Calibration of the Sandia Array Performance Model Using Indoor Measurements

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***Abstract* — The Sandia Array Performance Model (SAPM) describes the DC output of a PV module under a range of irradiance and temperature conditions. Coefficients for SAPM are normally obtained through a sequence of on-sun tests, which can be expensive and time-consuming. We report progress towards developing test methods and analysis procedures to obtain coefficients for SAPM from indoor testing. We compared module output predictions from SAPM with coefficients extracted from indoor test results, to measured on-sun module output, and found biases in the predicted performance. We hypothesize that these biases result from the uniform cell temperatures during indoor testing, whereas measured cell temperatures vary by up to 10°C among cells during on-sun conditions. However, we also hypothesize other explanations for the observed biases.**

***Index Terms* — Modeling, Parameter extraction, Performance analysis, Photovoltaic systems, Solar power generation.**

I. Introduction

The Sandia Array Performance Model (SAPM) [1] relates module voltage and current at three key points on the I-V curve (open circuit, short circuit, and maximum power) to effective irradiance and cell temperature. The full model also estimates two additional points lying between short circuit and maximum power, and between maximum power and open circuit. Model parameters are estimated by regression of measurements of current and voltage to measured irradiance and temperature. Methods for parameter estimation and analysis of parameter uncertainty are reported in [2].

To date, parameters for SAPM have been determined from on-sun measurements of module performance. Modules are mounted on a two-axis tracker and I-V curves are measured across a range of irradiance and temperature conditions. The tracker is rotated away from the sun to determine angle-of-incidence effects. Model parameters obtained from on-sun measurements thus represent the module's performance in outdoor conditions. However, the test process requires multiple days of measurements to capture module performance across the appropriate range of environmental conditions. Currently, only Sandia National Laboratories and TUV Rheinland PTL in Tempe, AZ, USA, offer these test services.

In contrast, I-V curves can be rapidly measured indoors over a wide range of conditions by means of a solar simulator. CFV Solar Test Laboratory, Inc. has recently fielded a capability to control module temperatures during flash testing, adding a degree of control to testing not previously available. Sandia National Laboratories and CFV partnered to develop methods for calibrating SAPM using I-V curves measured at CFV's facility. Successful calibration would significantly reduce the time and cost involved in calibrating SAPM for new PV modules and would also extend capability to obtain SAPM coefficients broadly to the testing industry.

In this paper, we first summarize SAPM and describe the determination of model parameters from outdoor and indoor measurements. The model is calibrated for a SunPower 305 W_{STC} crystalline silicon module that was characterized by outdoor testing in Albuquerque, NM, by Sandia National Laboratories, and indoor testing by CFV Solar Test Laboratory, Inc., of Albuquerque, NM. We compare SAPM results using parameters determined from both indoor and outdoor testing.

II. Performance Model

SAPM [1] is an empirical model of module output at open-circuit, short-circuit and maximum power conditions. The fundamental equations in SAPM are:

$$V_{OC} = V_{OC0} + N_S n\delta(T_C)\ln(E_e) + \beta_{OC}(T_C - T_0) \quad (1)$$

$$V_{MP} = V_{MP0} + C_2 N_S n\delta(T_C)\ln(E_e) + C_3 N_S \left(n\delta(T_C)\ln(E_e)\right)^2 + \beta_{MP}(T_C - T_0) \quad (2)$$

$$I_{SC} = I_{SC0} f_1(AM_a) E_e \left(1 + \alpha_{SC}(T_C - T_0)\right) \quad (3)$$

$$I_{MP} = I_{MP0}\left(C_0 E_e + C_1 E_e^2\right)\left(1 + \alpha_{MP}(T_C - T_0)\right) \quad (4)$$

$$E_e = E_b f_2(AOI) + E_{diff} f_d \quad (5)$$

Variables and physical constants are defined in Table 1. The remaining terms (e.g., β_{OC}, C_0, n) are parameters that are to be estimated. The subscript $\sim_0$ indicates a constant evaluated at reference irradiance of 1000 W/m^2 (i.e., 1 sun) and reference cell temperature T_0 (typically 25°C). The empirical function $f_1(AM_a)$ of absolute airmass, AM_a, corrects I_{SC} to account for atmospheric attenuation of the solar spectrum. The empirical function $f_2(AOI)$ of angle of incidence, AOI, corrects E_b to account for reflection losses at the module surface. The coefficient f_d quantifies the fraction of incident diffuse irradiance captured by the module, and is assumed to equal 1 for flat-plate modules.

