Field-based albedo characterization station: assessing ground reflectivity for enhanced modeling of bifacial photovoltaic systems

Kevin Luiz Rocha De Azevedo[1]; Marília Braga[1]; Anelise Medeiros Pires[1]; Thamires Alves Silva[1]; Camila Do Valle[2]; Helena Flávia Naspolini[1]; Ricardo Rüther[1]

[1]Fotovoltaica - UFSC Laboratory, Florianópolis (Brazil)

[2] Azul Pack, Jacutinga (Brazil).

Abstract

The rapid growth of bifacial photovoltaic technology has increased the need for accurate assessment of ground reflectivity and reflective surface characterization, as PV modules benefit from both front and rear-incident irradiance. One of the most effective strategies to enhance rear-side energy gain is by modifying the surface albedo beneath the modules. This study presents the setup installed at the Fotovoltaica/UFSC research lab in Florianópolis, Brazil (27°S, 48°W) for albedo characterization, featuring precise and fast measurements using spectroradiometers, pyranometers and reference cells, to achieve a better match with the spectral and optical characteristics of flat silicon PV modules. Three artificial surfaces — two films and a white geomembrane — were evaluated and compared to natural ground types. The results confirm significant reflectivity differences between materials, with the white geomembrane reaching the highest albedo values (79% measured with reference cells, 74% with pyranometers). The study highlights the importance of detailed field-based albedo characterization in supporting the design and evaluation of bifacial PV systems and reinforces the need for integrating such tools into site assessment practices.

Keywords: Albedo Characterization, Bifacial PV, Ground Covers, Albedo Enhancement, PV Performance Optimization.

1. Introduction

The global photovoltaic (PV) market is rapidly shifting toward bifacial PV module technologies, which generate energy from both the front and rear sides. As of 2024, bifacial modules already account for over 60% of utility-scale PV installations. According to the 2025 edition of the International Technology Roadmap for Photovoltaics (ITRPV), this share is expected to rise to 80% by 2035, highlighting the growing technical and commercial appeal of the technology (VDMA, 2025). Bifacial modules stand out for their ability to increase energy yield by capturing not only the irradiance on the front side but also the irradiance incident on the rear side of the module. As a result, the optical properties of the surface beneath the array play a key role in overall system performance (IEA PVPS, 2021).

One of the most influential properties in this context is albedo, the ratio of reflected to incident irradiance. High-albedo surfaces can significantly enhance rear-side irradiance and therefore the energy yield of bifacial systems. As a result, altering or optimizing the ground surface to increase albedo has become an important strategy in project design and performance optimization. Consequently, there is a growing need to accurately model rear-side irradiance to account for this effect in energy simulations. In this context, accurate characterization of ground albedo under real-world conditions is essential (Dittmann et al., 2019). This is particularly true when comparing alternative materials or validating simulation models.

In the Brazilian context, albedo characterization in utility solar installations is traditionally governed by stringent technical and regulatory guidelines. For example, reference solarimetric stations must utilize instrumentation that meets strict standards, such as the requirement for the albedometer to be constituted of

10.18086/swc.2025.03.31 Available at http://proceedings.ises.org

a pair of pyranometers of Class I or superior, as standardized by ISO 9060 2018, for the measurement of global horizontal irradiance.

These instrument requirements and specifications are determined by the EPE (Empresa de Pesquisa Energética), a Federal Government agency. The document EPE-DEE-RE-065/2013 (dated March 23, 2016), entitled "Instructions for requesting registration and technical qualification with a view to participating in electricity auctions," dictates the necessary requirements for qualifying photovoltaic power plant projects in government-promoted electricity auctions. Any company or investor planning to construct a solar power plant and sell its energy in an auction must, in advance, complete a mandatory study of the plant's generation potential, which requires the mandatory measurement of the terrain's solar irradiance over a minimum period of 12 months.

However, broadband measurements, while essential for energy modeling, fail to capture the wavelength-specific reflectivity variations that most significantly influence crystalline silicon conversion, thus highlighting a demand for a finer, more comprehensive data resolution. Addressing this critical gap and ensuring alignment with the technical rigor demanded by reference standards, the Fotovoltaica/UFSC research laboratory at the Federal University of Santa Catarina (UFSC) developed a dedicated albedo station, conceived to enable on-site characterization of various materials, in addition to providing continuous, top-tier sensor measurements, encompassing both high-resolution spectral and broadband data.

