Thermal Modeling of Bifacial PV Modules on High-Albedo Surfaces

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Abstract

This work experimentally evaluates three steady-state temperature models—Ross, Faiman, and PVsyst®—for bifacial photovoltaic modules installed over surfaces with markedly different albedo levels. Measurements were carried out at a controlled PV pilot plant in southern Brazil, featuring highly reflective geomembranes and conventional gravel. Both front-side and effective irradiance inputs were tested, and model coefficients were tuned using field measurements. The results demonstrate that the Faiman/PVsyst® formulation achieves superior accuracy compared to the Ross model, especially under high-albedo conditions. Site-specific calibrated coefficients significantly improved temperature-prediction accuracy, while default commercial parameters produced notable deviations, particularly for bifacial modules. These findings reinforce the need for adjusted thermal parameters for high-albedo environments and for different PV module technologies, providing guidance for improving thermal modeling practices and energy-yield simulations of bifacial PV systems.

Keywords: Bifacial PV modules, thermal modeling, geomembrane, albedo, temperature estimation

1. Introduction

Accurate estimation of photovoltaic (PV) module temperature is essential for reliable performance prediction, particularly in scenarios with high irradiance and demanding operating conditions. Classical steady-state thermal models such as those proposed by Ross (1976), Faiman (2008), and PVsyst® (2023) are widely adopted in simulation tools and academic studies due to their simplicity and practical applicability. However, these models were originally conceived for monofacial systems and therefore do not explicitly account for the unique thermal behavior of bifacial photovoltaic modules, which absorb solar irradiance on both front and rear surfaces. With bifacial modules surpassing 90% of global PV deployment in 2024 (ITRPV, 2025), there is growing interest in adapting and validating thermal models for this technology, especially considering its increasing use in modern PV plants.

Recent research has demonstrated that default thermal-loss coefficients available in commercial simulation software can result in significant discrepancies in module temperature estimation when applied to bifacial systems, particularly under conditions of enhanced rear-side irradiance (Leonardi et al., 2021; Mannino et al., 2022). The presence of high-albedo surfaces such as sand, gravel, and engineered geomembranes—intensifies rear irradiance contribution, potentially altering thermal equilibrium and challenging the applicability of conventional coefficients. Studies have suggested that adjusting model coefficients and incorporating effective irradiance, rather than front-only irradiance, can substantially improve prediction accuracy (Kirsten Vidal de Oliveira et al., 2025). Nevertheless, experimental validation of these approaches remains limited, especially with real operating data collected under well-controlled surface-albedo conditions. This gap underscores the need for field-based investigations capable of capturing the coupled effects of irradiance distribution, albedo, and environmental variables.

This work presents an experimental validation and comparative assessment of the Ross, Faiman, and PVsyst®

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models applied to bifacial modules operating under distinct albedo scenarios in southern Brazil. The analysis is based on high-resolution measurements from a dedicated pilot site equipped with single-axis trackers, bifacial glass-glass modules, and multiple reflective ground surfaces, including high-reflectivity geomembranes and regular gravel. Temperature estimates from the models are compared to field measurements using front-only and effective irradiance inputs, and thermal coefficients are calibrated through linear regression using measured data. The objective is to evaluate the models' ability to represent the thermal behavior of bifacial PV systems under varying albedo conditions and to identify parameter configurations that support more accurate thermal and energy-yield modeling for utility-scale applications.

2. Methods

This study was conducted at a PV pilot plant in Florianópolis, Brazil (27.43°S, 48.44°W), under humid subtropical climate conditions (Fig. 1). The facility includes six independent PV systems, four of which are single-axis trackers equipped with bifacial N-type glass-glass modules. In this work, data were analyzed for systems installed over distinct ground surfaces, including high-reflectivity geomembranes (albedo ≈ 0.53 and albedo ≈ 0.54), sand (≈ 0.41) and regular grey gravel (albedo ≈ 0.26), enabling comparison of thermal behavior under different rear-side irradiance conditions. The data were also compared to a previous study that analyzed the same pilot plant when installed with P-type modules over natural surfaces with varying albedo, including sand (≈ 0.41), kaolin (≈ 0.43), and white gravel (≈ 0.52) (Kirsten Vidal de Oliveira et al., 2025).

Figure 1: Aerial view of the PV pilot plant at UFSC, showing bifacial PV trackers installed over gravel (top of the image) and geomembrane Surfaces.

