MEASURING IRRADIANCE, TEMPERATURE AND ANGLE OF INCIDENCE EFFECTS ON PHOTOVOLTAIC MODULES USING A SOURCE-METER-BASED TEST-BED

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ABSTRACT

A photovoltaic (PV) module testing system was installed at latitude 42.6978 and longitude 83.2419 in 2010 for the purpose of evaluating the impacts of irradiance, temperature and angle-of-incidence effects on PV performance. The system consists of a source-meter coupled with a data acquisition system that collects readings from weather-station instruments tracking irradiance, temperature and wind speed. Current, voltage and power observations, correlated to our weather-station device readings, were collected from c-Si, a-Si and CIGS PV modules. We observed thermal annealing in a-Si and the effects of temperature on c-Si and CIGS. c-Si module temperatures above 25°C appear to diminish power by approximately 0.5%/°C. Our results also support the hypothesis that a-Si modules deliver more energy (kWhrs) per peak-watt (Wp) than other PV materials. This is important because PV is typically sold on a $/Wp basis. The Wp rating is based on a module’s performance under standard test conditions of 1000W/m², 1.5 AM and 25°C module temperature. However, these conditions rarely occur simultaneously in nature and the performance of PV materials varies over time and by geographic location based primarily on differences in temperature and AM [2]. The IEC has proposed PV rating standards (IEC 61853) that include characterizing module performance based on a matrix of various weather conditions, including high temperature conditions (HTC), STC, nominal operating cell temperature (NOCT), low temperature conditions (LTC) and low irradiance conditions (LIC). The criteria for these conditions appear in Table 1.

TABLE 1: IEC 61853-1 Matrix-based text conditions

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Irradiance (W/m²)</th>
<th>Module Temp. (°C)</th>
<th>Ambient Temp. (°C)</th>
<th>Wind Speed (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTC</td>
<td>1000</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STC</td>
<td>1000</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOCT</td>
<td>800</td>
<td></td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>LTC</td>
<td>500</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>LIC</td>
<td>200</td>
<td></td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

With its proposed ratings standards, the IEC seeks to improve the method by which PV module performance is evaluated by measuring PV power under a set of testing conditions, instead of only STC. The standards also establish guidelines for rating PV based on energy yield (watt-hours) and performance ratio (PR) [3, 4].

We designed a test-bed capable of characterizing PV modules and began regular testing of 20 modules in March 2010 by performing current-voltage (IV) sweeps on each module every ten minutes during daylight-hours. It also

1. INTRODUCTION

Variations in weather and air mass (AM) as well as non-linear performance characteristics of various module technologies influence photovoltaic (PV) module and array performance. Manufacturers, distributors and developers typically sell PV on a cost per peak-watt ($/Wp) basis. A module’s Wp rating, also known as its Pmax, is based on its performance under Standard Test Conditions (STC) consisting of 1000W/m², 1.5 AM and 25°C module temperature. However, these conditions rarely occur simultaneously in nature and the performance of PV materials varies over time and by geographic location based primarily on differences in temperature and AM [2]. The IEC has proposed PV rating standards (IEC 61853) that include characterizing module performance based on a matrix of various weather conditions, including high temperature conditions (HTC), STC, nominal operating cell temperature (NOCT), low temperature conditions (LTC) and low irradiance conditions (LIC). The criteria for these conditions appear in Table 1.
records basic meteorological conditions with each sweep, including plane of array (POA) irradiance, ambient and module temperature, and wind speed. We collected and bundled field observations into the standard’s categories representing various test conditions in order to verify the capability of our measurement system to test IEC 61853-1.

Once we applied our test method, we were able to determine that our results were consistent with our expectations based on existing literature, highlighted in the next section. In this paper, we report on the relationships we found between power and irradiance as well as between power and module temperature based on observations taken from select amorphous silicon (a-Si), crystalline silicon (c-Si), and copper indium gallium selenide (CIGS) modules from July through December 2010. (Observations from December 14th through 20th were ignored because many of the modules were covered in snow.) We were unable to obtain cadmium-telluride (CdTe) modules due to the manufacturer’s tight control of its distribution channel.

