Correcting Bias in Measured Module Temperature Coefficients

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***Abstract* — Temperature coefficients for PV modules describe the change with temperature of current, voltage and power. Coefficients are commonly determined by linear regression using measured module output at fixed irradiance and varying temperatures. We compare temperature coefficients determined for the same modules from both outdoor and indoor measurements. We find systematic bias in the temperature coefficients for voltage and power, with values derived from indoor measurements consistently smaller in absolute value than values derived from outdoor testing during which the module temperature is measured as specified in IEC 61853-1. Our work suggests that the bias results from a corresponding bias in the estimated module temperature. However we have not identified an alternative arrangement of a few thermocouples that would result in consistent values for temperature coefficients from either indoor or outdoor measurements.**

***Index Terms* — temperature coefficient, photovoltaic modules, testing.**

I. INTRODUCTION

Accurately predicting energy yield from a PV system requires knowledge of the effects of temperature on the current and voltage of the PV system. Commonly, performance models for PV systems (e.g., [1], [2]) assume that current and/or voltage changes linearly with a change in temperature; the slopes of these linear relationships are termed the temperature coefficients. Values can be derived for individual modules by measuring module output under fixed irradiance while varying module temperature. Both indoor and outdoor methods have been described (e.g., [3]).

In earlier work done by CFV Solar Test Laboratory, temperature coefficients were measured for a selection of monocrystalline silicon (mcSi), polycrystalline silicon (pcSi), and heterojunction with intrinsic layer (HIT) silicon modules using both indoor and outdoor methods (Table 1) and following the procedures described in IEC 61853-1 [4]. Systematic differences were noted: temperature coefficients for voltage and for power were consistently smaller in absolute value when determined from indoor measurements. Other analyses have reported variations among temperature coefficients determined for the same modules using a variety of indoor methods [5], [6]. These results indicate a need to investigate more carefully the methods used for determining temperature coefficients with a goal of obtaining more consistent values.

Here, we report a detailed comparison between temperature coefficients determined for two mcSi modules indoors using a temperature-controlled flash tester and outdoors using various thermocouple configurations for measuring module temperature. We i) describe the measurement methods and equipment used (Sect. II); ii) present the measured temperatures and estimated temperature coefficients for the two modules (Sect. III); and conclude with comments regarding the challenge of obtaining consistent temperature coefficients for either indoor or outdoor testing (Sect IV).

TABLE I
COMPARISON OF TEMPERATURE COEFFICIENTS FROM INDOOR AND OUTDOOR METHODS

Module	βVmp (%/°C)		γPmp (%/°C)	
	Indoor	Outdoor	Indoor	Outdoor
mcSi	–0.29	–0.31	–0.29	–0.32
mcSi	–0.42	–0.46	–0.40	–0.50
pcSi	–0.43	–0.46	–0.42	–0.48
HIT	–0.30	–0.30	–0.30	–0.33

II. MEASUREMENTS

A. Indoor measurements

Indoor testing was carried out by CFV Solar Test Laboratory, Inc, of Albuquerque, NM. CFV uses a HALM flash solar simulator with an integrated thermal chamber that can control module temperature between 25° and 70° C and irradiance between 0.1 and 1.1 suns. The temperature chamber uses laminar air flow on both sides of a module to ensure uniformity in module temperature and is equipped with a sliding glass pane that allows the module to be kept at a consistent temperature and flashed simultaneously. The CFV system exceeds the IEC 60904-9 AAA rating for modules up to 2.1m x 1.4m and is capable of both light and dark I-V measurements. Flash pulse width is configurable from 10ms to 50ms and calibrated reference cells are used to control irradiance.

Prior to testing control modules are measured at standard test conditions (STC) to ensure consistency of the equipment. The STC performance of the module under test is then measured to establish a reference for equipment configuration during temperature sweeps. The flasher setup is modified by moving the reference cell from its usual place inside the temperature chamber to a secondary location outside the chamber to obviate the need to correct measured irradiance for reference cell temperature. The module being tested is re-measured with the new configuration to ensure agreement in measurements. PT100 temperature sensors are attached to the back sheet of the module and are covered with 6cm x 6cm pieces of polyethylene foam so that the sensor temperature more closely reflects the cell temperature of the module.

Testing evaluated the performance of the PV module at from 25 °C to 65 °C at roughly 2 °C increments. Module performance is measured using two 50ms flash pulses. The first flash pulse drives the module voltage from I_{SC} to V_{OC} and second flash pulse drives the module from V_{OC} to I_{SC}. The reported I-V curve is the average of these two datasets.