This paper presents the albedo station setup, along with the results from albedo monitoring campaigns evaluating different natural and artificial ground materials. Two high reflective film variants and a white geomembrane were tested under operational conditions using the dedicated albedo station. The study aims to highlight the importance of field-based albedo characterization and to provide insights into the optical performance of engineered reflective surfaces for bifacial PV applications.

2. Methods

The albedo characterization in this study was performed using a dedicated monitoring station at the Fotovoltaica/UFSC solar research lab, specifically designed to provide continuous, high-resolution measurements of ground reflectivity. As shown in Fig 1, the station features a custom mounting structure that supports a range of high-precision instruments (detailed in Fig 2) at a height of 1.5m, with a material sample size covering a 7 m radius, enduring comprehensive data acquisition. This setup integrates two Kipp & Zonen SMP22 Class A pyranometers for continuous measurements of global and reflected irradiance over a broad spectral range, with a temporal resolution of one second. Additionally, two IMT Si-mV-85-Pt100 Class A reference cells were used to measure albedo with spectral and optical sensitivity, as these flat silicon-based sensors closely resemble the response of bifacial PV modules. To complement these continuous measurements, a portable EKO MS-720 spectroradiometer was used for periodic measurements, enabling detailed spectral albedo analysis in the 350–1050 nm range, under clear and cloudy conditions.

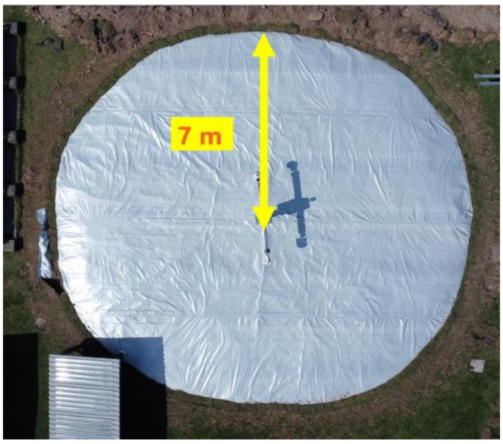

Fig 1: Dedicated monitoring albedo station at the Fotovoltaica/UFSC solar research lab.

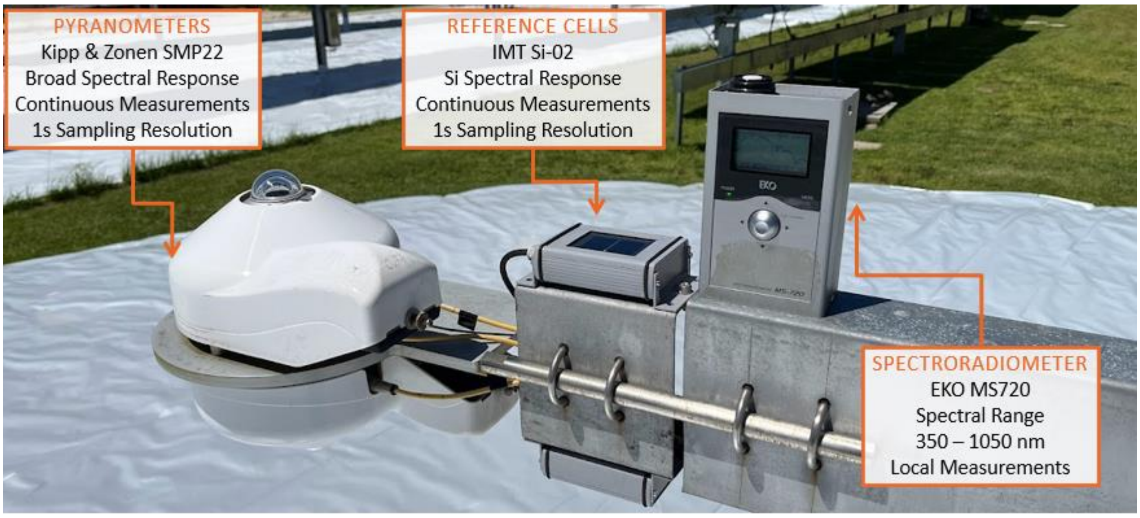

Fig 2: Instruments used for albedo characterization: Kipp & Zonen SMP22 Class A pyranometers, IMT Si-mV-85-Pt100 Class A reference cells, and EKO MS720 spectroradiometer.