In order to isolate the key constituents that contribute to PV power, the proposed standard calls for evaluating open-circuit voltage \( V_{oc} \) and short-circuit current \( I_{sc} \), and fill-factor (FF) against both irradiance and module temperature [4]. FF indicates a module’s relative efficiency. We designed and built a system capable of measuring all of these parameters and others including \( V_{mp} \). In addition to presenting our results, we also discuss the limitations and shortcomings of the test-bed system. For example, the system is also not equipped to measure AM.

2. BACKGROUND

For decades, PV research scientists have asserted that STC ratings alone are inadequate for predicting PV module performance, instead suggesting that module performance be characterized by categories of weather conditions (hot sunny, cold sunny, hot cloudy, cold cloudy, and nice) [2, 5]. The IEC’s current proposed standard also seeks to address this need [4].

Through an examination of existing literature, we identified the key variables that affect PV power generation and the various methods for measuring those variables effectively. From there, we defined our performance metrics and the scope of our study.

Irradiance has the greatest impact on PV power. Beyond irradiance, module temperature, angle of incidence (AOI) and AM also affect a module’s or an array’s power and production [4, 6, 7]. Module temperature is in turn, influenced by ambient temperature, cloud patterns and wind speed. Additionally, under rapidly changing and extreme weather conditions, inverter ramp-times and clipping both diminish AC power generation [8].

Secondary-standard and first-class thermopile-type pyranometers measure irradiance throughout the range of frequencies to which PV responds (300-2800nm). However, silicon diode pyranometers only respond to a narrower range of frequencies (400-1100nm), but they are still used in PV weather stations because they are less expensive than thermopiles and because they are actually more sensitive than thermopiles in the range of frequencies to which they do respond.

Measuring module temperature is important because c-Si and other PV materials produce less power at high temperatures, by as much as 0.5% less power per °C. Estimating module temperature is achieved with the use of a thermocouple attached to the back of the module. However, under most conditions, the module temperature is likely to be warmer than the back of the module. Furthermore, module temperature is not likely to be consistent throughout its entire surface. For these reasons, researchers apply a standard adjustment to the back of the module temperature reading to compensate for the temperature difference between the back of the module and surface of the module and they may place more than one thermocouple in several specific positions on the back of a module in order to calculate an average temperature.

A high AOI can significantly reduce PV power generation. Reda and Andreas provided the solar position algorithm that we used to find zenith, declination, and azimuth angles required to calculate AOI in order to plot it against \%P_{max} and other variables [9].

When the actual solar spectrum deviates from AM1.5 or the spectral response of the PV differs from the reference device (i.e., the pyranometer), the impact of AM on PV module or array performance is stated as a spectral mismatch factor (K) [10]. They observed readings fitting Equation 1.

\[
K = 0.0781 \times AM + 0.8826 \tag{1}
\]

Our work did not include correcting for spectral mismatch, however, Emery, del Cueto, and Zaaiman offer a spectral correction factor derived from a polynomial fit of short-circuit current \( I_{sc} \) measured under natural sunlight divided by the full spectrum irradiance as a function of air mass [11]. Their equation is:

\[
CV = \frac{I_{sc}}{E_{tot}} \times \frac{\int_{0.3\mu m}^{4.0\mu m} E_r(\lambda) S_T(\lambda) d\lambda}{\int_{0.3\mu m}^{4.0\mu m} E_S(\lambda) S_R(\lambda) d\lambda} \times \frac{\int_{0.3\mu m}^{4.0\mu m} E_S(\lambda) S_T(\lambda) d\lambda}{\int_{0.3\mu m}^{4.0\mu m} E_r(\lambda) S_R(\lambda) d\lambda} \tag{2}
\]
where $E_{tot}$ is total irradiance, $E_R(\lambda)$ is the spectral irradiance of the reference spectrum, $S_R(\lambda)$ is the spectral irradiance of the solar spectrum, $S_R(\lambda)$ is spectral responsivity of the reference detector, and $S_P(\lambda)$ is the spectral responsivity of the test device with measured $I_{sc}$ [11]. They found that using a matched reference cell to measure total irradiance reduces uncertainty in spectral correction but makes the correction equation dependant on the detector employed and the air mass based spectral correction factor is both location and time dependent. They also note that a-Si is much more sensitive to water vapor and turbidity than c-Si, CIGS and CdTe. Because we did not have CdTe under test, we relied on existing literature to provide a basic comparison to our results for c-Si, a-Si and CIGS modules [4].

