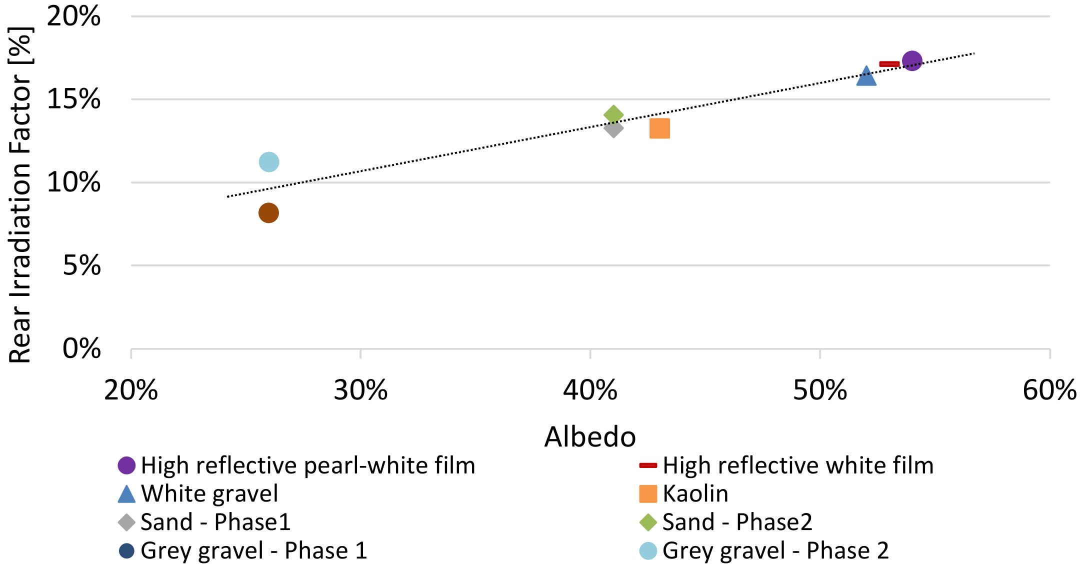

Figure 8: Annual rear irradiation factor for all natural and engineered ground surfaces evaluated in the two study phases.

Monthly variation analysis of the rear irradiation factor (Figure 9) indicates that seasonality had a limited effect for most surfaces, although higher-reflectivity soils were more sensitive to environmental changes. This trend is exemplified by the grey gravel reference surface, which showed a maximum month-to-month absolute variation of 1.5%abs (relative variation of 15%) and an annual mean rear irradiation factor of 8.2%, compared with white gravel (albedo 0.52; mean factor 16.4%), which exhibited absolute variations up to 2.8%abs (relative variation of 25%). This greater variability in high-albedo surfaces is attributed to their higher susceptibility to soiling and environmental conditions. Natural albedo is also subject to variation, for example, wet soil often reflects less than dry soil, and vegetation growth can further modify ground reflectivity over time.

Similarly, the behavior of the kaolin surface requires specific consideration. In this study, kaolin was mixed with coarse aggregate (Grey gravel), to improve mechanical stability, as pure kaolin would not have been suitable for outdoor exposure. Although initially expected to outperform sand, the surface showed a sharp drop in performance after the first month due to the washing of fine particles by heavy rainfall. This highlights the vulnerability of some high-albedo materials to environmental degradation. After this initial loss, the albedo stabilized in subsequent months.