Three high-reflectivity surfaces were evaluated: two engineered films — a high reflective white film and a high reflective pearl-white variant — and a white geomembrane. Albedo values were determined through continuous monitoring of the ratio between reflected and global horizontal irradiance, with all measurements synchronized through the station's integrated data acquisition system.

For a more detailed analysis, the assessment also included the daily climatic conditions for each tested surface. For this purpose, the Clear Sky Index ($\mathbf{k_c}$) concept was utilized. This parameter was calculated using the ratio of the measured global horizontal irradiance (GHI) to the clear sky GHI modeled for the specific site and instant. The clear sky GHI was determined using the Ineichen clear sky model as implemented within the open-source pvlib python library, ensuring a standardized and reproducible calculation for the clear sky reference.

Based on the calculated $\mathbf{k_c}$ values, the evaluation periods were segmented into three distinct atmospheric conditions: clear days ($\mathbf{k_c} > 0.8$), partially cloudy days ($0.4 < \mathbf{k_c} <= 0.8$), and cloudy days ($\mathbf{k_c} <= 0.4$). This segmentation allowed for the individual assessment of how specific atmospheric conditions, such as the increased ratio of diffuse radiation on cloudy or partially cloudy days, influence the resulting measured albedo values for each material, as shown in the comparative analysis presented in the results section. Furthermore, a day was considered valid only if a minimum of 80% of data was valid within the measurement period.

This methodology was specifically developed to meet the critical need for robust field-based albedo characterization in the design of bifacial photovoltaic systems, providing high-fidelity empirical data to support both performance modeling and material selection. The approach integrates several layers of analysis: The high temporal resolution of one-second measurements enabled detailed analysis of transient reflectivity behavior. Simultaneously, the inclusion of the clear sky index ($\mathbf{k_c}$) allows for the segmentation of data based on daily climatic conditions, enabling a comparison of the obtained values and verifying whether the results show consistency or present any anomaly for different conditions. Furthermore, the addition of spectral measurements offered crucial insights into the wavelength-dependent performance of each material, particularly within the ranges most relevant to crystalline silicon photovoltaic energy conversion.

3. Results

The albedo station was used to characterize six different ground materials so far, including natural and engineered surfaces: grey gravel, white gravel, white film, high reflective pearl-white film, high reflective white film, and a white geomembrane.

Preliminary analysis of long-term data - 414 consecutive days - for the reference grey gravel surface indicated that seasonal variability did not significantly influence the measured albedo values. Sky clearness, on the other hand, caused variations in the measured albedo, as it will be addressed later in this section. As shown in Fig 3, this observed stability throughout the year supports the hypothesis that a full one-year data registration period is not necessarily mandatory for validating the reflectivity results of surfaces, thus allowing the remaining tested materials to be subjected to considerably shorter analysis windows.