Temperature sensors (PT1000 Class A) were affixed to the rear surface of representative modules using IEC compliant methods. Each tracker is equipped with pyranometers (EKO MS-80S) and reference cells (IMT Si) mounted in the plane of the array and behind the modules, capturing front and rear irradiance separately. Ambient temperature and wind speed were monitored using calibrated sensors installed at 2 m height, with data acquisition every second and subsequent averaging to 1-minute resolution.

Three temperature models were implemented using the PVLib library in Python: Ross (1976), Faiman (2008), and the PVsyst® steady-state model (PVsyst, 2023).

The Ross Model (Ross, R. G. Jr., 1981), a more traditional approach, was applied using eq. (1) below:

$$T_R = T_a + k \times G \qquad \text{(eq. 1)}$$

In this equation:

- T_R is the cell temperature in °C;
- Ta is the ambient temperature in °C;
- K is is the Ross coefficient in °C/(W/m²);
- G is the irradiance incident on the module plane in mW/cm².

The Faiman Model uses an empirical heat-loss factor approach (Faiman, 2008) and is adopted in IEC performance standards. The corresponding eq. (2) is defined as follows:

$$T_F = T_a + \left[\frac{G}{(U_0 + U_1 v)}\right] \qquad \text{(eq. 2)}$$

Where:

- T_F is the module temperature in °C;
- Ta is the ambient temperature in °C;
- v is the wind speed in m/s;
- G is the irradiance incident on the module plane in W/m²;
- U0 is the constant heat-loss coefficient of the module in W/m².°C ;
- U1 is the coefficient accounting for the effect of wind in Ws/m³.°C .

U0 and U1 are coefficients that depend on the system mounting configuration and are calculated through linear regression using measured irradiance, ambient temperature, and module temperature data. This procedure is followed in this study, and the coefficients are determined for each time-interval configuration. The cell-temperature model used in the PVsyst software (PVsyst, 2023) has a structure similar to the Faiman model, with additional parameters related to efficiency and absorption, as defined in eq. (3):

$$T_P = T_a + \left[\frac{(\alpha G(1 - \eta_m))}{(U_c + U_v v)}\right] \qquad \text{(eq. 3)}$$

Where:

- T_P is the module temperature in °C;
- Ta is the ambient temperature in °C;
- v is the wind speed in m/s;
- G is the irradiance incident on the module plane in W/m²;
- Uc is the constant heat-loss coefficient of the module in W/m². °C ;
- Uv is the coefficient accounting for wind-driven heat loss in Ws/m³. °C ;
- α is the solar irradiance absorption coefficient, with a standard value of 0.9;
- ηm is the PV module efficiency. In this work, the efficiency used was the manufacturer's datasheet value under STC without bifacial gain (standard), 20.8%.

For each model, two irradiance scenarios were tested:

- **Front-only irradiance (Gfront):** traditional modeling approach.
- **Effective irradiance (Geff):** front irradiance plus rear irradiance weighted by the module bifaciality factor (0.8 for n-type, according to the manufacture's datasheet).

The thermal-loss coefficients of the models (k, U0, U1, Uc, Uv) were determined through linear regression using measured irradiance, ambient temperature, and module temperature data. In PVsyst, Uv is set to zero by default, due to the limited availability of high-quality, high-frequency wind-speed data and because wind measurements are typically taken at higher elevations and open-field environments, which may not accurately represent PV system operating conditions.

In this work, we evaluated different thermal-loss coefficient configurations for comparison:

- • Uc and Uv obtained through linear regression using measured data — in this case, the resulting temperatures match those of the Faiman model (Anderson, Kemnitz, and Boyd, 2021);
- Uv=0 Ws/m³. °C and Uc obtained through regression, to isolate the effect of wind speed on temperature estimation in PVsyst;

- Uc=29 W/m². °C and Uv=0 Ws/m³. °C, the default values recommended by PVsyst for ground-mounted systems;
- Uc=40 W/m². °C and Uv=0 Ws/m³. °C, values commonly suggested by manufacturers for simulating glass-glass bifacial modules.

The performance of the models was assessed by comparing estimated temperatures with measured values using Mean Absolute Error (MAE), Root Mean Square Error (RMSE). This analysis was carried out separately for each surface condition and at multiple temporal resolutions (15, 30, and 60 minutes). All data were filtered for quality assurance, including exclusion of events such as system maintenance or sensor faults.

