A New Approach to Indoor Characterization of PV Module Energy Yield Parameters

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Abstract — **Temperature and solar irradiance are among the most relevant parameters that affect the energy yield of photovoltaic cells and modules. A rise in the module temperature leads to a significant decrease in the open circuit voltage and a small increase in the short circuit current. Here we use a new tool to determine temperature coefficients as well as to assess power rating of multi c-Si, mono c-Si, CdTe, and CIGS-based PV modules in controlled indoor conditions per IEC 60891 and IEC 61853-1. We use the tool to explore how nonuniformities in module temperature affect the accuracy of the temperature coefficients.**

I. Introduction

Photovoltaic (PV) modules are typically rated at standard test conditions (STC) of 1000 W/m^2, 25°C and air mass 1.5 global spectrum tabulated by the standard IEC (International Electrotechnical Commission) 60904-3 [1]. However, the energy delivery and financial return of photovoltaic (PV) modules depend critically on the annual variations in temperature and irradiance that the modules see for a particular installation. Modules produce more power at higher irradiances, but the response is not purely linear. The module power (P_{max}) and the open circuit voltage (V_{oc}) decreases with temperature while the short circuit current (I_{sc}) increases, but these responses vary greatly across different PV technologies and designs. Therefore, accurate measurements of module performance as a function of both irradiance and temperature are critically important, and the PV community has created IEC Testing Standards to detail how these tests should be performed. In particular, IEC 61853-1 [2] has been established for PV modules to be rated using a target performance matrix combining various temperatures and irradiance levels. It is worth noting that these measurements at various temperatures and irradiance are more challenging under outdoor conditions (using real solar power) as compared to controlled indoor conditions (using solar simulator to collect data). A large body of high-performance flatbed solar simulators has been installed at testing laboratories over past decades that would be well suited to perform such tests, but until now, there has been no commercially available, temperature controlled tool to interface with these simulators. In this work we describe the design and test results of a new tool to fill this gap. Additionally, since a large number of testing labs do not have access to tools that allow for the tight control of temperature as per the IEC standards, it is of interest to explore how wider spatial temperature variations may be affecting their measurements. This new tool can also enable such investigations.

II. Experimental and Description of the TempCoSpot

Fig. 1. The TempCoSpot chamber sitting on a flash tester (glass side facing down). The module is loaded into the box through a hinged door. A blower unit forces air to circulate inside the box via the yellow ducts.

At NREL, the TempCoSpot tool shown in Fig.1 enables the measurement of PV module I-V curves over the temperature range 15 - 75 °C in order to assess module power rating as per IEC 61853-1 and determine module temperature coefficients as per IEC 60891 [3]. While large systems for testing sideways-flashing solar simulators are available from other vendors, to our knowledge, the TempCoSpot tool is the only compact and sufficiently lightweight system to sit on top of a flatbed simulator.

In contrast to the commonly used approach of removing a module from an oven and then collecting I-V data as it cools down, using the TempCoSpot results in more accurate data due to significantly improved temperature uniformity across the face of the module and minimal temperature differences across the thickness of the module. The TempCoSpot tool consists of an insulated enclosure and a carriage which holds the module and rolls into the box through a hinged door. Hot or cold air is directed down the length of the box to control the temperature, and advanced algorithms based on feedback from an air temperature sensor and up to 16 sensors fixed to the module allow tight spatial and temporal temperature control [4]. By placing the tool on an upward flashing solar simulator, the sunnyside-down facing module is illuminated through the glass bottom of the enclosure using a Spire 5600 SLP Pulsed Solar Simulator with a long-arc pulsed xenon lamp (100-ms flash duration). Prior to the measurements, a secondary reference module is placed into the TempCoSpot chamber (at the same position as the PV module under test) to set the light level of the solar simulator.

III. Results and Discussions

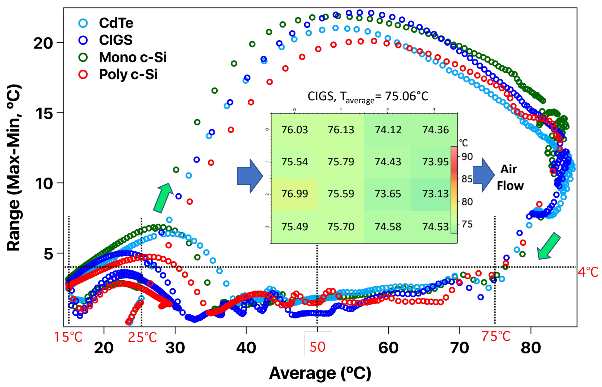

Fig. 2. Temperature range of the module (maximum-minimum) vs average module temperature during a 75 °C to 15 °C "ramp down" run. Inset is a schematic of a module temperature distribution at 75 °C using 16 temperature sensors to measure temperature distribution across the module.