For accurate measurement of voltage and current, each I-V curve must be acquired at a constant irradiance and temperature during the I-V sweep duration. We assume cell temperature to be constant over the duration of the I-V curve acquisition; however, the irradiance from the lamp may vary slightly during the flash pulse. Because of these variations the measured module current is corrected to a constant target irradiance over the entirety of the I-V sweep according to Eq (3) of IEC 60891 ed. 2 [7].

B. Outdoor measurements

Outdoor measurements were carried out by Sandia National Laboratories in Albuquerque, NM. To determine temperature coefficients, modules were placed on a 2-axis solar tracker to maintain the module normal to the sun (Figure 1). Each module was initially cooled to near-ambient temperature by shading the module from the sun. The back of the module was insulated and the shade was removed. Once the shade is removed, the module heats to operating temperature over the course of perhaps 30 minutes. I-V curves were swept as rapidly as possible as the module temperature increases. Module temperature is monitored via Type T thermocouples installed on the back of each module in a checkerboard pattern on every other cell: 36 thermocouples on the 72 cell module (6 x 12 cell configuration) as indicated in Figure 2, and 18 thermocouples in a similar pattern on the 36 cell module (4 x 9 cell configuration). For reference the three thermocouple locations specified in IEC 61853-1 [4] are indicated in Figure 2 by blue squares.

Thermocouples were coated with thermally conductive paste before attachment to increase the accuracy of temperature readings. Temperature measurements were recorded using 2 Logic Beach Intelliloggers that recorded 15 second averages of instantaneous readings every 3 seconds.

C. Determination of average cell temperature during outdoor testing

For indoor testing there is no ambiguity regarding cell temperature because the test chamber and module under test are isothermal. However, for a module operating outdoors there can be substantial temperature variations among the module's cells, raising the question: what temperature should be considered as the cell temperature?

Fig. 1. 72 cell module mounted on tracker with data loggers.

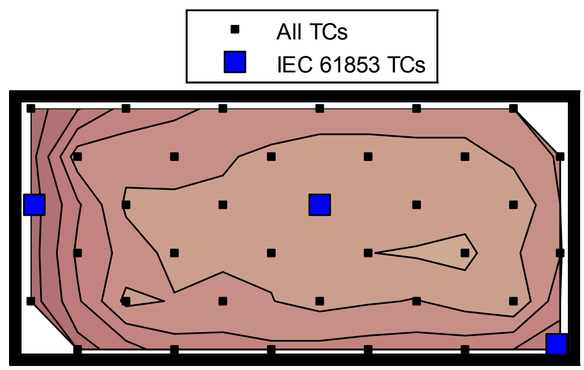

Fig. 2. Thermocouple locations on the 72 cell module.

Temperature coefficients represent the change in an electrical characteristic (voltage, current or power) with a change in temperature which is unambiguously defined for a single cell in isothermal conditions. For predicting output from a PV system it is most likely that the model assumes a single temperature for the array, and to be useful the temperature coefficients should be determined consistent with this modeling assumption. Current is nearly insensitive to a change in temperature for most types of cells. Because it is reasonable to assume that cells comprising a module are generally well-matched we may also assume that module current is nearly insensitive to changes in temperature. Cell voltage, however, may change significantly with changes in temperature. The single temperature value which serves as the best index for module voltage is the average cell temperature because module voltage is additive along the module's series connected cells.

The attached thermocouples measure the back-surface temperature rather than cell temperature. The primary heat capacity resides in a module's glass face and heat transfer is primarily normal to the module rather than laterally within the module. Consequently, it is likely that the module back-surface measurements are offset from cell temperatures by a relatively constant temperature difference that is fairly uniform across the module. Because the temperature coefficient is determined from the slope of a linear model (e.g., voltage vs. temperature), a constant offset in temperature does not affect the temperature coefficient. For these reasons, we regard the average back-surface temperature (i.e., average module temperature) as a reasonable surrogate for average cell temperature, and use these averages to estimate temperature coefficients.