3. Results

3.1 Time-Resolution Effects on Model Accuracy

Fig. 2 presents the MAE values obtained for the Ross and Faiman/PVsyst® models under different albedo conditions (0.26 and 0.58) and temporal resolutions (15, 30, and 60 minutes), using only front-side irradiance as model input. The thermal coefficients obtained from linear regression were used for the calculations. As PVSyst and Faiman models produce the same output when adjusted coefficients are used, they are presented together. As expected, the models performed better at lower temporal resolutions due to their steady-state nature. Nonetheless, performance remained stable even at 15-minute intervals, with MAE values below 4 C in all cases.

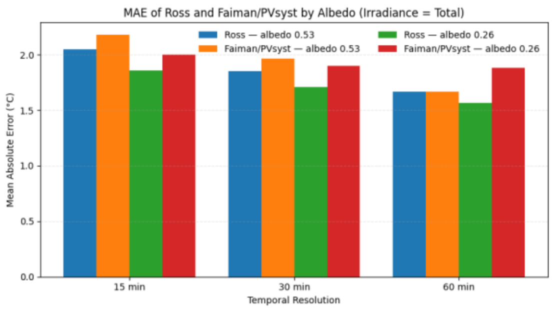

Fig. 2: (Left) MAE of Ross and Faiman/PVsyst® models under different time resolutions and albedo conditions using frontside irradiance only.

For both albedo conditions, the Faiman/PVsyst® and Ross models showed comparable accuracy, with similar estimation errors. The use of calibrated coefficients based on field data contributed significantly to reducing the estimation errors, highlighting the importance of location-specific model tuning. The Ross model showed higher sensitivity to albedo variation, with MAE decreasing as albedo decreased.

3.2 Influence of Irradiance Inputs and Thermal Coefficients

Fig. 3 presents the MAE values for the Faiman and PVsyst® models under different albedo conditions and irradiance inputs, while Table 1 presents the corresponding thermal coefficients (U0, Uv and Uc obtained for each case, based on 1-hour-resolution data. The comparison between front-only and effective irradiance scenarios shows that incorporating rear-side irradiance (effective G) leads to systematically higher thermal loss coefficients (U0 and Uc) and lower errors. For example, the PVsyst® model under albedo 0.53 showed a Uc of 21.01 W/m²·°C for front-only irradiance and 33.5 W/m²·°C when using effective irradiance—both different from the default of 29 W/m²·°C.

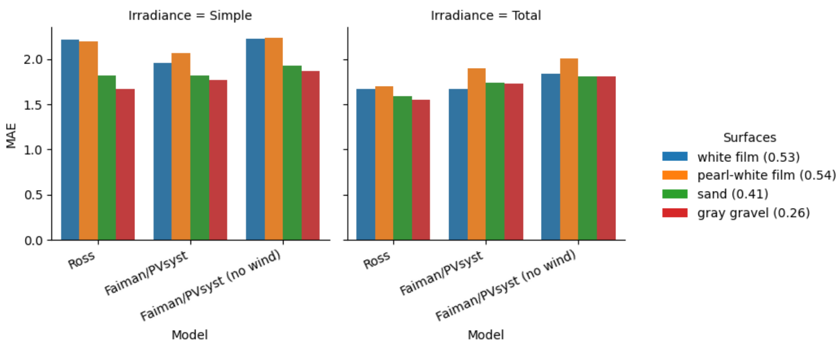

Fig 3: MAE for Faiman and PVsyst® models under different albedo values and irradiance inputs (front-only and effective).

Interestingly, most of experimentally derived coefficients—particularly those from the Faiman model—are considerably higher than the literature ranges. While literature values typically range between 24 W/m². °C and 27 W/m²·°C for U0, values measured in this study reached up to 54.93 W/m²·°C. These results underscore the limitations of using standard thermal parameters in commercial tools like PVsyst® when modeling bifacial modules over high-reflectivity surfaces. It is also visible that the values vary according to the albedo of the surface.

Table 1: Thermal coefficients U0, Uv, and Uc obtained for Faiman and PVsyst® models under different albedo values and irradiance inputs (front-only and effective), based on 1-hour resolution data.

