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MEASUREMENTS MATTER:

CHOOSING THE RIGHT PARTNER FOR IAM CHARACTERIZATION

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Incidence angle modifier (IAM) characterization of solar PV modules is technically challenging, but when experienced labs use proven measurement techniques, custom IAM profiles increase certainty of energy yield forecasts and project valuations to help developers optimize plant valuation.

INTRODUCTION

IAM profiles describe variation in PV module performance as the sun changes position daily and seasonally. The angle of incident sunlight on the module surface impacts solar power generation, especially for PV modules with anti-reflective (AR) coatings.[1] Since default IAM profiles in most modeling tools typically do not account for AR gains properly, solar project developers who rely on defaults often undervalue projects.

This round robin study conducted by PV Evolution Labs (PVEL), EDP Renewables, and Cypress Creek Renewables illustrates the unique technical challenges of IAM characterization. We compared different IAM characterization methods by using six profiles developed by five different labs around the globe to build energy yield assessments of a hypothetical fixed tilt PV project in South Carolina (single central inverter block – 1.7MW). Results from three labs that characterized IAM indoors were within six MWhs of each other, but the other forecasts varied by as much as 108 MWhs. We averaged the forecasts of the three consistent forecasts to produce a "consensus estimate."

We also compared the energy yield estimates derived from IAM profiles to the project's theoretical maximum and minimum energy yields. These limits were calculated by creating a model of an IAM profile through a combination of Snell's Law and the Fresnel equations that describe reflection and transmission of unpolarized light. This process is described in detail later in this paper.

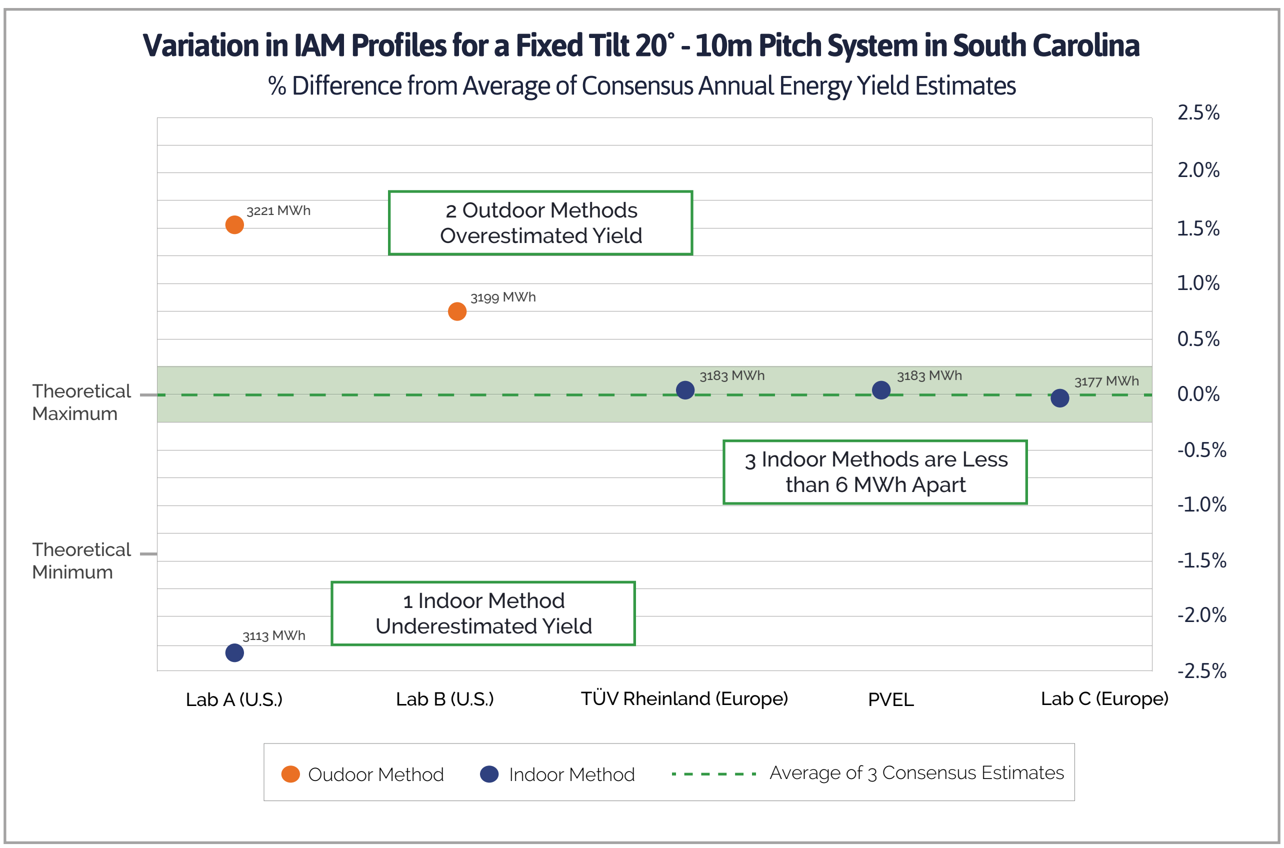

Figure 1: The chart above compares annual energy forecasts based on six different IAM profiles for a single inverter block of a PV power plant in South Carolina rated at 1.7MWac (DC/AC ratio = 1.2). Profiles from three labs using indoor methods produced consistent, similar results. One U.S. lab provided two IAM profiles – one using an indoor method and one using an outdoor method – but both are outliers.