We also recorded wind speed and ambient temperature with each module’s IV sweep, even though Myers showed no strong correlation between power and either wind speed or ambient temperature [6].

Existing literature also provided a basis for understanding the level of uncertainty we could expect from our analysis. There are several sources of uncertainty including a lack of precision in the measurement devices and rapidly changing conditions (e.g., irradiance) during test periods. During one experiment conducted in 1998, Bill Marion at NREL found that “Because of errors in measurements and energy-rating methodology, differences of 8% or less in the energy ratings of two PV modules are not significant. If one of the modules is a-Si, differences of 13% or less in the energy ratings of two PV modules are not significant.” [12]

3. METHODS

![System diagram](image)

**Fig. 1: System diagram**

**Fig. 2: Sample IV-curve with Y-axis A (left) and Power-curve with Y-axis W (right)**

Figure 1 shows the key elements of the measurement system including the connections between the PV modules under test and the measurement devices and other components within the test-bed. The heart of the test-bed is a 1kW Keithley Instruments (KI) model#2430 source-meter (with current source accuracy within 0.045% and voltage sense accuracy of 0.015%). We obtain power measurements by sourcing current to a module under test while sensing its voltage. The first step in conducting an IV sweep is to find $V_{oc}$ (where $I=0$). Then the program instructs the source-meter to increase current at such an interval to allow for approximately 80 points or steps before the voltage reads zero (which occurs at $I_{sc}$). The result is an IV curve with $P_{max}=I_{mp} x V_{mp}=I_{sc} x V_{oc} x FF$, where the product $I_{sc} x V_{oc}$ represents the module’s theoretical maximum power and FF reflects its relative efficiency, as shown in Figure 2.

Note that the illustration above shows a standard first quadrant IV curve, but that the system in fact carries out fourth quadrant sweeps. In addition to $V_{oc}$ and $I_{sc}$, the file also records $P_{max}$, FF [=$(V_{mp} x I_{mp})/(V_{oc} x I_{sc})$] and a timestamp. The system initiates an IV sweep ever ten minutes when irradiance is greater than 20W/m². This is not as frequently as some other monitoring systems (e.g., NREL’s OTF) which take measurements every minute or more.

Alternated with its sweeps, the software calls for readings from devices connected to the data acquisition system, namely a Maximum model #41 three-cup anemometer, type-K thermocouples attached to the back of each module and two ambient points (shaded and not shaded), and several Kipp & Zonen SPLite2 photodiode detector pyranometers. In March 2011, we added a secondary standard Kipp & Zonen CMP-21 to our test-bed. As previously stated, all of the other findings in this report are based on observations taken between July and December 2010. However, the findings based on CMP-21
measurements were taken between March and July 2011. The measured correlation between a SPLite2 and the CMP-21 appears in Figure 3.

![Fig. 3: Indexed pyranometer readings](image)

The KI#2430 is capable of sourcing or sensing up to +/-10 A and +/-100Vdc in pulse mode with a four-wire connection. (We set our pulse width at 0.0025 milliseconds and our pulse delay at 0.05 milliseconds.) However, the system’s KI#7053 switching cards can only handle up to 4 A. We were able to double the switching cards’ tolerance to 8 A by splitting the current between the cards’ two channels (H/L). This was important because the Isc of many PV modules, including some modules that we wanted to test, exceeded 3.2 (≈4/1.25 safety factor). Splitting the current between the cards’ H/L channels allowed the circuit to accommodate the expected maximum current from all of our modules under test, but this is still insufficient for testing high-current modules on the market. Figure 4 shows the switch-card connection required for current over 4 A.