Recipes can be run in a "ramp up" (heating up) or "ramp down" (cooling down) mode as shown in Fig. 2. However, "ramp down mode" gives a better control for temperature uniformity across the modules while testing at different irradiances and temperatures. We have devoted our efforts in optimizing recipes for speed and uniformity in the "ramp down mode", and as such the temperatures during the ramp up portion of the recipe vary widely. It is worth noting that for temperature coefficient measurements, the IEC 60891 standard requires performing I-V measurements when the module temperature is uniform within ±2 °C. In order to run the experiments in a ramp down mode at 75, 65, 55, 45, 35, 25 and 15 °C, the temperature has first to be ramped from room temperature up to 85 °C. This takes about 30 minutes. The temperature gradient across the panel increases when swiftly ramping up the temperature (heating to higher setpoints), to reach a value of approximatively 23 °C (range between the maximum and minimum temperature measured on the module). When ramping up, the hot air heats up the leading edge of the module, and then gradually loses heat to the panel and to the chamber such that the leading edge of the panel is hotter than the trailing edge. The faster the ramp rate, the greater the gradient will be. The overshoot temperature at 85 °C (above the desired highest setpoint which is 75 °C) is necessary to establish the desired uniformity across the panel when cooling down. By reducing power to the heating element, the recirculating air is now colder such that the leading edge begins to cool, thus achieving good uniformity. Feedback algorithms take into account the temperature difference between the leading and trailing edges to control the heating elements to maintain the

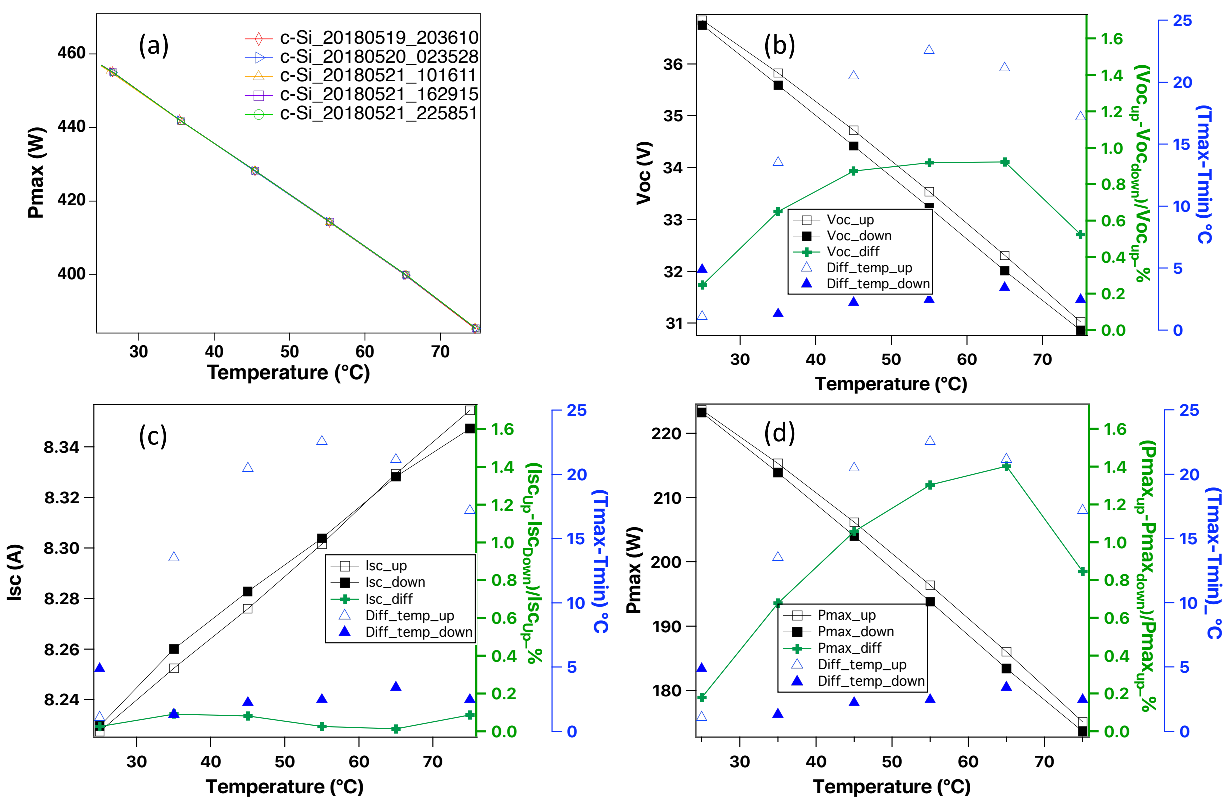

Fig. 3. (a) For each type of module, the measurement is repeated five times and the repetition shows very good correlation between experiments (the repetition is shown here for a monocrystalline PV module as an example). (b), (c), and (d), show the effect of module temperature range on V_{oc}, I_{sc}, and P_{max} respectively for a multicrystalline Si PV module. Tmax and Tmin are the maximum and the minimum temperatures respectively measured across the module. The average temperature is shown on the X-axis.

desired uniformity. One can see that the temperature range is less than 4 °C (or ±2 °C) during the entire cooldown period and in a good uniformity for a period long enough to perform an I-V test.