		Faiman			PVsyst		
	Albedo	$U0$	$U1$	$U0$ **when** $U1$**=0**	Uc	Uv	Uc **when** Uv**=0**
Front irradiance	0.26	43.86	5.53	54.95	31.07	3.92	38.92
	0.53	30.05	4.72	39.51	21.01	3.30	27.63
Effective irradiance	0.26	47.3	5.62	58.55	33.5	3.98	41.47
	0.53	38.53	4.6	47.74	26.94	3.21	33.38
Literature Values		24 to 27	6 to 8		29 (mono) or 40 (bifacial)	0	29/40

Fig. 4 shows the thermal loss coefficient Uc obtained through linear regression from PVsyst®-type modeling, plotted against surface albedo. Only front-side irradiance was considered in the simulations, with wind influence disregarded (Uv=0 Ws/m³. °C). The values for P-type modules were derived from a previous study conducted on the same pilot plant under natural ground surfaces (Kirsten Vidal de Oliveira et al., 2025), while the N-type data correspond to the current analysis over high-reflectivity geomembranes. A consistent decreasing trend in Uc with increasing albedo is observed for both technologies, suggesting enhanced thermal dissipation under more reflective conditions.

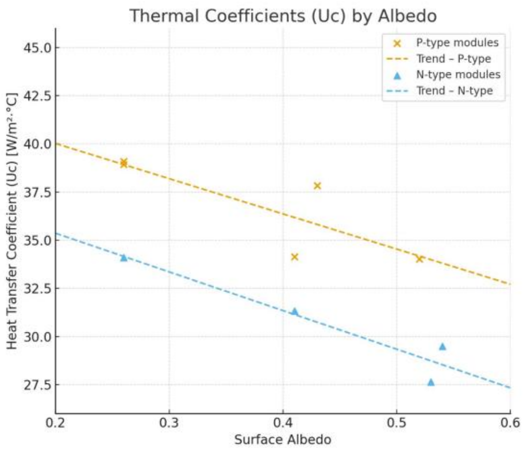

Fig.4: Heat transfer coefficient Uc derived from PVsyst®-type modeling with Uv=0, plotted against ground albedo.

Figure 5 summarizes the PVsyst model performance under four thermal-coefficient scenarios:

(i) Uc and Uv derived from linear regression;

(ii) Uv=0 Ws/m³. °C and Uc from regression;

(iii) Uc=29 W/m². °C and Uv=0 Ws/m³. °C (PVsyst default for ground-mount); and

(iv) Uc=40 W/m². °C and Uv=0 Ws/m³. °C (manufacturer-recommended for bifacial glass-glass).

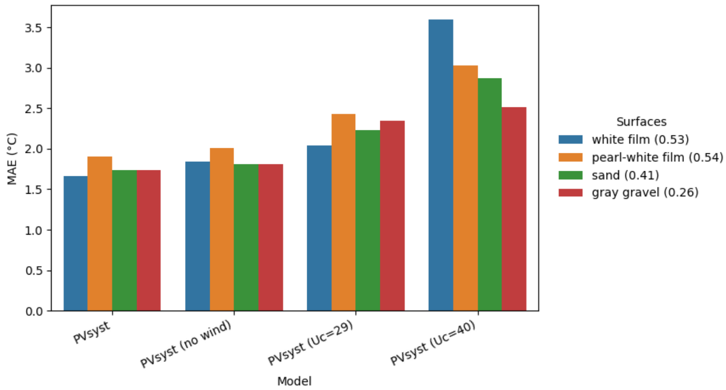

Figure 5: MAE for different coefficient strategies.

The results demonstrate a clear trend: the lowest temperature-estimation errors were consistently obtained when the coefficients were obtained via linear regression. This confirms that site-specific calibration provides the most accurate representation of module thermal behavior, especially for bifacial systems operating under enhanced rear-side irradiance conditions.

When default values were evaluated, the PVsyst standard coefficients (Uc=29 W/m². °C, Uv=0 Ws/m³. °C) resulted in higher errors. The manufacturer-recommended value (Uc=40 W/m². °C) produced even larger deviations, indicating that adopting a generic “bifacial value” does not necessarily ensure improved accuracy. Instead, the optimal Uc value depends on technology and installation configuration.

These findings highlight that thermal performance in bifacial systems cannot be reliably represented using fixed default coefficients, and that the model strongly benefits from regression-based fitting using on-site measured temperatures and irradiance inputs.