![Fig. 4: KI#7053 Switch-card connection for A>4](image)

Other key components of the system include a 10-slot Keithley Instruments #7002 switching mainframe and a KI#2700 data acquisition system. The switching mainframe directs the system to select a module under test while keeping the other modules routed to fixed load resistors when not under test. The data acquisition system collects readings from the system’s thermocouples, pyranometers and anemometer.

All system devices are controlled by a standard personal computer with an IEEE-488 general purpose interface bus (GPIB) and Visual Basic (VB.net) code.

From the recorded measurements, we adjusted Vdc instrument readings into calibrated W/m² and m/sec values. We indexed Pmax based on the modules’ STC rating using the simple equation:

$$\%P_{\text{max}} = \frac{\text{measured } P_{\text{max}}}{\text{STC rated } P_{\text{max}}}$$  

(3)

We calculated energy yields as:

$$E_{\text{yield}} = \int \text{average } P_{\text{max}} \times \text{time lapsed},$$  

(4)

with a time increment between measurements set to ten minutes during daylight hours.

We then indexed power and energy by area (m²) and we estimated module temperature as measured back of module temperature plus 3°C per 1000W/m², based on the industry standard.

Finally, using Equation 5, we calculated for power correction based on temperature coefficient in order to help assess the impact of module temperature and to estimate the effects of AM and other factors:

$$\%P_{\text{max-corrected}} = \%P_{\text{max-observed}} \times [1 + \alpha \times (T_{\text{module}} - 25^\circ \text{C})]$$  

(5)

with temperature coefficient, α

Specifications for the PV modules under test appear in Table 2.

**TABLE 2: PV Modules under test**

<table>
<thead>
<tr>
<th>Tech</th>
<th>Pmax (W)</th>
<th>Isc (A)</th>
<th>Ismp (A)</th>
<th>Voc (V)</th>
<th>Vmp (V)</th>
<th>Temp Coeff (%/°C)</th>
<th>Area (m²)</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>160</td>
<td>5.0</td>
<td>4.66</td>
<td>43.2</td>
<td>34.4</td>
<td>-0.48</td>
<td>1.277</td>
<td>12.5%</td>
</tr>
<tr>
<td>a-Si</td>
<td>60</td>
<td>1.19</td>
<td>0.9</td>
<td>92</td>
<td>67</td>
<td>NA</td>
<td>0.950</td>
<td>6.3%</td>
</tr>
<tr>
<td>CIGS</td>
<td>30</td>
<td>2.2</td>
<td>1.7</td>
<td>25</td>
<td>17.5</td>
<td>-0.5</td>
<td>0.394</td>
<td>7.6%</td>
</tr>
<tr>
<td>CIGS</td>
<td>165</td>
<td>2.74</td>
<td>2.37</td>
<td>93.9</td>
<td>69.6</td>
<td>-0.24</td>
<td>1.966</td>
<td>8.4%</td>
</tr>
<tr>
<td>a-Si</td>
<td>68</td>
<td>5.1</td>
<td>4.13</td>
<td>23.1</td>
<td>16.5</td>
<td>-0.0021</td>
<td>1.123</td>
<td>6.1%</td>
</tr>
</tbody>
</table>
4. RESULTS

In accordance with del Cueto’s recent study, we reported our results in a series of graphs plotting percentage P max, I sc, V oc and FF against POA irradiance, as well as percentage P max against AOI, percentage P max and FF against module temperature, and FF and percentage P max over time intervals [4]. We also calculated linear and polynomial line fits for percentage P max versus irradiance because the IEC proposed rating standard calls for linear interpolations of I sc, V oc, V mp and P max with respect to temperature and irradiance as well as a polynomial interpolation of P max to irradiance and the equation V (POA Irr) = v1 x ln(POA Irr) + v2 to interpolate V oc to irradiance. Table 3 shows the equations that we found for fitting percentage P max to irradiance.

