Spectral Correction for Systems with CdTe Modules During the Capacity Test

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Bahram Emami and David Auslender
McCarthy Building Companies, Inc. – Renewable Energy

Abstract

- Earth's atmosphere experiences continual fluctuations in composition impacting atmospheric conditions.
- Photovoltaic modules are tested under a standard spectrum, AM1.5, but outdoor conditions will deviate, affecting module performance.
- Spectral correction, mainly driven by air mass, varies in its impact on different PV technologies[1] and [2].
- Incident light spectrum distribution can cause up to a 6% variation in PV system performance (see Fig. 9), affecting different technologies differently.
- Different photovoltaic technologies, such as CdTe, respond differently to incident light spectrum variations due to diverse spectral responsivities.

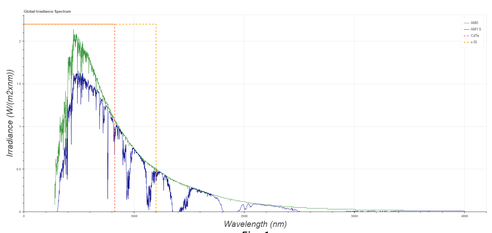


Fig. 1

Capacity Testing

- Capacity testing is a fundamental practice in the solar industry, crucial for assessing system performance pre-completion, with detailed procedures outlined in ASTM E2848-13 standard.
- During capacity testing, system performance is evaluated against a contracted energy model, subject to stringent filtering criteria to eliminate non-linearity, shading, clipping, and similar issues, with irradiance being a key factor considered.
- Pyranometers, measuring the POA irradiance, capture a broad range of wavelengths, but CdTe modules have limitations in converting specific wavelengths into electricity, especially impacted by humidity-induced wavelength absorption.
- The Global irradiance spectrum (ASTM G173) and Quantum Efficiency (QE) curve for CdTe cells demonstrate operational ranges, typically from 280 to 900 nm [6], contrasting with a thermopile pyranometer's broader spectral responsivity (SR) of 280 to 3000 nm.
- This disparity is particularly noticeable when humidity variations result in POA value gains in one dataset and losses in another, highlighting the impact of environmental factors on system performance.
- In short, there is a difference between the measurement of irradiance through POA sensors and the "**Effective POA Irradiance**" that is available for CdTe modules.

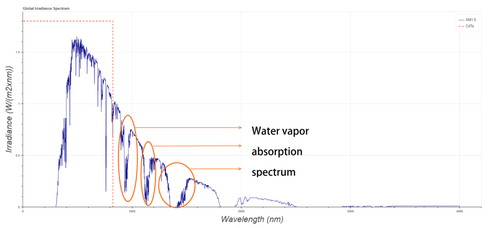


Fig. 2

Spectral Shift Factor

- The spectral shift in CdTe modules is primarily driven by the presence of precipitable water (Pwat), which can be effectively calculated as a function of Pwat.
- In cases where direct Pwat measurements are unavailable, its estimation can be achieved using a formula based on ambient temperature in Kelvin and relative humidity in percentage [3].

$$P_{wat} = 0.1\left(0.4976 + 1.5265\frac{T}{273.15} + e^{\left(13.6897\frac{T}{273.15} - 14.9188\left(\frac{T}{273.15}\right)^3\right)}\right) \times \left(\frac{216.7\,RH}{100\,T} e^{\left(22.33 - \frac{4914}{T} - 10.922\left(\frac{100}{T}\right)^2 - \frac{0.390157T}{100}\right)}\right)$$

- Two methods exist for calculating the Spectral Shift Factor. One method relies solely on Pwat, while the other considers both Pwat and Air Mass (AM).

Method 1- Spectrum Corrections for Precipitable Water Content

- Spectral shift factors for Series 4, and higher, modules can be calculated using specific formulas, allowing for the determination of effective irradiance by multiplying the spectral shift factor to measured Plane of Array (POA) values [4].

$$M1 \approx 1.266 - 0.091e^{(1.199(P_{wat}+0.05)^{-0.21})}$$

$$\text{Effective Irrdiance} = M1 \times POA$$

Method 2 - Spectrum Corrections for Air Mass and Precipitable Water Content

- In this method, the spectral shift factor can be calculated as a function of both Precipitable Water Content (Pwat) and Air Mass (AM) [5].
- This approach can also be applied to c-Si module technology.

$$M2 = b_0 + b_1 \times AM_a + b_2 \times Pwat + b_3 \times \sqrt{AM_a} + b_4 \times \sqrt{Pwat} + b_5 \times \frac{AM_a}{\sqrt{Pwat}}$$

Module	b_0	b_1	b_2	b_3	b_4	b_5
CdTe	0.7946	-0.05423	-0.01319	0.1724	0.08372	-0.004376

- The coefficients for c-Si modules vary.

Comparative Analysis of Spectral Shift Factors - Method 1 vs Method 2

- After conducting a thorough comparison between the spectral shift factors calculated using method 1 and method 2, it became evident that these factors often diverge significantly from each other. This disparity highlights the substantial influence of Air Mass (AM) on the comparison, suggesting that variations in AM can lead to notable discrepancies in the calculated spectral shift factors.
- While the impact of AM on the comparison is apparent, determining which method is more accurate falls outside the scope of this poster.