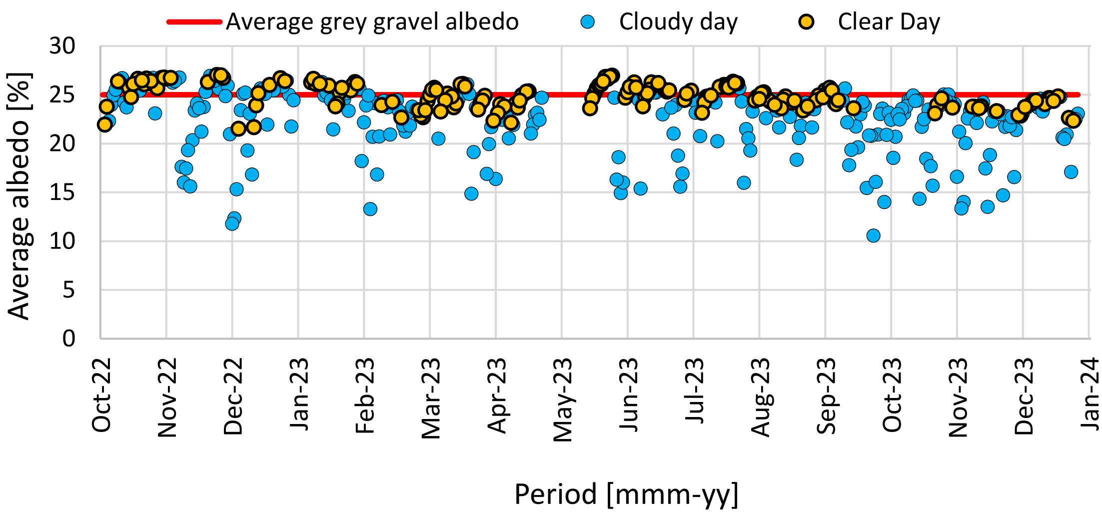

Fig 3: Daily albedo during the evaluation period of the reference grey gravel soil. The red line indicates the global albedo for the material during the evaluated period (25%).

In addition to analyzing the seasonal stability observed in gray gravel, a complementary analysis was performed for the highly reflective white film over a period of 216 consecutive days. As shown in Fig 4, this analysis indicated a gradual decrease in albedo over time, mainly attributed to the accumulation of soiling deposited on the film's surface. The impact of this accumulation was empirically validated by two cleaning events performed on July 31, 2024, and November 19, 2024. The continuous monitoring data clearly illustrates a sharp elevation in the measured albedo following these cleaning events, directly demonstrating the effect of soiling on the reflective performance of the engineered surface.

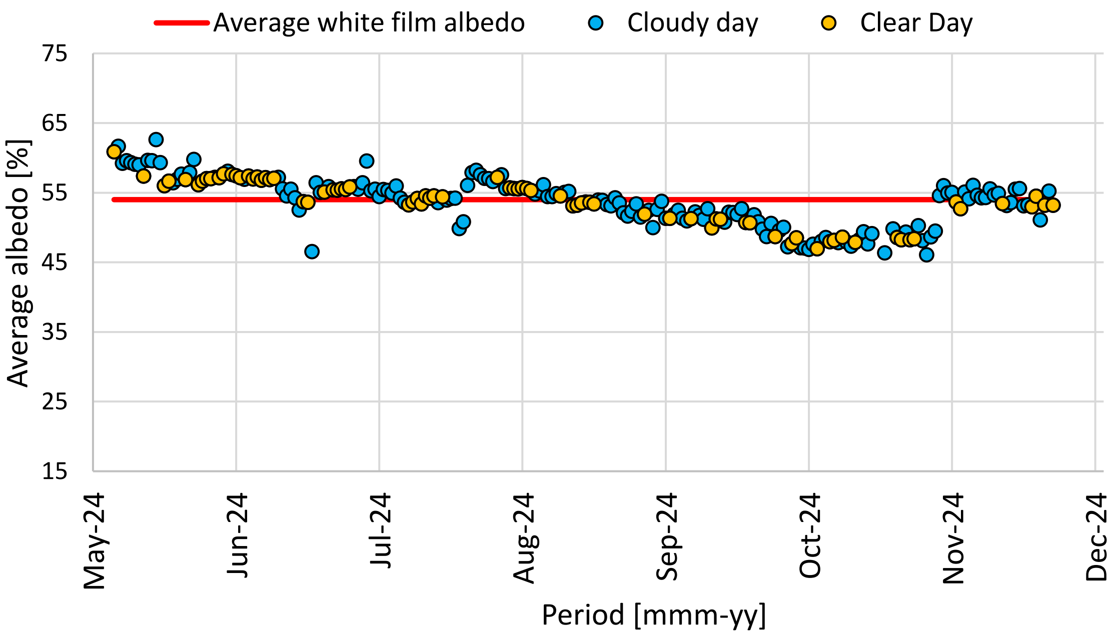

Fig 4: Daily albedo during the evaluation period of the white film. The red line indicates the global albedo for the material during the evaluated period (54%).

In line with this initial observation, the analysis of albedo values segregated by the clear sky index (**k_c**) revealed a distinct behavior between the reference surfaces. For the gray gravel reference, as shown in the Fig 5, the albedo exhibited a higher dependence on atmospheric clarity: lower **k_c** values corresponded to a reduction in the measured albedo. On the other hand, as shown by the Fig 6, the white film showed a different response, demonstrating no substantial variations under different sky conditions. This divergent behavior may be attributed to the influence of rainfall on the reflectance of natural ground surfaces, as their color varies with moisture content. Nonetheless, a dedicated analysis correlating rainfall and albedo would be necessary to confirm this hypothesis.