IAM CHARACTERIZATION CHALLENGES

Building an IAM profile experimentally requires measuring the amount of power produced by a module at different incidence angles of sunlight. The test can be conducted indoors or outdoors. In both cases, the module is typically mounted on a rotating mounting structure (like a solar tracker) or a custom mounting system that rotates to change the angle of incidence (AOI). Next, the module is positioned at precise angles in increments of 5 to 10 degrees and exposed to light. Voltage and current are measured at each angle of incidence to acquire the data comprising the IAM profile.

Whether the electrical characterization is conducted inside or outside, the lab must ensure that the solar module is not exposed to stray light rays from other incidence angles. If scattered light from another source such as reflection from the flash tunnel, lab indoor lighting or a white building or car is captured and included in the measured power output, the IAM data will produce an erroneous profile. Including scattered light in the IAM profile typically results in overestimation of energy yield. Similarly, if light from the desired AOI does not reach the solar module due to bulb characteristics or clouds, using the IAM profile results in underestimated energy yield.

Outdoor vs. Indoor Characterization

While possible, outdoor IAM characterization is extremely challenging because appropriate management or measurement of scattered light is so difficult. The test must be conducted during clear conditions[2] , and the following common sources of error must be controlled:

- Reflected light from clouds, cars, nearby ground surface, or buildings and other obstructions
- Reflected light from the atmosphere, horizon and solar corona

There are also testing challenges in a controlled lab environment, but they can be addressed by using the right equipment instead of waiting for ideal environmental conditions, and by following robust quality practices to achieve repeatability.

While there is no interference from clouds, the lab's ambient lighting and angular distribution of the light must be controlled for – if the light spreads out too much or the lab lights add signal, results will not be accurate. The following factors must be considered for an indoor IAM test setup:

- The shape and angular output distribution of the light bulb
- The size of the sample (i.e.: module or cell)
- The distance of the bulb from the sample
- All ambient lighting
- The number of bulbs used

Collimated light sources are expensive, but they are the most direct way to measure IAM. These unique lamps have extremely small bulbs that produce parallel rays. As a result, the rays spread minimally as they travel from the lamp, so they hit the module at precise angles. Using a non-collimated light source with a sufficient distance between the light source and the PV module (e.g., an 8m tunnel), can also result in a very direct method to measure IAM profiles as long as the voltage/current response during the test is acquired from a single cell tapped in the center of the PV module aligned directly with the light source instead of measuring the electrical response from the entire PV module.

In this specific case, the error in the IAM profile resulting from small AOI deviations between the center and the edge of the cell being measured is quite small and insignificant.[3] Both TÜV Rheinland (Europe) and Lab C (Europe) characterize IAM indoors with non-collimated light sources and a long tunnel and have shown successful measurements of IAM profiles that are within expected values and very close to profiles measured by PVEL with a collimated light source.

THEORETICAL LIMITS

We compared the annual energy yield estimate resulting from each lab's IAM characterization to the theoretical maximum and minimums for the project using Snell's Law and the Fresnel equations. The minimum yield limit is calculated by eliminating the AR coating and setting the index of refraction of the glass to a value of 1.7. The maximum yield limit is calculated by setting the index of refraction of the AR coating to a value of 1.25 and the index of refraction for the glass to 1.53. The results of the indoor IAM tests have a striking level of good agreement with the theoretical Fresnel calculation for glass with AR coating.

The model focuses purely on the interface between air, an anti-reflective coating and the glass, but does not consider secondary effects such as sub-wavelength optical interference or light absorption differences in the glass as the incident angle is changed. For reference, a tool is available in PVSyst since version 6.67 to generate IAM profiles using the Fresnel equations/Snell's Law (see Figure 2 below), but it is quite straightforward to do the calculations directly.