III. ANALYSIS

A. Estimates of average cell temperature during outdoor testing

We first compared estimates of average cell temperature using different combinations of thermocouple locations. We regard the average of all attached thermocouples as the most accurate estimate of average cell temperature. Figures 3 and 4 show the average cell temperatures for the 72 and 36 cell modules, respectively, with traces illustrating all thermocouple temperatures in the inset of each plot. For comparison the average temperature from three thermocouples in the configuration (Figure 2) specified in IEC 61853-1 [4] is also shown. It is clear that the average temperature from 3 thermocouples in the IEC 61853-1 configuration consistently underestimates the average temperature over all thermocouples. Systematic underestimation of the average module temperature causes a steepening of the slope of a line fit to the voltage (or power) vs. temperature data and a corresponding bias in the temperature coefficient.

We observed temperature differences of up to 10°C among the thermocouples, as indicated by the insets. Figure 5 and 6 display temperature maps at various times during the outdoor tests to illustrate the variation of temperature among the cells over time. Figure 5 and 6 were generated using a triangulation method to interpolate between data points (which causes cut-off at two of the corners due to insufficient data). Both modules show a definite bulls-eye pattern that persists as temperatures increased with time. The 36 cell module was warmer in the center and on the left edge where the junction box is located, indicating that the junction box may contribute to unequal cell temperatures.

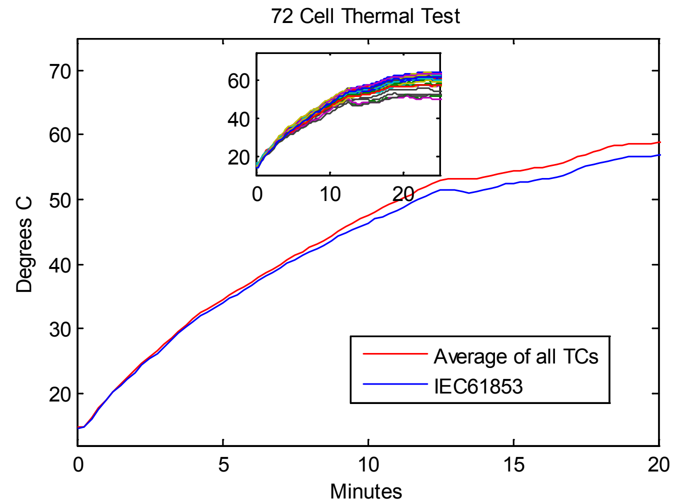

Fig. 3. Temperature measurements for the 72 cell module.

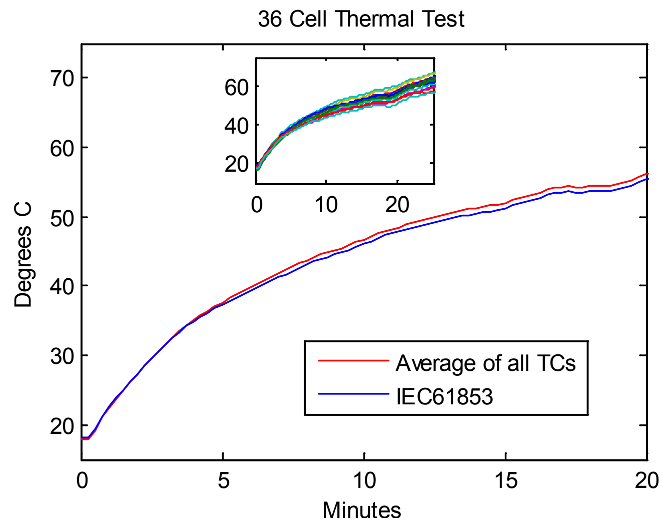

Fig. 4. Temperature measurements for the 36 cell module.

To accurately estimate average cell temperature using only a few thermocouples, appropriate locations must be selected. We explored various combinations of 3 and 4 thermocouples for the 72 cell module and compared their averages with the average module temperature. Figure 7 displays three such alternative combinations: three thermocouples corresponding to the coldest row of cells in the module; a line of 4 thermocouples averaged from the center to the edge furthest from the junction box; and a line of 3 thermocouples from the center to the middle of a long edge.