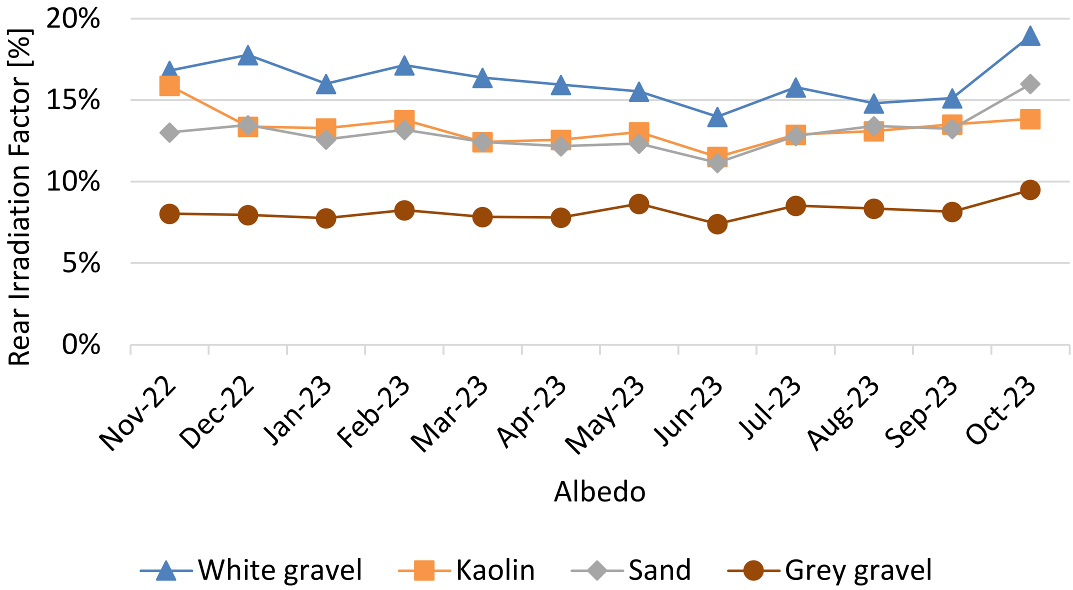

Figure 9: Seasonality variations of rear irradiation factor during phase 1.

The additional irradiance from high-albedo surfaces translated directly into higher energy generation (Table 3). For example, in Phase 1, white gravel provided a 4.7% gain relative to the reference ground, while in Phase 2, the white film and pearl-white film reached 9.5% and 8.3% before baseline correction. Initially, it may appear that the surface with the second-highest albedo (White Film) achieved the highest gain, but when taking into consideration the differences observed during the baseline period, the adjusted gains would be 7.0% for the white film and 8.2% for the pearl-white film, highlighting the importance of these compensation of intrinsic gains for a fair comparison among ground types.

Beyond energy impact, the use of high-reflectivity films offers operational benefits, such as vegetation suppression and reduced dust accumulation, improving system efficiency and lowering operation and maintenance costs. However, environmental challenges, such as changes in soil permeability, may arise and were not addressed in this study.

A direct comparison between cell technologies was then performed in two steps:

Before the quantitative analysis, it is important to note that energy gains between technologies depend not only on albedo or the rear irradiation factor but also on intrinsic characteristics of photovoltaic cells. Among these, the bifaciality factor defines the fraction of additional rear irradiance that can be converted, while the spectral response determines the efficiency with which each cell type converts specific wavelengths into electrical energy. These properties influence how each technology utilizes the reflected irradiance, leading to performance differences even under similar optical conditions.

Table 3: System evaluation results: albedo, rear irradiation factor, energy yield, energy gain and irradiance-weighted operating temperature.

Parameters	Gray Gravel	Sand	Kaolin	White Gravel	Pearl-White Film	White Film
Albedo	26%	41%	43%	52%	54%	53%
PHASE 1						
Rear irradiation factor	8.2%	13.3%	13.3%	16.4%	-	-
Energy Yield [kWh/kWp.day]	3.46	3.53	3.53	3.62	-	-
Energy Gain	-	2.0%	2.0%	4.7%	-	-
Operating Temperature	40.7°C	42.1°C	41.4°C	42.1°C	-	-
PHASE 2						
Rear irradiation factor	11.2%	14.0%	-	-	17.3%	17.1%
Energy Yield [kWh/kWp.day]	3.20	3.40	-	-	3.51	3.55
Energy Gain	-	3.4%	-	-	8.3%	9.5%
Operating Temperature	38.9°C	40.3°C	-	-	40.8°C	41.6°C

In the first step, the performance of p-type and n-type modules was evaluated under reference albedo conditions (gray gravel) during Phase 2. Even under identical reflectivity, n-type modules showed superior performance, with higher energy yield, confirming their intrinsic advantage over p-type modules (Table 4).

Table 4: Comparison between p-type and n-type system results under reference albedo conditions in phase 2: energy yield, and irradiance-weighted operating temperature.

Parameters	n-type	p-type
Energy Yield [kWh/kWp.day]	3.24	3.15
Operating Temperature	38.9°C	37.8°C

In the second step, energy gains were analyzed under higher albedo conditions by comparing n-type modules (Phase 2) with PERC modules (Phase 1) installed over sand. Although the measurements were carried out in different time series, comparing the relative gains of sand with respect to the reference ground (gray gravel) allowed the isolation of the technology effect. Results showed that n-type modules achieved a 1.4 % absolute higher energy gain than PERC modules on the same ground type, demonstrating their greater ability to convert additional rear-side irradiance into useful energy.

