Reduced Uncertainties in CdTe Performance Characterizations

Daniel Zirzow
GroundWork Renewables, Inc.

Outdoor Performance Measurements with Measured Spectral Data

Statement of Problem

Outdoor PV performance evaluation depends on accurate spectral correction, but standard practice relies on parameterized empirical models that compress full atmospheric state into a handful of parameters. Using measured spectral irradiance data improves the consistency of spectral corrections compared to empirical models.

- Empirical models (those incorporated into pvlib[3], PVsyst and other modeling software, e.g. pvlib spectral_factor_*) often take only a few inputs such as PW and airmass. However, aerosol optical depth (AOD), aerosol type, and other site conditions that dictate SED shape may be absent. These models are commonly adopted by the industry during capacity testing and other performance monitoring.
- CdTe and other thin-film technologies are spectrally selective and require high-fidelity corrections to the measured broadband irradiance.

Methodology

Comparison of string-level module performance analysis using calculated spectral mismatch factors (MMF) against empirical spectral correction methods and spectrally matched reference modules at the GroundWork PVTL in Albuquerque.

1. Measurement & filtering

- Spectrafy SolarSIM-G filtered-photodiode spectroradiometer, 280–1200 nm at 1 nm resolution.
- Co-located MET station: GHI, POA, TAmb, RH [%], atmospheric pressure, tracker angle, etc.
- Data measured at 15-second intervals, rolled into 1-minute averages.

2. SMARTS 2.9.5 Atmospheric Parameter Retrieval

- The native wavelength range of the spectrometer is 280-1200 nm. The class A pyranometer used in this work was spectrally sensitive from 280 to 2800 nm. The IR “tail” needs to be modelled.
- Fit measured spectrum over the 700–1200 nm window where H_2O bands (720, 820, 940, 1130 nm) and NIR continuum slope separate AOD from PW
- Three free parameters: airmass, precipitable water (Gueymard 1994 from TAmb, RH[%]), aerosol optical depth (AOD). Other parameters (e.g. ozone) remain fixed.
- Levenberg–Marquardt based optimizer fits spectral shape, decoupled from absolute calibration between spectrometer and pyranometer. A bounded scale factor is included to account for calibration offsets between sensors. Calibration differences appear as a step-function discontinuity in the spectrum at 1200 nm.
- Levenberg–Marquardt least_squares fitting method used.

3. Spectrum stitching (280–2800 nm)

- SolarSIM-G measured data retained for 280–1200 nm.
- SMARTS best-fit parameter spectrum extrapolated to 2800 nm (from 1200 nm and up).

4. Spectral Mismatch Factor Calculation

- MMF calculations per IEC 60904-7 [5] using representative CdTe and PERC spectral response data (PERC analysis not covered in this work).
- Pyranometer spectral response assumed to be flat from 280 to 2800nm.

$$MMF = \frac{\int E_{REF} SR_{REF} d\lambda \int E_{MEAS} SR_{DUT} d\lambda}{\int E_{REF} SR_{DUT} d\lambda \int E_{MEAS} SR_{REF} d\lambda}$$

5. Outdoor Performance Monitoring (String-Level)

- Modules installed outdoors on single-axis trackers. Modules are were operated at MPP, no clipping or curtailment. Measurements of sting level DC voltage, DC current, module temperatures, local MET made at 15-second intervals, rolled up to 1-minute averages. A separate module of the same type as the test modules was installed as an effective irradiance sensor. The follow performance metric was calculated for evaluation:

$$PR = \frac{Pmp_{Temp-Translated}}{Pmp_{Baseline}} \frac{1000\ W/m^2}{G_{Eff}}, G_{eff} = POA_{Broadband} \cdot MMF$$

- Two data periods were selected for analysis, summer (47 days) and winter (63 days).
- Pre-filter: POA ≥ 600 W/m² to exclude near-horizon and cloud-affected periods. Additionally, this is to reduce the need to model the module efficiency losses at low-irradiance.
- Data is aggregated into daily averages for final analysis.