**TABLE 3: Trends in power by PV material**

<table>
<thead>
<tr>
<th>Module Material</th>
<th>%P max Trendline</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-Si</td>
<td>0.0010Irr - 0.0740</td>
<td>0.986</td>
</tr>
<tr>
<td>CIGS</td>
<td>4 x 10^-7 Irr^2 +0.0012Irr - 0.0187</td>
<td>0.974</td>
</tr>
<tr>
<td>c-Si</td>
<td>0.000898Irr - 0.0138</td>
<td>0.994</td>
</tr>
</tbody>
</table>

A linear relationship between power generation and irradiance clearly emerges in all cases. A polynomial equation for CIGS provides a better fit than a linear equation, especially below 1000W/m². As shown in Table 4, despite the strong linear relationship between power and irradiance, other factors (most notably, temperature and air mass) also affect power generation resulting in the following ranges of %P max readings at (1000W/m²):

**TABLE 4: Power at 1000W/m² by PV material**

<table>
<thead>
<tr>
<th>Module Material</th>
<th>%P max at Full-Sun (+/-0.5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>a-Si</td>
<td>101.1%</td>
</tr>
<tr>
<td>CIGS</td>
<td>78.9%</td>
</tr>
<tr>
<td>c-Si</td>
<td>86.2%</td>
</tr>
</tbody>
</table>

As indicated in Figure 5, the a-Si module clearly demonstrates a superior power index to irradiance performance ratio. This corresponds to the equations presented in Table 3 above and is due to temperature coefficient. The manufacturers’ state temperature coefficients of -0.38%/°C, -0.48%/°C, and -0.0021%/°C for their CIGS, c-Si and a-Si modules respectively.

For a-Si and c-Si, module temperatures typically average 50-60°C at full-sun. For c-Si, one can expect a 50-60°C module temperature to reduce power by 12.5-17.5% [(60-25) x 0.48% = 17.5%] to a P max between 82.5-87.5% of STC. This is consistent with our results.

Correcting for temperature on the c-Si module, a linear fit of P maxcorr = 0.000106 x POA Irr - 0.0582 (R² = 0.976) yields 100.2% P max at 1000W/m². A polynomial fit of P maxcorr = 1.2 x 10^-2 POA Irr^2 + 0.00118 POA Irr - 0.711 yields 98.9% P max at 1000w/m². Temperature-corrected observations and their corresponding linear and polynomial fits appear in Figure 6. This implies that at high irradiance conditions, when AM typically ranges between 1 and 2, AM does not significantly affect power. However, AM can exceed 10 near dawn and dusk and has a much greater influence over power under those, but not all low irradiance conditions.
Because our test-bed lacks the ability to measure AM and due to inaccuracies in its measurements of module temperature, our ability to measure and isolate temperature dependence is limited. However, having captured both nearby ambient and back of module temperatures along with power generation, POA irradiance and wind speed, we were able observe PV performance under a variety of real-world conditions. Like Myers, we did not see a direct correlation between power and either wind speed or ambient temperature [6].

Also as expected for a-Si, we see an oscillation in fill factors (i.e., efficiency) throughout the seasons from approximately 0.60 in mid-July to 0.53 in late December (Fig 7). The downward trend from summer to winter is the result of an increased Staebler-Wronski effect under low temperature conditions and thermal annealing during warm periods [13]. c-Si and CIGS module FFs, on the other hand, remain steadier during the test period at 0.70 and 0.64, respectively (c-Si Figure 8). The manufacturers list FFs of 0.55, 0.64 and 0.74 for a-Si, CIGS and c-Si, respectively.

Decreasing fill factors at higher levels of irradiance indicates series-resistance. Refer to Figures 9 and 10.
In Figure 12, the upper-band of observations up to 105° AOI represents clear sky conditions whereas the lower mass of observations reflect measurements taken under overcast conditions. Outliers above the band most likely indicate mostly sunny conditions with scattered clouds enhancing power through diffuse irradiance that enhances overall irradiance without obstructing direct sunlight. In these extreme cases, total POA irradiance exceeds 1000W/m².