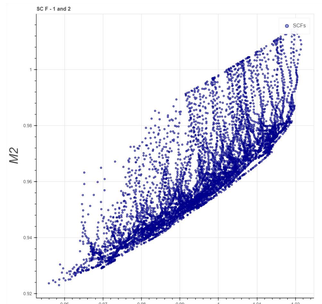


Fig. 3

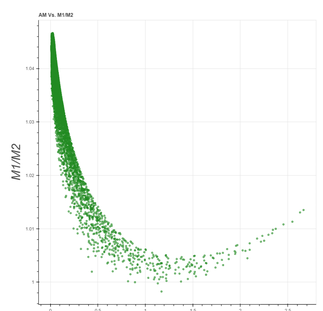


Fig. 4

- Given PVsyst's reliance on Method 2 for modeling spectral shift effects on CdTe module systems' production, employing this method enhances accuracy in calculating the Spectral Shift Factor for Capacity Testing.

Methods For Spectral Shift Correction

Energy Model/Target Capacity:

Using TMY File and First Solar Tool:

- One commonly used method involves running the energy model with spectral shift data using a tool developed by First Solar. This approach calculates spectral shift impact based on hourly data for each month, alongside average soiling loss for each month.
- However, this method has limitations; soiling loss cannot be negative, hindering modeling spectral correction via soiling profiles. Addressing this requires updating module quality loss. Additionally, it simplifies spectral shift effects by grouping all periods in a month under the same conditions, and excluded periods still influence new soiling and module quality losses.

Using Measured Weather Data and First Solar Tool:

- Another approach is to use measured data to update the energy model, employing the same tool to adjust soiling and module quality losses.
- However, this method encounters challenges in obtaining sufficient data points, particularly as MET stations are often commissioned shortly before testing begins. Additionally, data availability and reliability before and after the testing period can be inconsistent.

Using TMY File and Enabling Spectral Correction in PVsyst:

- Utilize the TMY (Typical Meteorological Year) file and enable spectral correction in the energy model, now available in PVsyst v7.0 and newer, to account for spectral shift effects on system production.
- Note that while this method addresses production considerations, it does not refine the accuracy of hourly data for Plane of Array (POA) irradiance.

Using TMY File, Enabling Spectral Correction in PVsyst and Post-Processing POA:

- Our proposed approach involves integrating spectral correction directly into the simulation process. This method computes the spectral shift factor for each period, enabling adjustment of the system's production through the PVsyst algorithm.
- Calculating the spectral shift factor for each period facilitates the determination of effective irradiance, allowing for post-processing of TMY file data to correct the Plane of Array (POA) values. This ensures both spectral shift and irradiance adjustments are accounted for.
- By adopting this comprehensive approach, we can more accurately address the impact of spectral shift on system performance while mitigating the limitations and challenges associated with other methods.

Measured Data/Measured Capacity:

Using Measured Weather Data:

- Utilize raw measured data without alterations for the second dataset, relying on its inherent characteristics.
- However, this approach overlooks the spectral shift's influence on system production, leading to discrepancies between measured POA data and actual system output.

Using Reference Module/Cell Measured Weather Data:

- Incorporating a reference module or cell is proposed as an alternative method to consider the available irradiance for CdTe modules, aiming for improved accuracy.
- However, challenges arise in the calibration process, particularly if not conducted in a laboratory setting, highlighting concerns regarding the selection of the reporting condition.
- Opting for STC as the reporting condition typically yields module/cell irradiance measurements that closely match POA pyranometer measurements under low absolute humidity conditions, aligning with expectations.
- Nevertheless, under high humidity conditions, this choice may result in module/cell irradiance measurements exceeding pyranometer values by up to 4%, highlighting potential overestimation concerns.

Using Measured Weather Data and Post-Processing the Measurements:

- Implement post-processing of measured data through pyranometers as the most effective approach to address the spectral shift effect on POA measurements.
- This method ensures alignment between the system's production and the actual POA irradiance convertible to electricity by the modules.
- By minimizing potential downsides associated with other methods, it offers a more accurate representation of the system's performance.

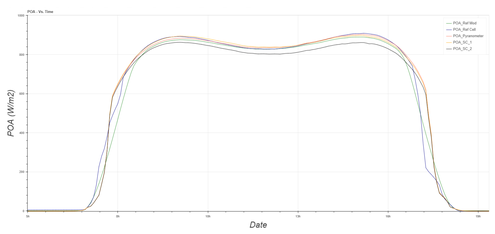


Fig. 5

Conclusion

- Post-process the measured and modeled POA irradiance using the formulas from the Spectral Shift Factor section for efficient and highly accurate consideration of the spectral shift effect and **Effective Irradiance** calculations for CdTe module systems.
- This approach exhibits no downsides and markedly enhances calculation accuracy.
- The proposed approach stands out in comparison to other methods typically employed for spectral correction, as illustrated in the accompanying table, emphasizing its superior accuracy and warranting its strong recommendation for capacity tests.