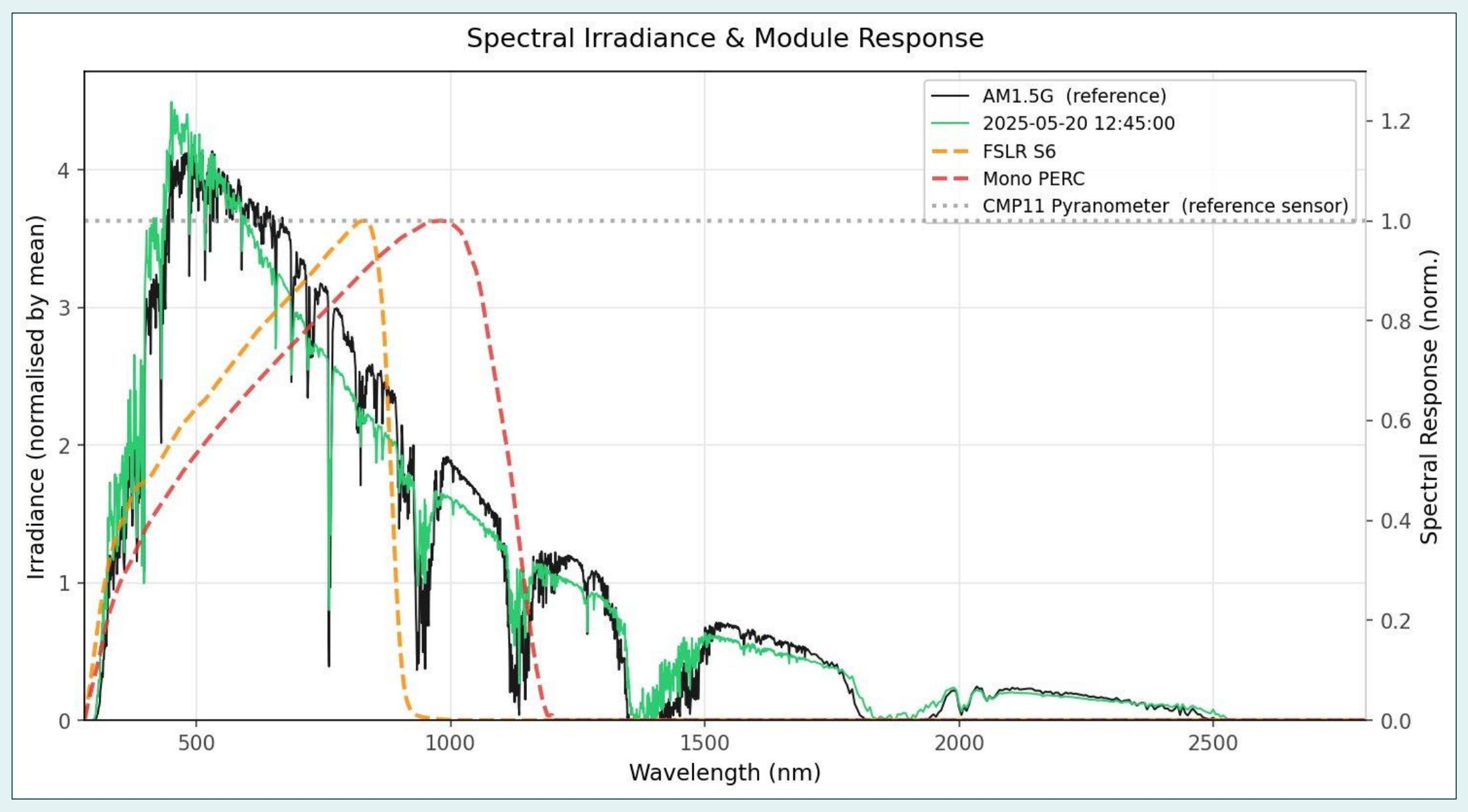

Fig. 1a: Measured field spectrum (2025-05-20) vs. AM1.5G; CdTe (FSLR S6) and mono-Si PERC SR overlaid.