TABLE I
DEFINITION OF VARIABLES IN SAPM

Variable	Definition
V_{OC}	Open-circuit voltage (V)
V_{MP}	Voltage (V) at maximum power
I_{SC}	Short-circuit current (A)
I_{MP}	Current (A) at maximum power
T_C	Cell temperature (K)
E_e	Effective irradiance (suns), i.e., the portion of incident irradiance converted to electricity.
E_b	Beam component of incident irradiance (suns)
E_{diff}	Diffuse component of incident irradiance (suns)
N_S	Number of cells in series
$\delta(T_C) = nkT_C/q$	Thermal voltage (V)
k	Boltzmann's constant, 1.38×10^{-23} J/K
q	Elementary charge, 1.62×10^{-19} C

III. TEST EQUIPMENT AND PROCEDURES

For the work described in this paper, one SunPower 305 watt module was characterized using both indoor and outdoor measurement procedures. Model parameters were derived separately from each data set.

A. Outdoor Testing

Sandia's outdoor characterization entails placing the module on a 2-axis solar tracker to control angle of incidence, and sweeping periodic I-V curves as the module is subjected to a series of three test sequences. During each of the test sequences, the module's temperature is monitored via thermocouples (typically three thermocouples), and weather conditions such as wind speed, ambient temperature, solar radiation, etc. are measured using Sandia's on-site weather instrumentation. The module I-V curve is collected and the module is held at maximum power by Sandia's custom data acquisition systems which employ electronic loads, multimeters, and power supplies.

1. Initially, a thermal test sequence is completed where the module is cooled to near-ambient temperature by shading the module from the sun. Once the shade is removed, the module heats to operating temperature over the course of perhaps 30 minutes. I-V curves are taken as the module temperature increases. The module maintains $AOI = 0$ during the thermal test.
2. An electrical performance test sequence is performed during which I-V curves are taken approximately every minute as the tracker follows the sun to maintain $AOI = 0$. The collected I-V data must include many hours with clear-sky conditions over a wide range of solar zenith angle, as well as many hours with variable irradiance over a wide range of zenith angles. Consequently, the electrical performance test may require several weeks to complete. Typically, several thousand I-V curves are collected which form the data from which to determine all remaining SAPM performance coefficients.
3. Finally, an incident angle test sequence is performed where the 2-axis tracker is rotated to orient the module away from the sun at controlled intervals and I-V curves are taken at each interval.

B. Indoor Testing

Indoor testing was employed to obtain I-V curves sufficient to estimate most, but not all, coefficients for the SAPM. In particular, variation in module performance due to changing air mass and incident angle could not be determined using the indoor test methods available. However, an indoor test program was devised to obtain measurements from which the other parameters could be determined.

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 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 as a reference for equipment configuration for 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 over the range of irradiance and cell temperature conditions specified in IEC 61853-1 [3]. I-V curves were measured at the combinations of temperature and irradiance indicated in Fig. 1a. For comparison, Fig. 1b displays the combinations of temperature and irradiance at which I-V curves were recorded during the electrical performance test outdoors, conducted in Albuquerque, NM, in December 2011, and which included 4 days with mostly clear-sky conditions, and three days with variable irradiance conditions. When the module is within 0.2° C of the target temperature and the variation in temperature among sensors is less than 1.2° C, 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.