The long-term daily albedo measurements for two surfaces — 414 days for the gray gravel reference and 216 days for the high-reflective white film — showed minimal variation throughout the monitoring campaigns. The observed fluctuations were primarily associated with sky conditions – and possibly rain events - for natural ground types and soiling for engineered surfaces, but not seasonality. This consistency among the materials studied, confirmed by high-resolution data, further supports the hypothesis that a full year of data recording is not necessarily required to validate the reflectivity results of surfaces, thus allowing the behavior observed in shorter periods to be extrapolated to longer periods.

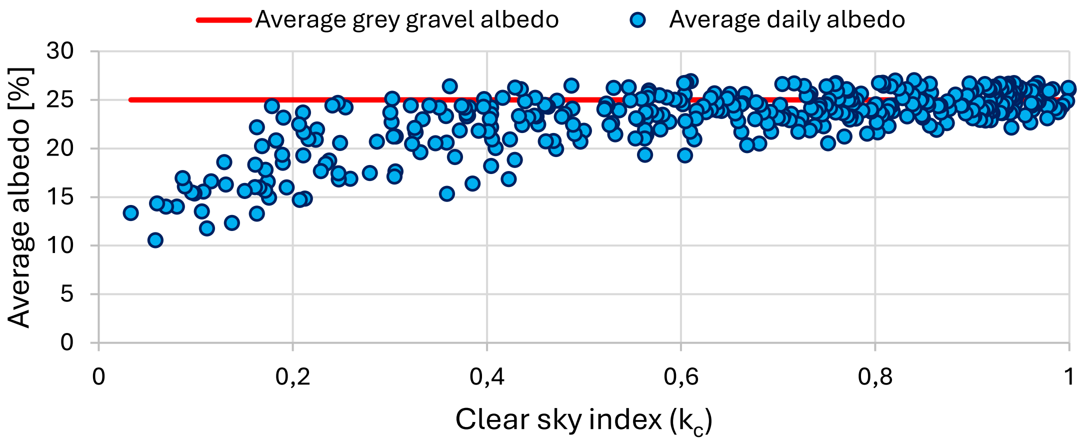

Fig 5: Correlation between daily albedo and daily k_c during the evaluation period for the reference gray gravel ground type. The red line indicates the global albedo for the material during the evaluated period (25%).

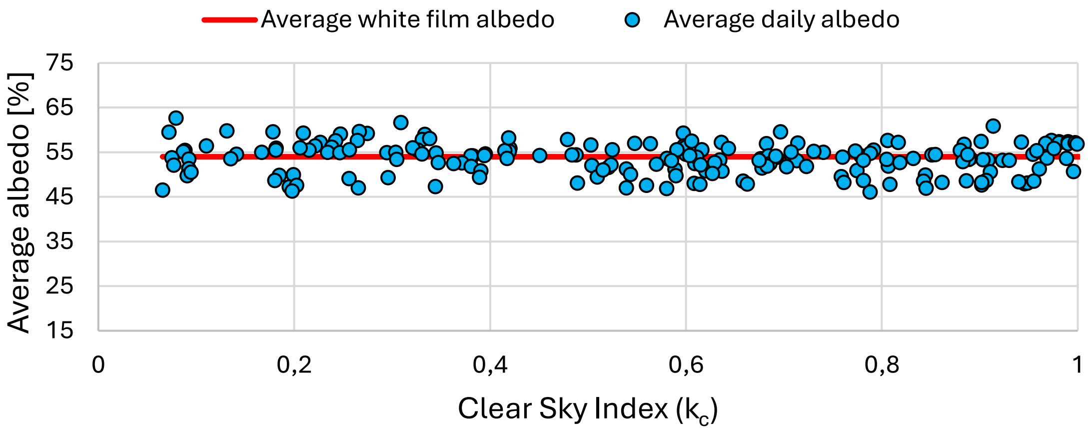

Fig 6: Correlation between average daily albedo and daily k_c during the white film evaluation period for the white film. The red line indicates the global albedo for the material during the evaluated period (54%).