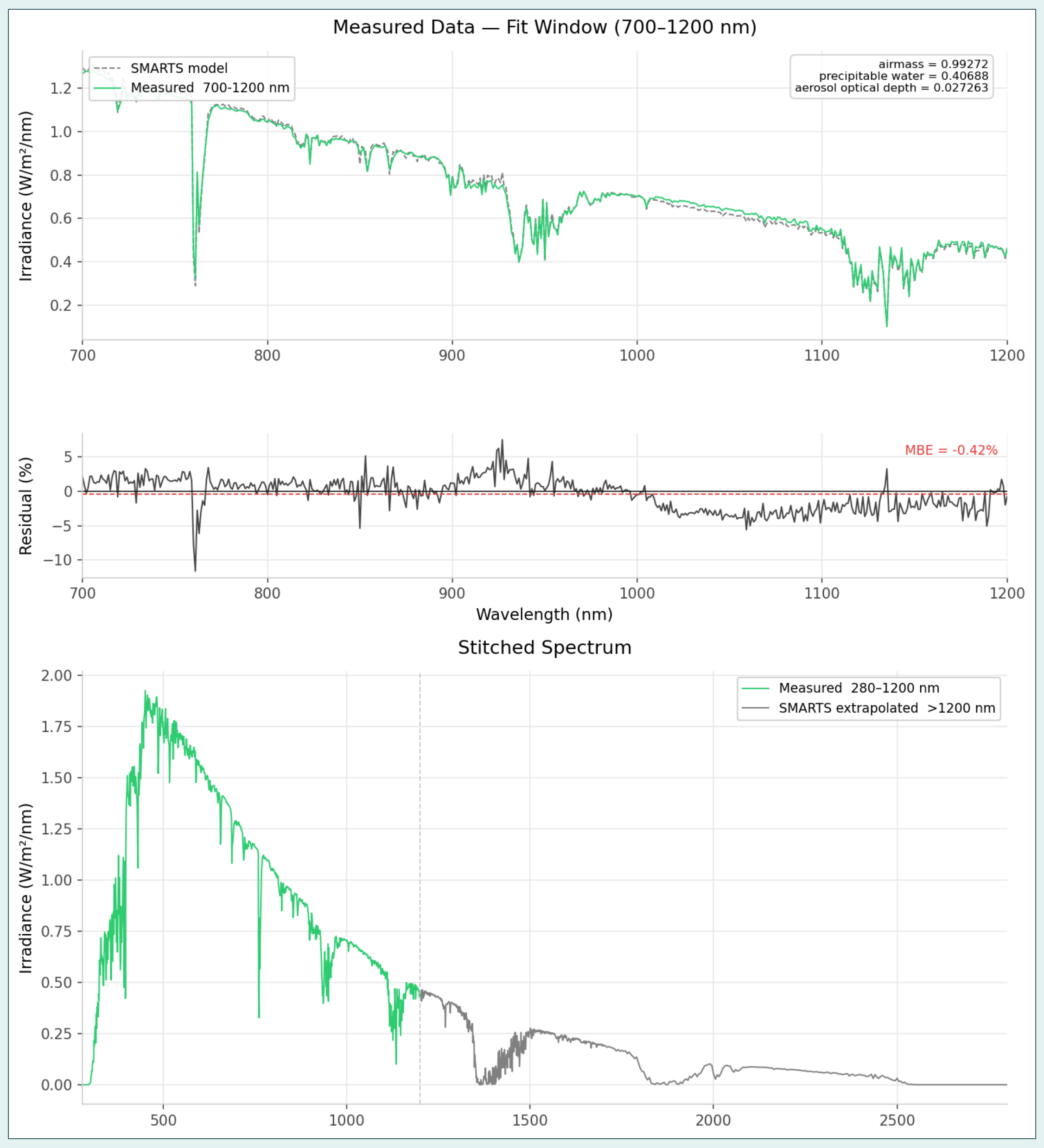

Fig. 1b: SMARTS fit example (2025-05-20). Top: 700-1200 nm fit. Middle: residuals ±5%. Bottom: stitched 280-2800 nm.

Results and Conclusions

The use of measured spectrum data improves the consistency of outdoor string level measurements when compared to parameterized models commonly used. Spectrally matched reference modules remain the most consistent method of effective irradiance measurement. Two CdTe strings were analyzed across non-overlapping summer/winter periods at the GroundWork PVTL. Performance Ratio values were normalized by a 5-day rolling mean of the reference module-derived data: lower daily variance indicates better spectral correction consistency.