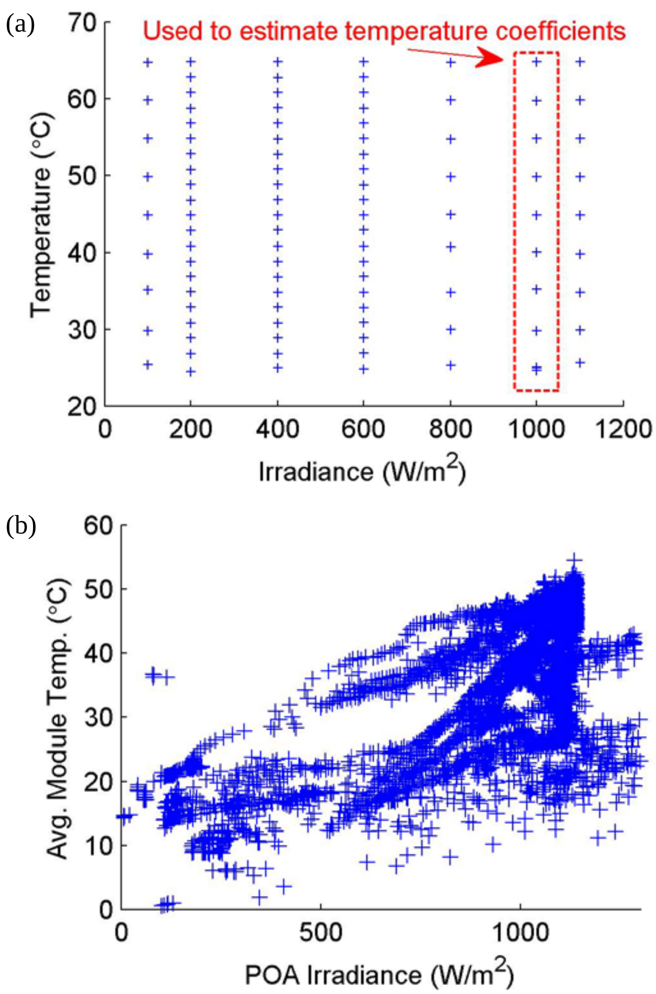

Fig 1. Temperature and irradiance corresponding to each recorded I-V curve: a) indoor measurements; b) outdoor measurements during electrical performance test.

For accurate estimation of parameters, 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.

Irradiance corresponding to each point on the I-V curve is measured by a reference cell near the PV module under test. Measured current is corrected for varying irradiance according to Eq (3) of IEC 60891 ed. 2 [4], which, because temperature is assumed constant during the flash pulse, becomes:

$$I_T = I_m + \frac{G_m}{G_{SC}} I_{SC} \left(\frac{G_T}{G_m} - 1 \right) \tag{6}$$

where G denotes irradiance, the subscript $\sim_m$ indicates a measurement, the subscript $\sim_T$ denotes a value at the desired irradiance, and the subscript $\sim_{SC}$ refers to short-circuit conditions. We considered but did not correct voltage for varying irradiance because corrections would be less than 0.1% of the measured values.

In most cases, the measured I-V data does not include a point exactly at $(V, I) = (0, I_{SC})$. The value for I_{SC} is found by linear interpolation between the two I-V points bracketing $V = 0$, or by extrapolation by a linear regression on I-V points within $0.75\text{V} \le V \le 2.0\text{V}$. A similar procedure determines V_{OC}. The maximum power point (V_{MP}, I_{MP}) is found by linearly interpolating between measured points.

IV. Parameter Estimation

A. Parameters from Outdoor Testing

As described in greater detail in [2], model parameters can be estimated using data obtained during the test sequences described in section III. Here, we outline the process for determining coefficients for the SAPM model from data measured outdoors:

1. Using data from the thermal test sequence, measured voltage and current are translated to values at a standard irradiance of 1000 W/m^2, using standard methods, and regressions of the I-V points taken at varying temperatures are used to determine module temperature coefficients (i.e., β_{OC}, β_{MP}, α_{SC}, and α_{MP}). For example, with irradiance at 1000 W/m^2, $E_e = 1$ sun, so Eq. 1 simplifies to

$$V_{OC} = V_{OC0} + \beta_{OC} \left(T_C - T_0 \right) \tag{7}$$

   and β_{OC} is obtained by a linear regression between V_{OC} and T_C.
2. From the data collected during the electrical performance test sequence, the remaining SAPM parameters are estimated in two-step process:
   a. Using the I-V curves collected during clear-sky conditions, and the value of α_{SC} previously determined, the parameter I_{SC0} is estimated by regression over the portion of these data for which $1 \le AM_a \le 2$. The parameters V_{OC0},

V_{MP0} and I_{MP0} and the empirical function $f_1(AM_a)$ are determined by regression from the full set of clear-sky data by assuming that $E_e = 1$ during these measurements and using the previously-determined temperature coefficients.

b. The temperature coefficients and the parameters determined in Step 2a are then used to estimate n and C_0 through C_3 by regression from the full set of I-V curves collected during the electrical performance test (i.e., including periods of clear-sky and variable irradiance).