A comparison between the regression cases with and without the wind-dependent term (Uv) shows that wind speed had minimal impact on temperature estimation accuracy. The difference between using Uc only versus both Uc and Uv was negligible across all albedo and technology conditions.

This suggests that, for the operational conditions of this plant, convection effects were limited relative to radiative gains, and simplified thermal modeling with Uv=0 Ws/m³. °C is feasible without compromising accuracy.

This aligns with PVsyst's practice of defaulting Uv to zero, but here it is validated experimentally for bifacial trackers under high-albedo surfaces, reinforcing the suitability of using only a single fitted thermal coefficient.

3.3 Module technology comparison: p-type vs n-type

The comparison between p-type and n-type modules (Figure 4) reveals a distinct inversion in optimal coefficient behavior. In previous measurements with p-type modules, simulations using Uc = 40 W/m². °C yielded lower errors than Uc = 29 W/m². °C. In the present study with n-type modules, the opposite occurred — Uc = 29 W/m². °C resulted in smaller errors than Uc = 40 W/m². °C. This indicates that the thermal behavior of the modules is technology-dependent, influenced by both cell type and installation configuration.

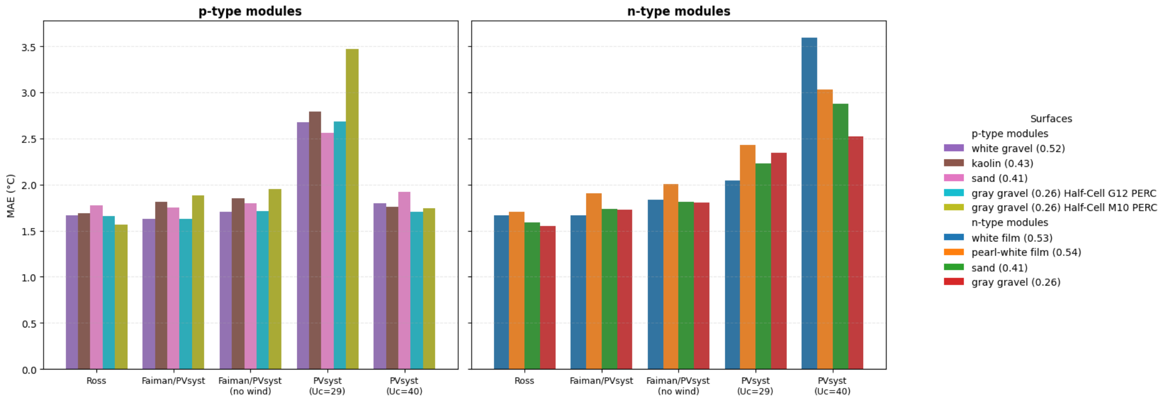

Figure 4: Performance for different cell technologies.

For the models using the coefficients obtained through linear regression, the estimation errors were similar for both module technologies. However, when using the fixed coefficient Uc = 40 W/m². °C for n-type modules, the errors increased, particularly under higher-albedo conditions. These results reinforce that site- and technology-specific calibration provides the most accurate representation of module temperature and should be preferred over default or manufacturer-recommended coefficients.

4. Conclusions

This study evaluated the performance of PV module temperature models under multiple thermal-coefficient strategies, focusing on bifacial systems installed over high-albedo surfaces. Overall, the coefficients obtained through linear regression produced the lowest temperature-estimation errors, outperforming all default parameter sets. The influence of wind speed was minimal, confirming that setting Uv=0 does not compromise model accuracy.

For bifacial n-type modules, the default PVsyst coefficient Uc=29 W/m². °C performed better than the manufacturer-recommended value of Uc=40 W/m². °C. The results also revealed that the optimal thermal coefficient depends on the cell technology: while Uc=40 W/m². °C favored p-type modules, Uc=29 W/m². °C yielded smaller errors for n-type modules. Despite these differences, regression-based coefficients consistently provided the most accurate temperature estimates for both technologies.

In summary, the findings demonstrate that site-specific calibration is essential for accurate thermal modeling of bifacial PV systems. Relying solely on fixed default coefficients may introduce unnecessary errors in both temperature and energy predictions. Incorporating field-derived parameters can substantially improve the reliability of performance estimates for emerging bifacial PV technologies.

5. Acknowledgments

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