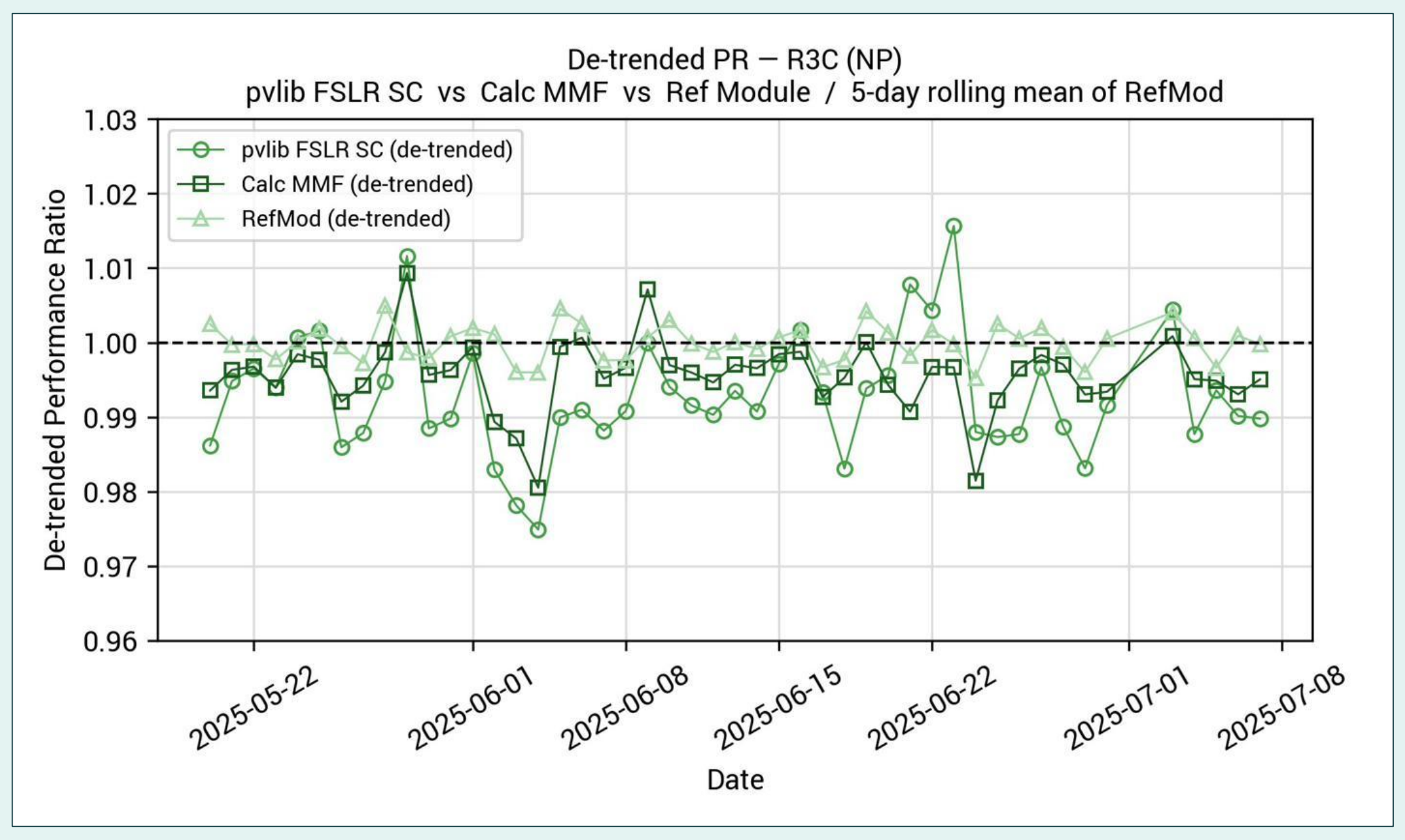

Fig. 1c: Period 1 (Summer, 2025-05-20 to 2025-07-07, n=47 days). High-PW, low-AM regime.