3. Data from the incident angle test sequence are used to estimate the empirical function $f_2(AOI)$. Beam and diffuse irradiance (E_b and E_{diff} , respectively) are estimated from measured total plane-of-array irradiance and direct normal irradiance. The combination of Eq. 3 and Eq. 5 are solved for $f_2(AOI)$ as a function of measured short-circuit current I_{SC}. Coefficients for the function $f_2(AOI)$ are determined by regression, using the previously estimated values for I_{SC0} , α_{SC} and $f_1(AM_a)$.

B. Parameters from Indoor Testing

From the indoor measurements, we estimated all parameters except for the empirical functions $f_1(AM_a)$ and $f_2(AOI)$ using a two-step approach analogous to that employed for outdoor measurements. The diffuse fraction f_d is assumed to be 1 for both outdoor and indoor testing. For indoor testing, we assumed that effective irradiance E_e was equal to the measured output of the flash tester, because output was measured with a reference cell having characteristics similar to the module under test, and the module was oriented to achieve near zero AOI . We also assumed that cell temperature T_C is equal to test chamber temperature, i.e., the minor heating caused by the flash and the electrical current within the module's cells is neglected. Moreover, for indoor measurements, AM_a is taken equal to 1.5, and thus $f_1(AM_a) = f_1(1.5) = 1$ by definition [2].

We first estimated temperature coefficients β_{OC} , β_{MP} , α_{SC}, and α_{MP} using only I-V curves measured with irradiance near 1000 W/m^2 and module temperature ranging from 25°C to 65°C. With values for β_{OC}, β_{MP}, α_{SC}, and α_{MP} in hand, and with the assumptions listed above, the other parameters in Eq. 1 through Eq. 4 were obtained by multiple regression between (E_e, T_C) and each of V_{OC}, V_{MP}, I_{MP} and I_{SC}. Table 2 lists parameter values obtained from outdoor and indoor measurements.

We also attempted other parameter estimation strategies, including:

– simultaneous estimation of all parameters;
– estimation of temperature coefficients as above, followed by estimation of the remaining parameters using I-V curves with measured temperature between 47°C and 53°C; and
– a more sequential process, where 1) temperature coefficients are obtained as above, then 2) temperature coefficients are used to estimate I_{SC0} , then 3) Eq. 3 is used to compute $\hat{E}_e$, which is then used in place of E_e to estimate the remaining parameters.

These alternative strategies showed either no improvement upon, or worse performance than, the two-step procedure outlined above.

TABLE II
PARAMETER VALUES FOR SAPM

Parameter	Outdoor Model	Indoor Model
β_{OC} (V/°C)	–0.195	–0.197
V_{OC0} (V)	65.044	64.882
β_{MP} (V/°C)	–0.183	–0.184
V_{MP0} (V)	54.193	54.15
α_{MP} (1/°C)	–0.00017	–0.000169
I_{MP0} (A)	5.623	5.631
α_{SC} (1/°C)	0.000425	0.000378
I_{SC0} (A)	5.976	5.969
n (unitless)	1.12	1.074
$C_0; C_1$ (unitless)	1.0121; –0.0121	1.0069; –0.0069
$C_2; C_3$ (unitless)	0.3114; –5.0257	0.3379; –4.7201
N_S (cells in series)	96	96

V. MODEL COMPARISON AND VALIDATION

We benchmarked the capability of SAPM to predict outdoor performance by using the parameters obtained from outdoor testing (the "outdoor" model) to predict the measured module output during the electrical performance test. During this test, the tracker maintained $AOI = 0$ and irradiance was measured in the plane of array by a reference cell. Accordingly, we set E_e equal to measured plane of array irradiance. We set module temperature T_m equal to the average of measurements from three thermocouples attached to the module's back surface, and calculate T_C as in [1], Eq. 12:

$$T_C = T_m + E_e \times \Delta T \quad (8)$$

where $\Delta T = 3°C$ is typical of flat-plate modules.