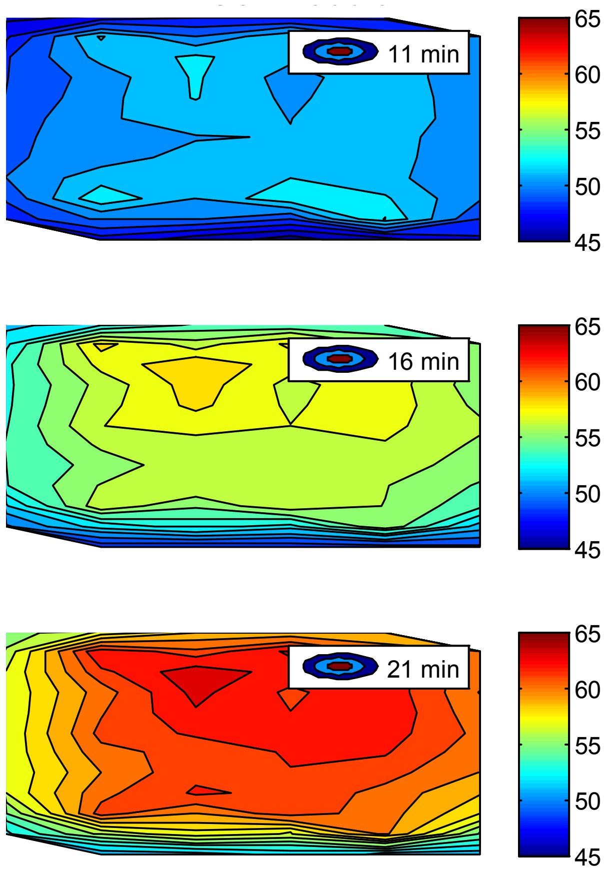

Fig. 5. Temperature maps for the 72 cell module.

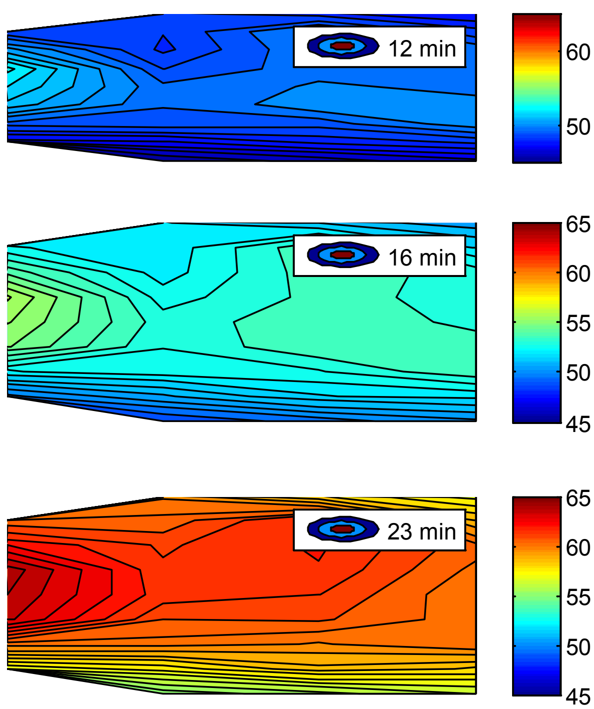

Fig. 6. Temperature maps for the 36 cell module.

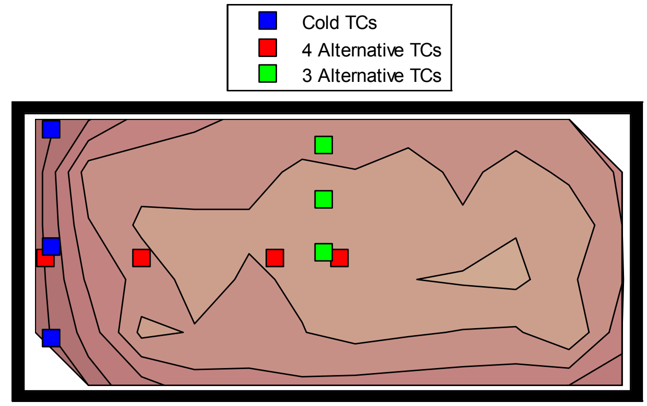

Fig. 7. Alternative thermocouple configurations.

Figure 8 shows the average temperature over time for each combination of thermocouples. Of the combinations shown, the average of the 3 thermocouples (green locations in Figure 7) most closely follows the average module temperature. The configuration specified in IEC 61853 tends to underestimate average module temperature, as does the 'cold' configuration (blue locations in Figure 7). The configuration of 4 thermocouples running from the center away from the junction box (red locations in Figure 7) over-estimates the average module temperature.