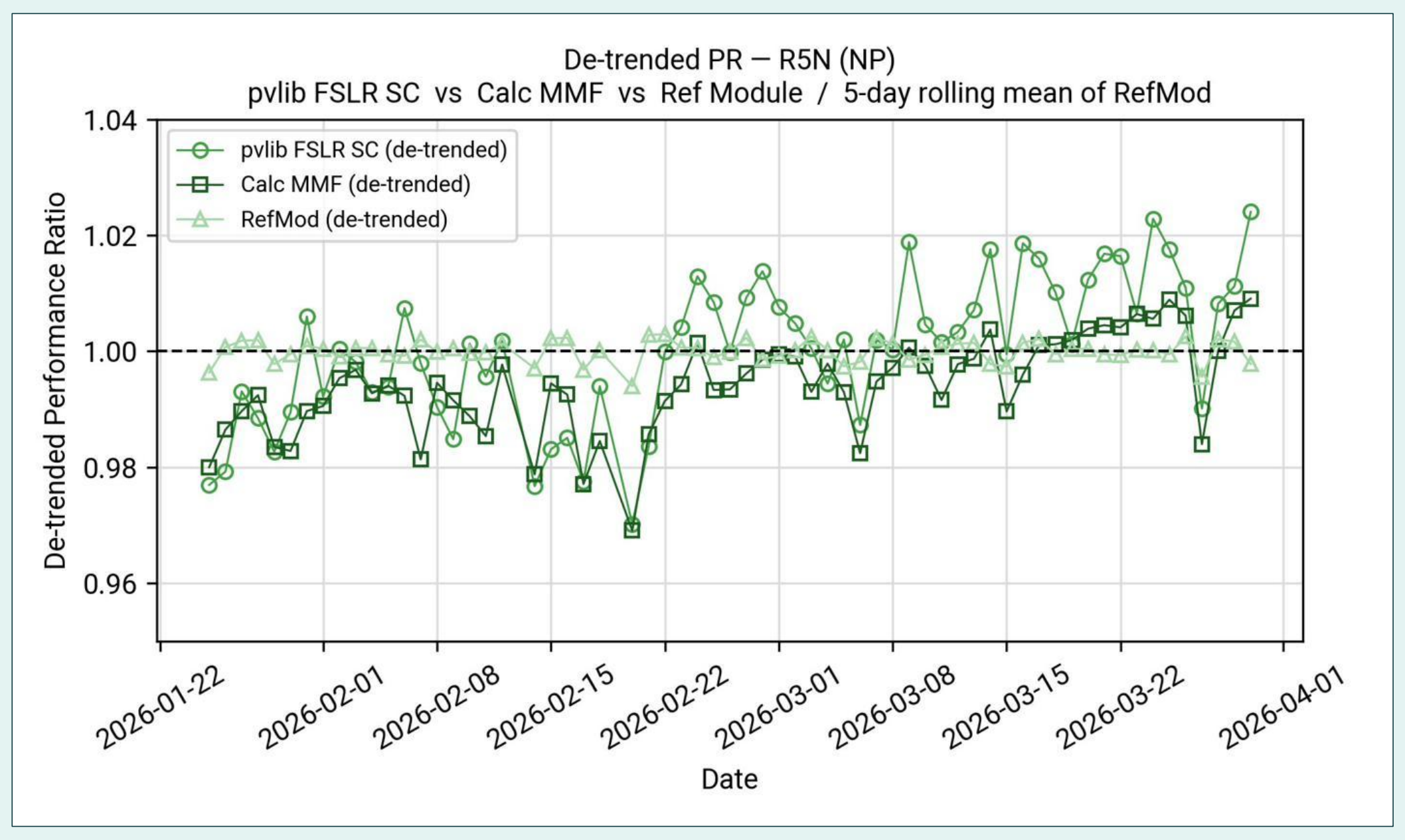

Fig. 1d: Period 2 (Winter, 2026-01-25 to 2026-03-30, n=63 days). Low-PW, high-AM regime. Note the trends present in both spectral correction datasets relative to the reference module-based PR data.

1. Daily PR Statistics

Spectral Correction Method	Moving 5-day PR Average Range and Daily Std. Dev.			
	Period 1 (Range)	Period 1 (Std.Dev.)	Period 2 (Range)	Period 2 (Std. Dev.)
pvlib FSLR SC	2.00%	0.79%	3.41%	1.25%
Calc MMF	**0.93%**	**0.49%**	**2.47%**	**0.84%**
Ref Module	0.20%	0.25%	0.21%	0.19%

2. Spread in 5-Day moving average PR reduced by ~50% by using measured spectrum and calculated MMF over empirical models

Calculated MMF correction halves the 5-day moving average variation relative to pvlib empirical model in summer; improvement is more modest in winter (~28%).
Variability in both the pvlib FLSR model and calculated MMF are both higher in the winter than the summer, though the calculated spectrum still has lower variance.