The I-V curve measurements were carried out during both heating up and cooling down of the PV module. The data were collected during the unoptimized heating-up portion to explore how poor uniformity affects the performance parameters. For each type of module, the measurement is repeated five times and as shown in Figure 3 (a), the repetition shows very good correlation between experiments (the repetition is shown here for a monocrystalline PV module during the cooling down process as an example). Fig. 3(b), (c), and (d), show the effect of module temperature range on I_{sc}, V_{oc} and P_{max} respectively for a multi c-Si PV module. During the unoptimized heating up process, the difference in temperature ΔT (Tmax-Tmin) between the maximum and minimum measured temperatures across the module is higher, spanning from 10°C to 23 °C (in the range of 30-75 °C module average temperature). During cooling down, ΔT is smaller with values lower than 4 °C (in the range of 75-15 °C average temperature). I-V curves are taken every 10 °C during the cooling down process to evaluate the influence of ΔT on the module's performance parameters. I_{sc} increases with temperature and follow the same trend when the module is heating or cooling. The variation in percentage (plotted in green) between values of I_{sc} taken at the same average temperature (X-axis) with different ΔT during the heating up and cooling down process is in the range of 0.05-0.1%. This variation is more pronounced for both V_{oc} and P_{max}. The variation is in the range of 0.3-0.9% and 0.2-1.4% for V_{oc} and P_{max} respectively. It is worth noting that both of those parameters follow the same trend when the module is heating or cooling. However, they exhibit a negative slope compared to I_{sc}. As shown in Fig. 3, the variation of the electrical parameters due to change in device temperature is a linear function. The slope of the linear regression is the absolute temperature coefficient (TC) reported in A/K for I_{sc}, V/K for V_{oc}, and W/K for P_{max}. The ratio of that slope value to the parameter's value at STC is defined as relative TC which is usually reported on the data sheet of PV modules in %/°C or %/K. The relative temperature coefficient of I_{sc} is called α, the one of V_{oc} is called β, and the one of P_{max} is called γ, as obtained in (1).

$$\alpha = \frac{1}{I_{sc}}\frac{dI_{sc}}{dT}\ ;\ \beta = \frac{1}{V_{oc}}\frac{dV_{oc}}{dT}\ ;\gamma = \frac{1}{P_{max}}\frac{dP_{max}}{dT} \qquad (1)$$

The temperature coefficients have been extracted from I-V curve measurements taken at different temperatures during the cooling down process (when the module temperature is uniform within ±2 °C according to IEC 60891). Table 1 shows the temperature coefficients of I_{sc}, V_{oc} and P_{max} from module measurements of different technologies (multi c-Si, mono c-Si, CIGS, and CdTe). The TC are determined at 1000 W/m^2 and compared with the manufacturer's values (in red). β and γ, have negative values while α is positive and by a factor 10 smaller than the other coefficients. The extracted temperature coefficient values are close to the ones reported by the manufacturer. However it is worth noting that different measurement methods may provide different temperature coefficients for the same modules [5].

Power rating experiments per IEC 61853-1 were performed. I-V curves at four different temperatures (15, 25, 50, and 75 °C) and six irradiances (200, 400, 600, 800, 1000, and 1100 W/m^2) have been collected. After linearity check [6], the modules showed linearity over several irradiance ranges and therefore, the calculated TC can be considered valid beyond 1000 W/m^2 according to IEC 60891.

TABLE 1

Temperature coefficients of the PV performance parameters for different technologies. The reported values from the manufacturer are in red.

Module Type	α (%/°C)	β (%/°C)	γ (%/°C)
CIGS	0.003±0.0001	-0.39±0.003	-0.43±0.03 -0.45±0.05
CdTe	0.03±0.004 0.04	-0.26±0.02 -0.28	-0.28±0.05 -0.29
Mono c-Si	0.03±0.004 0.04	-0.23±0.02 -0.24	-0.27±0.004 -0.29
Poly c-Si	0.05±0.006 0.06	-0.30±0.002 -0.33	-0.42±0.004 -0.45

IV. Conclusion

Temperature coefficients are performance parameters used in the simulation of energy yields of PV modules. By measuring module performance over a range of temperatures, we have shown how temperature coefficients are affected by uniform and non-uniform temperatures. More investigations are ongoing to evaluate the impact of the variations between the module performance parameters during the cooling down (uniform temperatures) and heating up process (non-uniform temperatures). Such investigations will help evaluate the difference in temperature coefficients extracted from uniform and non-uniform temperatures and how such a difference would impact the energy yield for a particular installation and return on investment of modules installed in different locations.

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