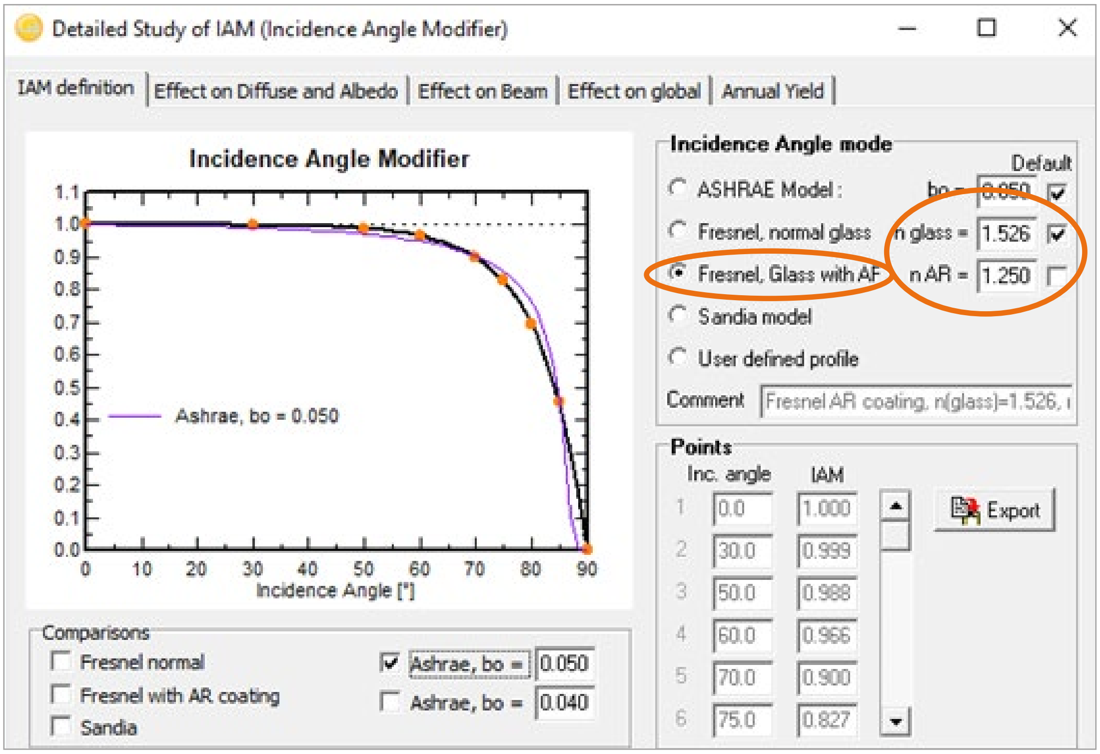

Figure 2: PVsyst tool for theoretical Fresnel calculations

STUDY FINDINGS

Even though all labs adhered to IEC 61853-2 requirements when characterizing IAM profiles, results varied. In general, results from the indoor characterization methods used by PVEL, TÜV Rheinland (Europe), and Lab C (Europe) were closely aligned. Each fell above the expected theoretical minimum values as modeled by the Fresnel equations for glass without an AR coating and within 4 MWh of the theoretical maximum as modeled by Fresnel equations for glass with an AR coating.

Both the indoor and outdoor characterizations performed by Lab A (U.S.) fall far outside the theoretical limits as calculated by the Fresnel equations under the modeled conditions. Lab A's indoor characterization methods drastically underestimated energy yield (~70MWh) relative to the other labs' results while its outdoor characterization method dramatically overestimated energy yield (~40MWh). In both cases, the IAM profile produced by Lab A fell outside the Fresnel theoretical limits described above.

Results from Lab B (U.S.), which also used an outdoor test, were closer to the results from PVEL, TÜV Rheinland (Europe), and Lab C (Europe) than with either of the results from Lab A. It should be noted, however, that while the outdoor IAM test results produced from Lab B (U.S.) deviate less from the consistent indoor test results, they still significantly exceed the theoretical limits based on the Fresnel equations and overpredict annual energy production by almost 1% in the case of the modeled hypothetical fixed tilt system in South Carolina.

While it is quite possible to acquire an IAM profile that is in line with the theoretical limits of the Fresnel equations, the two outdoor-based test results from Lab A (U.S.) and Lab B (U.S.) used in this study result in a material overprediction of the estimated annual energy production far beyond the theoretical physical limits modeled with the Fresnel equations.

These findings call into question the nature of outdoor testing of IAM profiles for PV modules as measured per the current procedures and requirements detailed in the latest version of IEC 61853-2.

BEST PRACTICES FOR DEVELOPERS

The results of this study demonstrate that different labs can produce wide-ranging IAM profiles depending on the characterization method and equipment used to measure performance at different AOIs. Selecting a lab with deep experience and the right equipment is key. While it could be possible to obtain good results from outdoor characterization methods, not one of the two labs employed in this round robin effort were capable of producing IAM profiles within a reasonable uncertainty relative to the maximum theoretical limit produced by modeling an IAM profile for glass with AR coating. It is clear that significant overestimation occurs when scattered light is not controlled.

Using energy production predictive models based on mischaracterized IAM profiles can result in significant deviations in predicted energy yield relative to actual energy yield in PV systems – but using robust, correctly measured profiles can accurately reflect expected profit margins. To mitigate the risk and maximize the benefits from custom IAM profiles, developers should thoroughly analyze the characterization method and equipment used in testing. They should always validate the resulting profile mathematically to confirm that it is theoretically sound.

Are you interested in IAM characterization?

To obtain an IAM profile from PVEL, visit us online at **pvel.com**

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