3. Reference module remains lowest variance method tested.

Reference module derived effective irradiance produces the lowest variance across all methods.
The logistics and calibration challenges around reference modules may offset the improvements in performance (cost, complexity, Isc drift).
Next steps are to perform additional testing with an expanded spectral range (280-4000 nm) to check if the hybrid model fundamentally limits this methodology.

Indoor Characterization of Bifacial CdTe

Statement of Problem

Single-sided illumination per IEC TS 60904-1-2 [1] does not fully capture the bifacial response of CdTe modules under real-world operating conditions.

- Single-side test method derives bifaciality through a simple ratio of rear-side and front-side performance (Isc & Pmp).
- Operating bifaciality may vary with irradiance level, departing from values derived under single-side illumination conditions. Irradiance geometry will also play a role. [2],[4]

Methodology

Following IEC TS 60904-1-2 (2024), both single-sided and dual-sided illumination performed on the same modules for direct comparison.

Single-sided method

- Front-only and rear-only IV sweeps at STC (1000 W/m², 25°C).
- Bifaciality coefficients φIsc, φVoc, φPmax derived ratio of single-sided measurements.

$$\varphi_{Param} = Param_{Rear} / Param_{Front}$$

Dual-sided method

- Simultaneous front + rear illumination in LED simulator.
- Direct measurement of Pmax at varying rear-side irradiance levels (0, 100, 200 W/m²).
- Bifacial gain parameters calculated from linear regression of Pmax and rear-side irradiance.