Fig. 12: Power vs AOI: c-Si

Due to weather conditions experienced at our Midwest test-site, none of our observations met IEC 61853-1 High Temperature Conditions. Table 5 reports observations near IEC 61853-1 Nominal Operating Cell Temperature (NOCT) and Low Irradiance Conditions (LIC) (+/- 50W/m² and +/-2.5°C).

TABLE 5: Test-bed PV Power (W) Observations fitting IEC 61853-1 NOCT and LIC parameters

<table>
<thead>
<tr>
<th>NOCT</th>
<th>a-Si %P&lt;sub&gt;max&lt;/sub&gt;</th>
<th>c-Si %P&lt;sub&gt;max&lt;/sub&gt;</th>
<th>CIGS %P&lt;sub&gt;max&lt;/sub&gt;</th>
<th>Avg</th>
<th>Min</th>
<th>Max</th>
<th>Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.766</td>
<td>0.72</td>
<td>0.632</td>
<td>46.0</td>
<td>39.3</td>
<td>52.6</td>
<td>95</td>
</tr>
<tr>
<td>LIC</td>
<td>%P&lt;sub&gt;max&lt;/sub&gt;</td>
<td></td>
<td></td>
<td>0.185</td>
<td>5.3</td>
<td>15.8</td>
<td>191</td>
</tr>
<tr>
<td></td>
<td>0.157</td>
<td>14.3</td>
<td>35.2</td>
<td>25.2</td>
<td>31.5</td>
<td>50.2</td>
<td>195</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>82</td>
<td>82</td>
<td>82</td>
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</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>95</td>
<td>95</td>
<td>95</td>
<td>95</td>
</tr>
</tbody>
</table>

5. CONCLUSION

Outdoor PV module testing systems, such as the one we developed can dramatically increase a PV company’s capability to evaluate PV under real-world conditions. PV manufacturers also utilize indoor simulators (e.g., Spire), accelerated testing and other means of testing PV in order to better understand and ultimately facilitate the advancement of PV technology.

Our test-bed is effective at testing PV modules with I<sub>sc</sub>=<6.4A (8/1.25 safety factor) and our results were consistent with both existing literature and the manufacturers’ stated ratings.

Irradiance impacts power, but it is both expensive and difficult to measure precisely. We enhanced the accuracy of our test-bed by adding a secondary standard thermopile-type pyranometer to the system [14]. It measures irradiance across a much wider range of wavelengths than the silicon diode pyranometers installed when we originally commissioned the system. Other factors, most notably module temperature and air mass also affect power generation. Based on both our observations and manufacturers’ claims, module temperatures under high temperature conditions can reduce P<sub>max</sub> by 25%. True air mass is also difficult to measure and can affect power +/-8% under ordinary midday conditions [10].

Numerous opportunities exist for further research based on data generated by the test-bed. Our results support, but do not confirm the hypothesis that a-Si modules deliver more energy (kWhrs) per peak-watt (W<sub>p</sub>) than other PV materials. Confirming the hypothesis would require both testing a statistically significant number of PV modules and performing a quantitative analysis of the accuracy of the test-bed. The test-bed accommodates and tests 20 PV modules, but this work compared the results of only three modules. Most of the other modules under test are current and next-generation a-Si. Better understanding of both the accuracy of the test-bed and the performance characteristics of a-Si could be attained by comparing measurements taken from the other modules under test. Data filtering provides another avenue for further study. Separating clear sky readings from overcast sky readings is required in order to fit AOI effects.

As presented in Figure 13, the modules in this study produced between 0.76 and 0.95 dcW per kWh of POA irradiance per m² per STC W P<sub>max</sub>. The modules under test produced between 51.5 and 105.1 dcW per kWh of POA irradiance per m². Amorphous Silicon modules generate more energy per peak-watt than other PV, performing better...
than its STC ratings indicates, but crystalline Silicon generates more energy per m² than the other PV we tested.

Fig. 13: Performance ratios for modules under test

6. REFERENCES