	Weather File	Spectral Correction Method for Measured POA	Method for Evaluating the Impact of Spectral Correction on Production	Effective POA Irradiance	Production	Note
Target Capacity	TMY File	-	Using First Solar Tool	❗	❗	
	Measured Data - POA Sensors	-	Using First Solar Tool	❗	❗	
	TMY File	-	Using PVsyst Spectral Correction	❗	✔	
	TMY File	Post-Processing	Using PVsyst Spectral Correction	✔	✔	Method proposed in this paper
Measured Capacity	Measured Data - POA Sensors	-	-	❗	✔	
	Measured Data - Reference Modules/Cells	-	-	✔	✔	If the module or cell calibrate in the lab accuracy is high
	Measured Data - POA Sensors	Post-Processing	-	✔	✔	Method proposed in this paper

Legend	
High Accuracy	✔
Low Accuracy	❗

References

- [1] D. King, W. Boyson, and J. Kratochvill, Photovoltaic Array Performance Model, SAND2004-3535. Albuquerque, New Mexico: Sandia National Laboratories, 2004.
- [2] D. King, J. Kratochvill, and W. Boyson, "Measuring solar spectral and angle-of-incidence effects on photovoltaic modules and solar irradiance sensors," in 261h IEEE Photovoltaic Specialists Conference, 1997, p. 1113-1116.
- [3] W. M. Keogh and A. W. Blakers, "Accurate measurement, using natural sunlight of silicon solar cells," Progress in Photovoltaics: Research and Applications, vol. 12, pp 1-19, 2004.
- [4] M. Lee, L. Ngan, W. Hayes, J. Sorensen and A. F. Panchula, "Understanding next generation cadmium telluride photovoltaic performance due to spectrum," 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC), New Orleans, LA, USA, 2015, pp. 1-6, doi: 10.1109/PVSC.2015.7356003.
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- [6] L. Nelson, M. Frichtl and A. Panchula, "Changes in Cadmium Telluride Photovoltaic System Performance due to Spectrum," in IEEE Journal of Photovoltaics, vol. 3, no. 1, pp. 488-493, Jan. 2013, doi: 10.1109/JPHOTOV.2012.2226868.

Comparison

- The following data was collected from the same site over two clear sky days, with a one-day gap between them
- Variations in relative humidity led to a noticeable effect on spectral shift, impacting the **Effective Irradiance**.
- Graphical representations underscore the superiority of post-processing as the preferred method for conducting capacity tests for systems featuring CdTe modules.

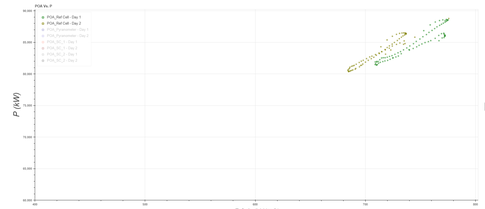


Fig. 6

The spectral shift manifests its effect as underperformance on Day 1 and overperformance on Day 2 when using raw data from POA sensors or Ref Cells

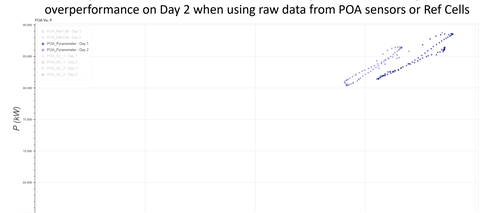


Fig. 7

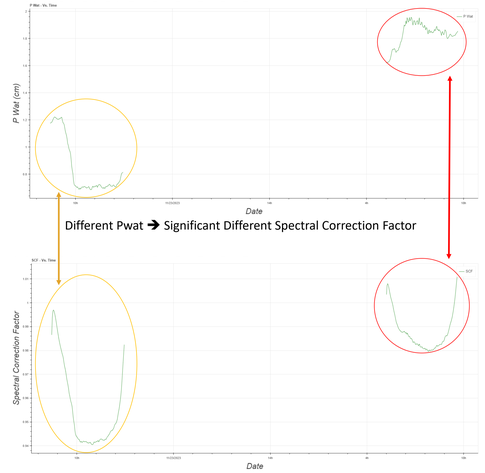


Fig. 8

Fig. 9

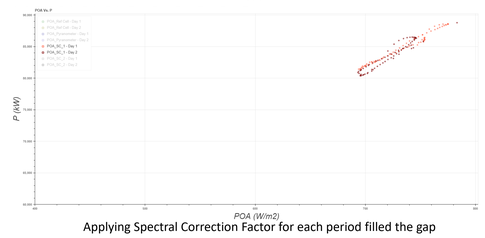


Fig. 10

Applying Spectral Correction Factor for each period filled the gap

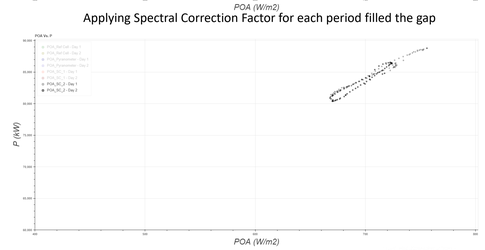


Fig. 11