Tab. 1 presents the overall results for albedo of the characterized materials under three different sky conditions, based on the clear-sky index. The measured albedo for all materials demonstrated some level of dependency on sky conditions. However, as previously discussed, natural ground surfaces exhibited greater susceptibility to reflectivity reductions under overcast conditions, a behavior likely associated with rainfall events and increased soil moisture affecting their reflective characteristics. The white geomembrane maintained its superior performance across all conditions, achieving the highest reflectivity values for clear days (74%), partial cloudy days (73%) and cloudy days (72%), confirming its robust performance under diverse real-world operating conditions.

Tab 1: Albedo characterization results divided according to sky conditions. The chosen k_c thresholds for segmentation are indicated. Results presented are based on pyranometer data.

Ground Material	Clear Day ($k_c > 0.8$)	Partial Cloudy Day ($0.4 < k_c < 0.8$)	Cloudy Day ($k_c < 0.4$)
Grey Gravel	25%	24%	20%
White Gravel	48%	50%	45%
White Film	56%	55%	52%
High Reflective Pearl-White Film	55%	54%	54%
High Reflective White Film	55%	53%	54%
High Reflective White Geomembrane	74%	73%	72%

Tab 2 presents the results obtained for the full evaluation periods using reference cells and pyranometers for all ground types. All engineered materials demonstrated significantly higher albedo values compared to the natural grey gravel reference surface, that presented a 25% reflectivity, confirming their effectiveness in enhancing reflected irradiance. The white geomembrane emerged as the top-performing material with 79% reflectivity measured with reference cells, substantially outperforming both the white and pearl-white film variants, with 59% and 60%, respectively. The largest differences between reference cell and pyranometer results arise for the white engineered materials. This is explained by their broad spectrally-resolved reflectivity.

Tab 2: Albedo characterization results for the different types of soils evaluated, measured on site.

Ground Material	Reference Cell Albedo	Pyranometer Albedo	Evaluation Interval
Grey Gravel	24%	25%	414 days
White Gravel	48%	48%	8 days
White Film	60%	55%	85 days
High Reflective Pearl-White Film	60%	55%	67 days
High Reflective White Film	59%	54%	216 days
High Reflective White Geomembrane	79%	74%	86 days

Fig 7 presents the spectrally-resolved albedo for various ground types measured at the Fotovoltaica/UFSC lab. While all evaluated natural ground surfaces exhibited increasingly higher reflectivity at longer wavelengths, the engineered films and geomembrane showed consistently broad and high reflectivity across the silicon response range, particularly pronounced at shorter wavelengths, where their reflectance far exceeds that of natural surfaces.