B. Comparison of temperature coefficients

We computed temperature coefficients from the indoor testing and compared with coefficients determined from outdoor testing using the average module temperature determined from all attached thermocouples and the configuration specified in IEC 61853-1 [4]. For the 72 cell module we also computed temperature coefficients for the alternative configurations illustrated in Figure 7. Tables 2 and 3 compare temperature coefficients for the 72 cell and 36 cell modules, respectively. The most important coefficient to the prediction of power is the temperature coefficient of Vmp.

TABLE II
TEMPERATURE COEFFICIENTS FOR 72 CELL MODULE

	αIsc (1/°C)	αImp (1/°C)	βVoc (V/°C)	βVmp (V/°C)
Indoor	3.36E-04	-2.49E-04	-0.1358	-0.1441
All TCs	3.56E-04	-1.87E-04	-0.1335	-0.1421
IEC 61853	3.77E-04	-1.97E-04	-0.1413	-0.1505
4 TCs	3.34E-04	-1.76E-04	-0.1253	-0.1335
Cold TCs	3.66E-04	-1.92E-04	-0.1371	-0.1461
3 TC Alternative	3.47E-04	-1.83E-04	-0.1302	-0.1386

TABLE III
TEMPERATURE COEFFICIENTS FOR 36 CELL MODULE

	αIsc (1/°C)	αImp (1/°C)	βVoc (V/°C)	βVmp (V/°C)
Indoor	6.54E-04	-5.68E-05	-0.0762	-0.0793
All TCs	5.94E-04	-4.88E-05	-0.0734	-0.0750
IEC 61853	6.10E-04	-5.01E-05	-0.0753	-0.0769

For the 72 cell module, good agreement is observed between the indoor values and the outdoor values determined from all thermocouples, except for the temperature coefficient of Imp. The temperature coefficients for voltage determined using the IEC 61853-1 configuration are both greater in absolute value than either the indoor value or the value determined outdoors using all thermocouples. Among the alternate configurations, the temperatures for the 3 TC alternative (green locations in Figure 7) is closest to the outdoor, all TC values (Figure 8). However, the resulting temperature coefficients are not close to the values determined from indoor testing and outdoors using all thermocouples. In fact, the difference between the 3 TC alternative configuration and the indoor value is similar to the difference between the indoor value and the outdoor, IEC 61853-1 value. This could partially be accounted for by the fact that the average temperature for the 3 alternative TCs does not match the average for all TCs until roughly 8 minutes into the test (inset of Figure 8).

For the 36 cell module we do not observe a distinct bias toward greater absolute values for temperature coefficients for the IEC 61853-1 configuration.

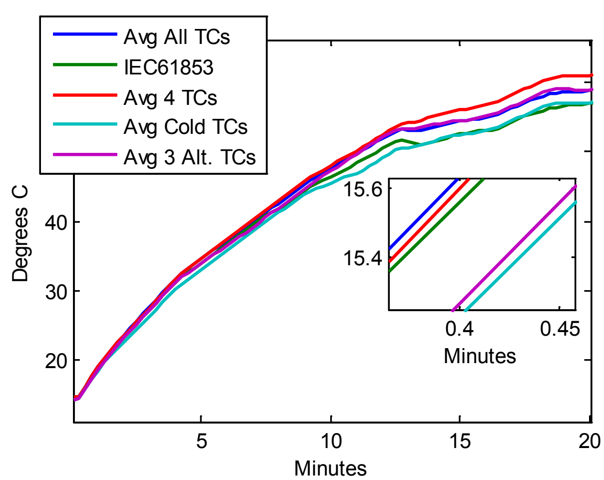

Fig. 8. Average temperatures for various combinations of thermocouples.

IV. CONCLUSIONS

Various studies have reported differences among temperature coefficients determined for the same modules using different indoor testing methods [5], [6]. Comparison between indoor and outdoor testing shows a systematic, but not universal, trend toward coefficients that are greater in absolute value is observed for outdoor testing. We suspect that this trend results from a biased estimate of average cell temperature when using the thermocouple placement as specified in IEC 61853-1, because this configuration appears to underestimate the average module temperature during outdoor testing. This underestimation may also be present during indoor testing when the testing method results in temperature variations among a module's cells.

We have explored whether alternative thermocouple configurations might result in a closer agreement among the temperature coefficients. Our limited exploration did not find an alternative arrangement of thermocouples which clearly overcomes the observed bias in temperature coefficients. More careful analysis is needed to determine better methods for measuring module temperature during outdoor testing, and these methods may depend on a module's geometry and/or materials.

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V. REFERENCES

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