$$P_{max}(G_R) = P_{max,STC} + \mathrm{BiFi} \cdot G_r$$

$$BiFi_{rel} = BiFi / P_{max,STC}$$

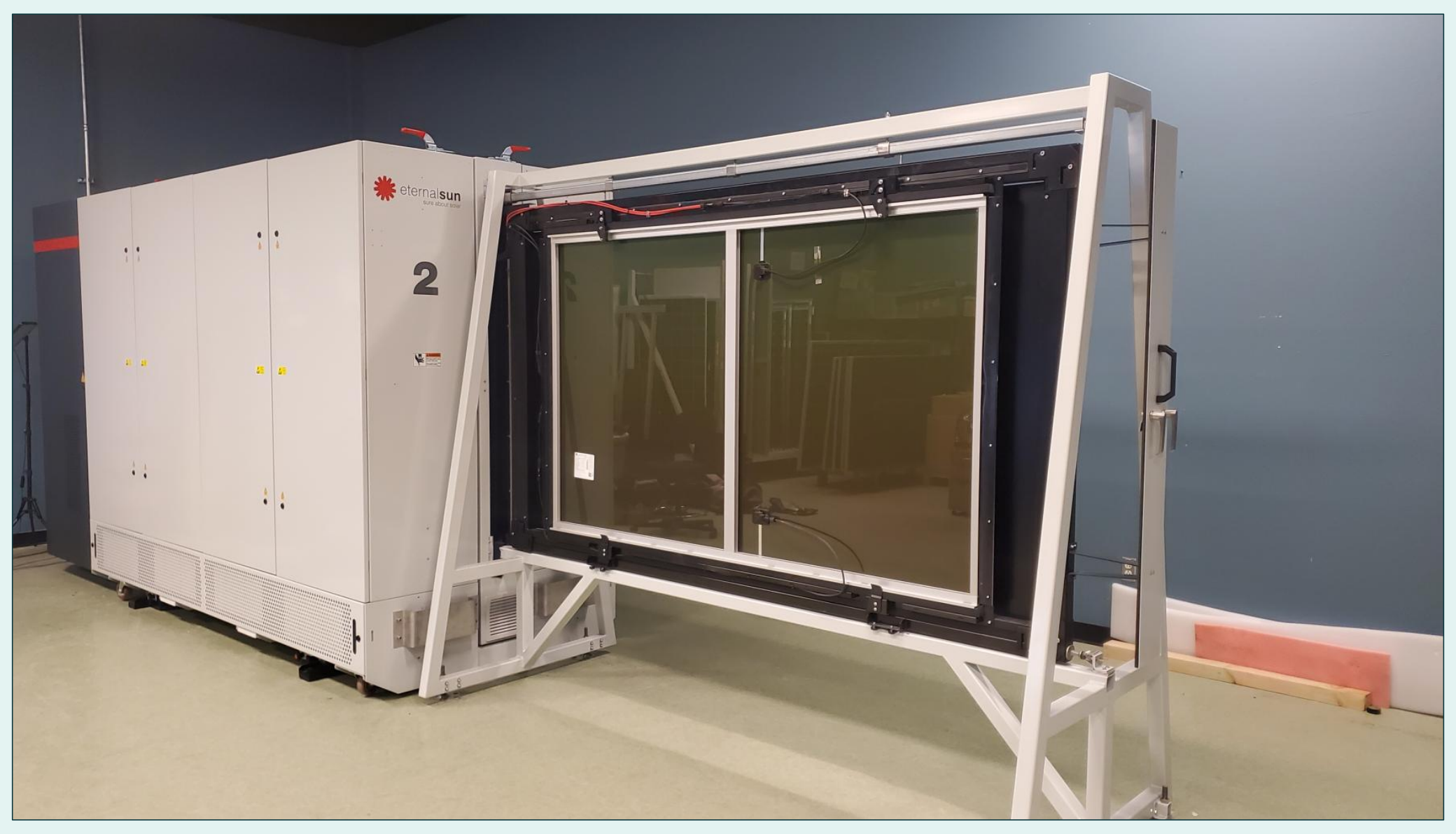

Fig. 2a: Eternal Sun LED solar simulator (enclosed closed chamber, dual-side capable).

Results and Conclusions

Early work suggest that dual-sided illumination is likely a requirement for accurate characterization of bifacial thin-film modules.

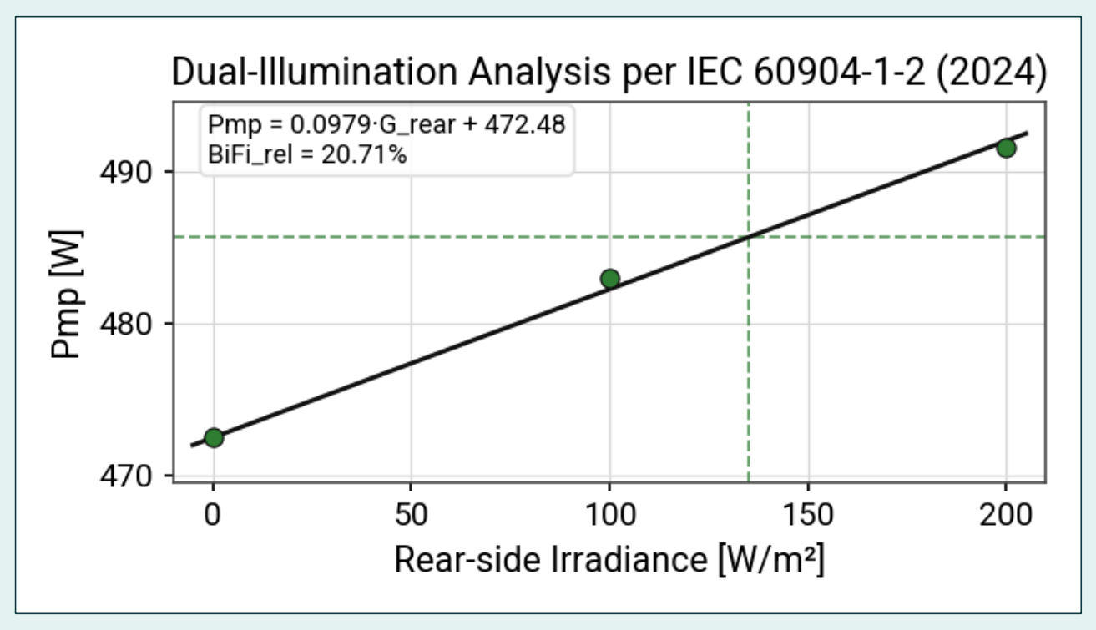

Fig. 2b: Dual-illumination fit per IEC 60904-1-2. Pmp vs. rear irradiance at G_front = 1000 W/m²; slope a yields BiFi and BiFi_rel.