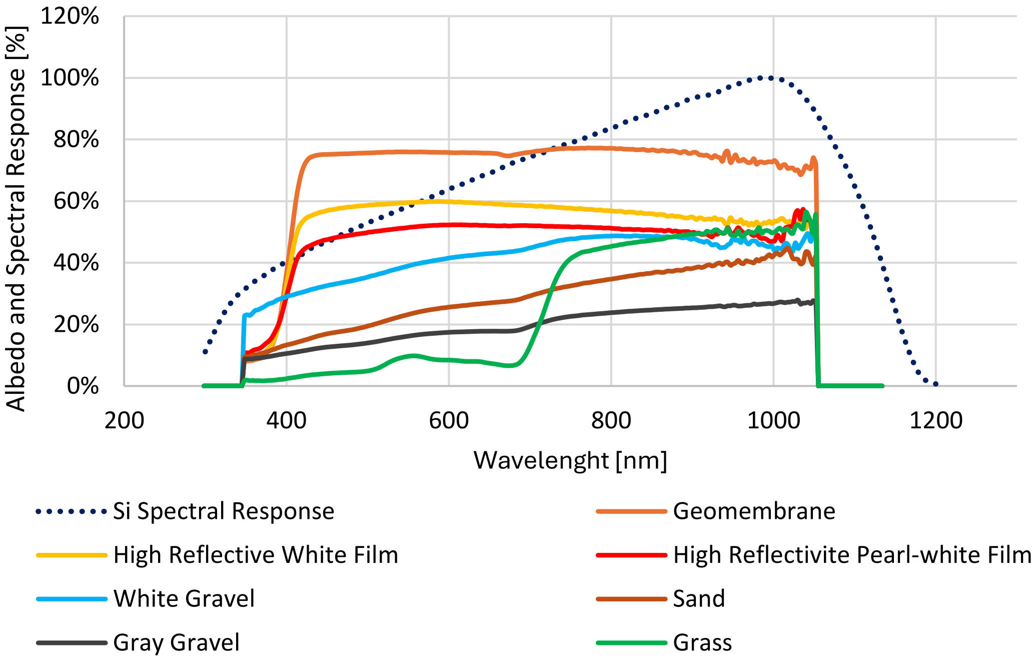

Fig 7: Spectrally-resolved albedo measurements for different ground types. Spectral response of a silicon cell is presented as a reference. Measurements were made on-site at the Fotovoltaica/UFSC Solar Energy Laboratory in Florianópolis-SC.

The spectral albedo analysis performed on specific clear and cloudy days, shown Fig 8, revealed notable variations in intensity directly correlated with cloud coverage. While the fundamental shape of the spectral albedo curves remained consistent for all materials under different atmospheric conditions, a decrease in overall albedo level—or intensity—was observed on cloudy days. These decreases varied among ground types; however, the observed differences did not align with the results from continuous measurements, possibly indicating challenges in measurement replicability. Indeed, the spectral measurements were not performed simultaneously, as only one spectroradiometer was available at the time. The non-simultaneous acquisition of front and rear irradiance data can lead to discrepancies due to rapidly changing sky conditions under overcast weather, where cloud thickness and brightness can fluctuate within short timescales.

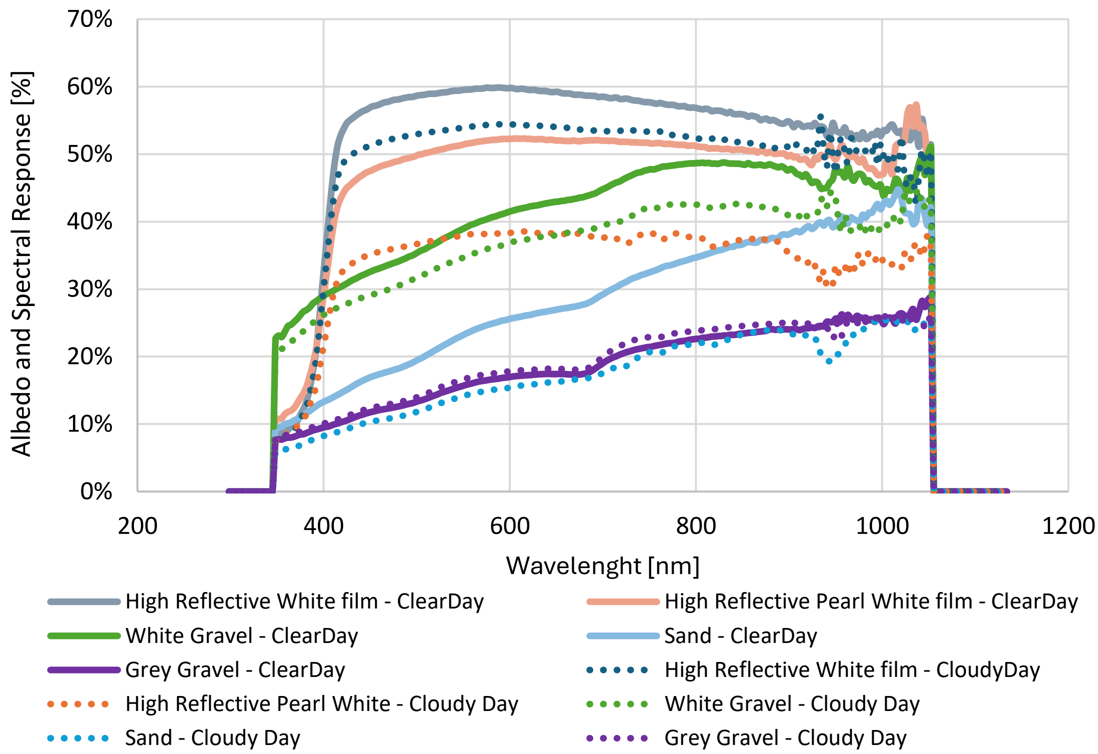

Fig 8: Albedo characterization and spectral response for the tested soils in different climate conditions. Measurements made on-site at the Fotovoltaica/UFSC Solar Energy Laboratory in Florianópolis-SC.