The analysis presented in Table 3 confirms a direct and quantifiable relationship between increasing albedo and energy yield, with more reflective surfaces enhancing rear-side irradiance and, consequently, total energy production. This trend was consistent across both experimental phases: in Phase 1 (PERC), the high-reflectance natural surface (white gravel) generated 4.7 % more energy than the low-albedo reference ground, while in Phase 2 (n-type), highly reflective films, particularly the white film, achieved up to 9.5 % higher yield compared to the system installed on gray gravel.

The same results are also presented graphically in Figure 10, which clearly illustrates the progressive increase in energy gain as ground reflectivity rises. Each bar in the figure represents the mean daily energy yield for a given surface, making the positive correlation between albedo and bifacial performance visually evident. The figure also highlights how engineered high-albedo surfaces, such as the white and pearl-white films, outperform natural materials like sand or gravel, emphasizing the strong influence of ground treatment on system productivity.

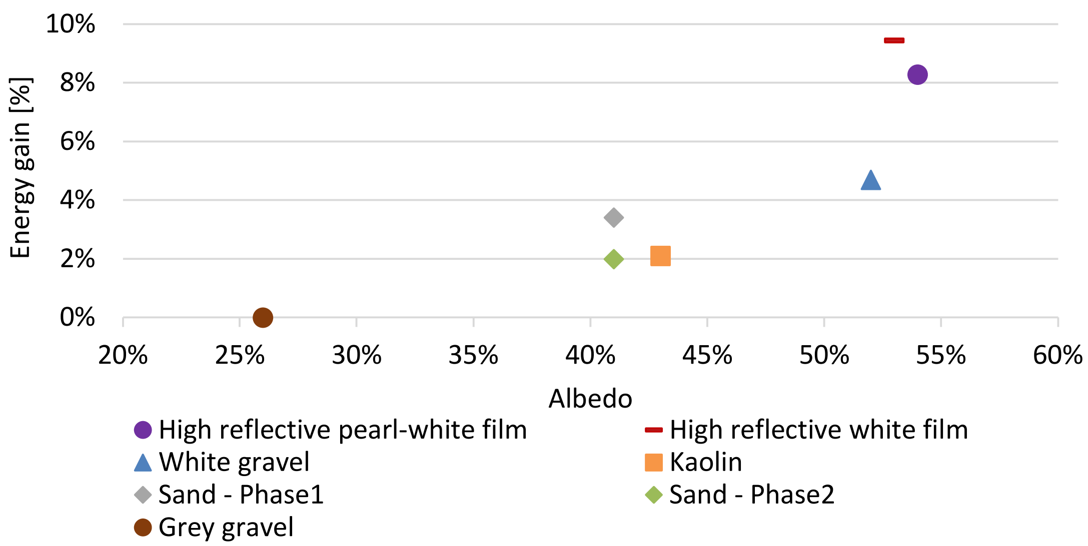

Figure 10: Energy gains associated with the various ground types evaluated in this study.

Although albedo directly influences energy gain, higher reflectivity levels are also associated with increased module operating temperatures, as additional rear-side irradiance raises the overall thermal load on the system. Figure 11 presents the relationship between surface albedo and the irradiance-weighted operating temperature for each evaluated ground type. The figure reveals a clear upward trend: as ground reflectivity increases, the average operating temperature of the modules also rises.

In Phase 1, the systems installed over higher-albedo surfaces such as sand and white gravel operated at around 42 °C, approximately 1.5 °C higher than the reference gray gravel (40.7 °C). In Phase 2, the white and pearl-white films exhibited the highest mean temperatures, 41.6 °C and 40.8 °C, respectively, while the gray gravel system remained below 39 °C. This temperature rise is consistent with the additional portion of reflected irradiance absorbed by the module, which contributes to heating rather than electrical conversion. Consequently, high-albedo surfaces induce small thermal penalties due to the negative temperature coefficient of photovoltaic cells.