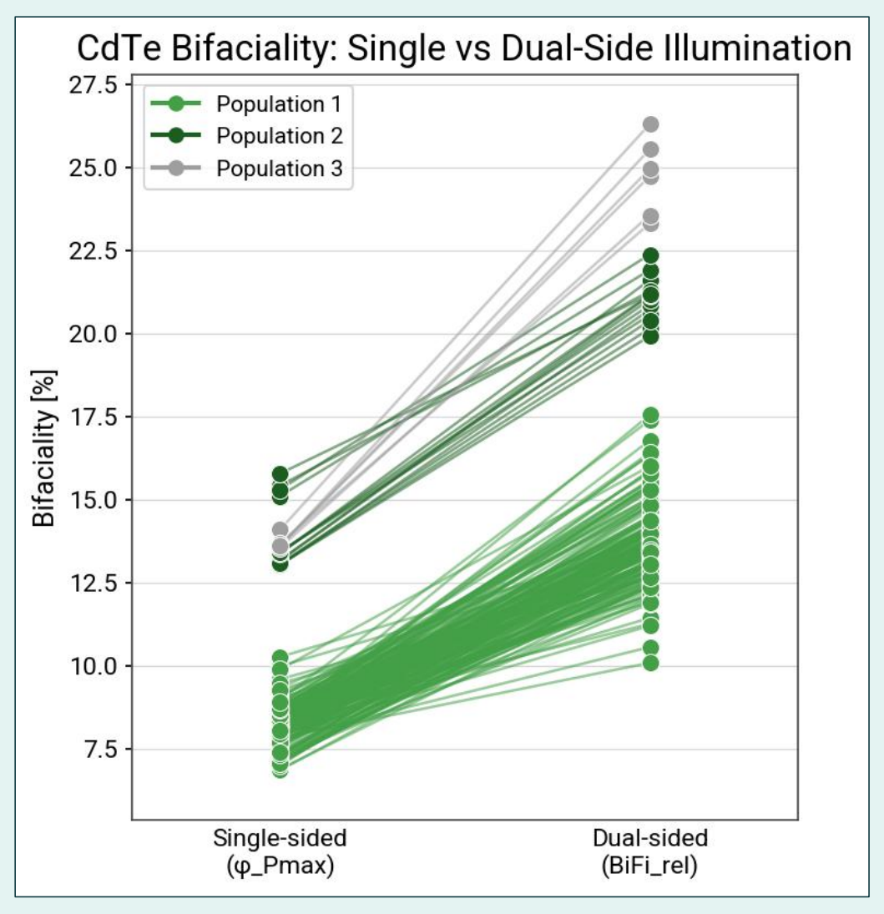

Fig. 2c: Per-module slopegraph — single-sided φ_Pmax (left) vs. dual-sided BiFi_rel (right). Each line is one module across three independent populations.

- Across three independent populations, dual-sided BiFi_rel is consistently and substantially higher than single-sided φ_Pmax for the same modules.
- Effect is systematic and reproducible — not measurement noise.
- Single-sided φ_Pmax samples only two operating points (rear-only, front-only); modules never operate in theses conditions in the field.
- φ_Pmax derived from single-sided measurements is potentially inadequate for screening; insufficient for energy-yield modeling of current-generation bifacial thin-film

References

[1] IEC TS 60904-1-2:2024, “Photovoltaic devices — Part 1-2: Measurement of I-V characteristics of bifacial photovoltaic devices,” 2nd ed., Int. Electrotechnical Commission, 2024.
[2] IEA PVPS Task 13, “Bifacial Photovoltaic Modules and Systems: Experience and Results,” Report T13-14:2021, 2021.
[3] Anderson, K., Hansen, C., Holmgren, W., Jensen, A., Mikofski, M., and Driesse, A. “pvlib python: 2023 project update.” Journal of Open Source Software, 8(92), 5994, (2023). 10.21105/joss.05994
[4] J. C. Sevillano-Bendezú et al., “Evaluation of the bifaciality coefficient of bifacial photovoltaic modules under real operating conditions,” *J. Cleaner Production*, 2023.
[5] IEC 60904-7:2019, “Photovoltaic devices — Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices,” 4th ed., Int. Electrotechnical Commission, 2019.
[6] Gueymard, C. A. (2005). SMARTS Code, Version 2.9.5: User's Manual. Solar Consulting Services, USA.

POWERED BY pvlib