The continuous measurement approach proved essential for capturing transient reflectivity behaviors that single-point measurements might miss, particularly the dynamic responses to weather conditions and solar position and incidence angles. These high-resolution field measurements provide valuable empirical data to feed bifacial performance models and inform material selection decisions for commercial-scale installations. The results demonstrate that engineered reflective surfaces can significantly enhance rear-side irradiance. Specifically, the geomembrane shows promise for long-term photovoltaic applications due to its combination of superior optical performance and the anticipated durability inherent to the material, though this long-term characteristic was not explicitly measured in this study. This durability is generally expected to surpass that of the reflective films.

4. Conclusions

This work successfully establishes a comprehensive, field-validated methodology for empirical albedo evaluation that integrates long-term datasets, spectral albedo and sky condition analysis, thereby providing a robust framework adaptable to diverse geographical locations and a wide array of natural or engineered surface materials. This study confirms that rigorous field-based albedo characterization, facilitated by the developed dedicated instrumentation, is essential for optimizing bifacial PV system performance and addressing the growing market need for accurate bifacial modeling. The white geomembrane emerged as the most promising solution, delivering up to 79% reflectivity (reference cell), substantially outperforming films and natural surfaces. Its performance proved stable under diverse real-world conditions.

Analysis segregated by the clear sky index (**k**$_c$) revealed distinct behavior, notably the albedo reduction for natural ground types under cloudy days, possibly associated with the impact of soil moisture on reflectivity. The soiling analysis further highlights the critical need for continuous monitoring, demonstrating that the accumulation of dirt can lead to measurable degradation in reflectivity of engineered surfaces, which is promptly recovered following cleaning events.

The comprehensive conjoint temporal analysis of both natural and engineered surfaces, based on 414 consecutive days of data evaluation for the grey gravel and 216 days for the white film, suggests that a mandatory one-year monitoring window for albedo validation may not be strictly necessary for stable ground surfaces, given the minimal seasonal influence observed in the measurements. Particular attention should be given to surfaces susceptible to vegetation growth and to reflectivity variations induced by soil moisture (in natural surfaces) or by soiling (in white films and geomembranes). These results support the efficiency of utilizing shorter evaluation periods for similar surfaces, provided that known temporal variability factors are effectively mitigated or monitored.

The results provide actionable data for system designers, with high reflective films and geomembranes showing high potential for enhancement of bifacial PV plant performance. However, further research should focus on long-term durability, environmental impacts, soiling mitigation, and site-specific economic considerations.

5. Acknowledgments

This research was carried out within the scope of the activities of the National Institute for Technological Development of Photovoltaic Solar Energy Applications, INCT-DAESF, CNPq/MCTI/Brazil, Process 408486/2024-4. The authors wish to acknowledge CTG Brasil for the financial support for this study through project PD-10381-0620/2020, conducted in partnership with SENAI-RN ISI-ER and UNESP-Ilha Solteira as part of the Research, Development, and Innovation (RDI) program of the Brazilian Electricity Regulatory Agency (Agência Nacional de Energia Elétrica - ANEEL). The authors also wish to acknowledge AzulPack TechReflex for supplying the high-reflectivity films and geomembrane used in this study.

6. References

Dittmann, S., Sanchez, H., Burnham, L., Gottschalg, R., Oh, S.-Y., Benlarabi, A., Figgis, B., Abdallah6, A., Rodriguez, C., Rüther, R., Fell, C., 2019. Comparative Analysis of Albedo Measurements at Multiple Sites Worldwide. Presented at the 36th European Photovoltaic Solar Energy Conference and Exhibition, Marseille.

IEA PVPS, 2021. Bifacial Photovoltaic Modules and Systems: Experience and Results from International Research and Pilot Applications (No. International Energy Agency Photovoltaic Power Systems Programm, Task 13, 2021.). https://doi.org/10.2172/1779379

VDMA, 2025. ITRPV 16th Edition - International Technology Roadmap for Photovoltaic. VDMA.