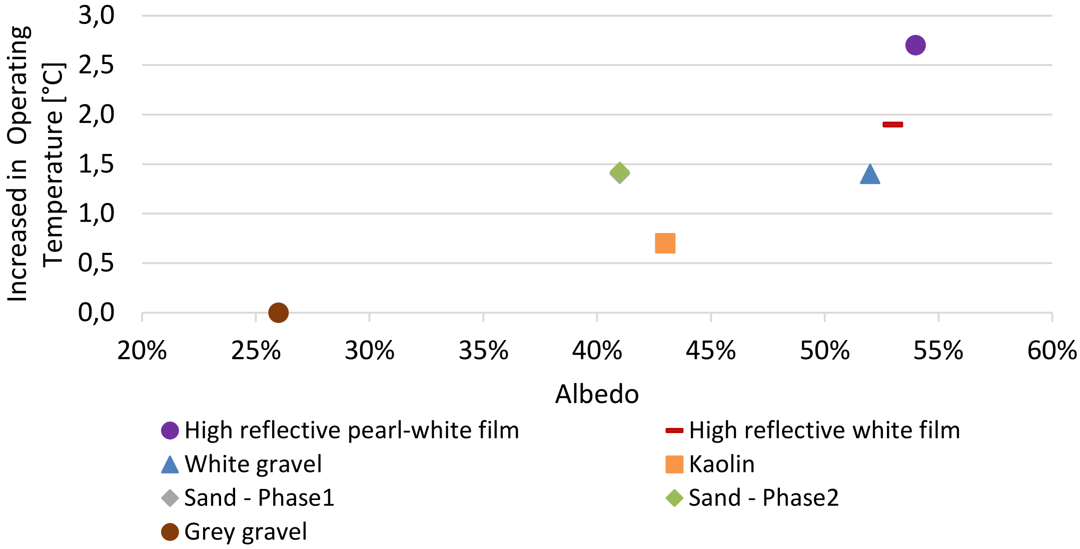

Figure 11: Increase in PV module operating temperature associated with the various ground types evaluated in this study.

However, as demonstrated by comparing Figures 10 and 11, the net effect remains strongly positive. The white and pearl-white films produced energy gains of 9.5 % and 8.3 %, respectively, far exceeding the minor thermal increase of only 2–3 °C. These results confirm that the benefits of enhanced rear-side irradiance under high-albedo conditions largely outweigh the additional heat load. Optimizing ground reflectivity therefore emerges as a viable and effective strategy for improving the performance of bifacial PV systems without compromising thermal stability.

4. Summary and Conclusions

The results obtained in Phases 1 and 2 confirm the optimization potential of bifacial photovoltaic systems across multiple dimensions. First, the direct comparison between cell technologies consistently demonstrated the superior performance of n-type modules. Under identical reflectivity conditions (gray gravel reference ground), n-type systems achieved an energy yield 2.9 % higher than p-type modules, while also exhibiting a lower temperature coefficient (–0.30 %/°C vs –0.35 %/°C). This improvement reflects both technological progress and the higher bifaciality of n-type cells, which respond more positively to albedo gains.

Secondly, the findings reinforce albedo as a key parameter in bifacial system design. High-reflectivity surfaces produced substantial yield increases: white gravel delivered a 4.2 % gain over the reference ground, whereas the white and pearl-white films achieved 7.0 % and 8.2 %, respectively, after baseline correction. Although these high-albedo conditions led to a modest 2–3 °C increase in average operating temperature, the additional energy captured from the rear side far outweighed the associated thermal losses.

When translated into equivalent module efficiency, these energy gains are remarkable. To achieve the same increase in energy yield, the p-type PERC module from Phase 1 would need to be 0.9 percentage point more efficient, while the n-type module from Phase 2 would require roughly 1.8 percentage points of additional efficiency. Historically, such improvements have taken the photovoltaic industry about 10–15 years to accomplish, underscoring how optimizing ground reflectivity can deliver system-level gains comparable to a decade of technological advancement.

Finally, increasing ground reflectivity emerges as a direct and effective strategy to enhance energy generation in future bifacial PV plants. Large-scale implementation, however, will depend on a cost–benefit assessment weighing the additional energy yield against the costs of acquiring, installing, and maintaining highly reflective surfaces. Moreover, the results presented here are specific to the climatic conditions and system configuration of Florianópolis, Brazil; extrapolation to other regions should account for local irradiance patterns and module thermal behavior.

5. Acknowledgments

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