We then used the parameters obtained from indoor testing (the "indoor" model) to predict module performance during the outdoor electrical performance test. In these predictions, we used the empirical function $f_1(AM_a)$ determined from outdoor measurements, due to the present inability to determine this function from indoor measurements.

Figure 2 shows that the outdoor model predicts power within 5W of measurement and without bias over the wide range of conditions occurring during the test (see Fig. 1b). Moreover, the indoor model also achieves the same level of accuracy in prediction.

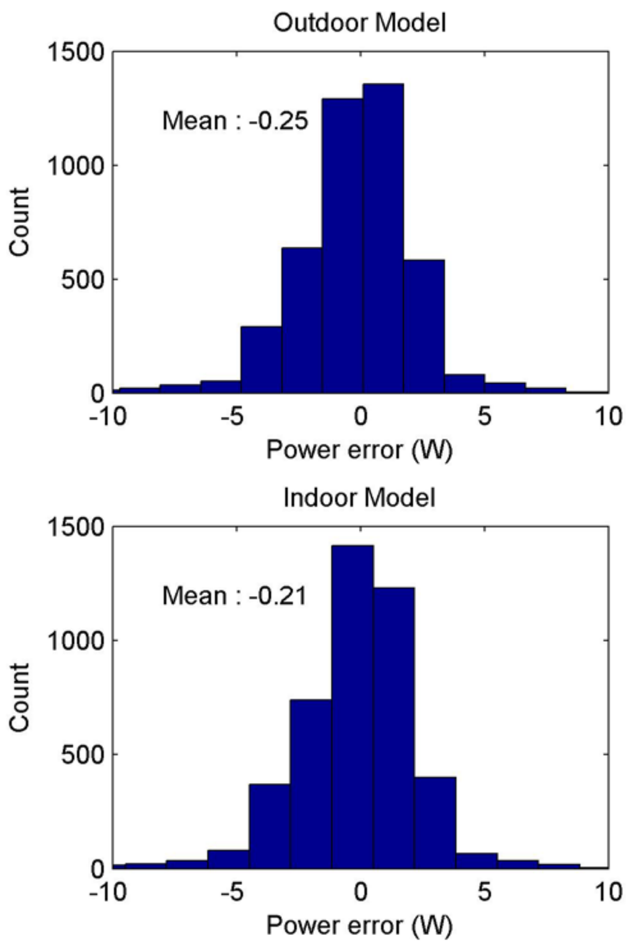

Fig 2. Error in predicted power for outdoor performance: outdoor and indoor models.

Surprisingly, despite the differences in test procedures, measurement equipment, and analysis processes, there is little difference in the power predicted by the two models (Fig. 3). A slight bias toward predicting higher power is evident for the indoor model but these occurrences are relatively rare.

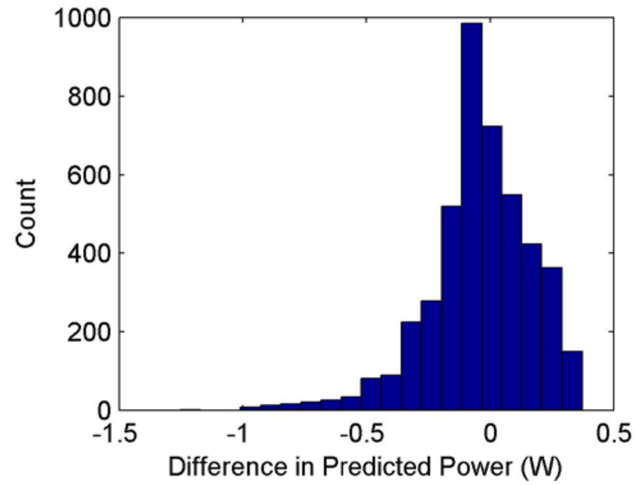

Fig 3. Difference in predicted power (W): Outdoor model minus Indoor model.

We also examined predicted V_{MP} and I_{MP} (Fig. 4), to confirm that the observed accuracy in power predictions did not result from offsetting errors in predicted voltage and current. We found predictions of voltage and current to also have small error.

VI. Solar Spectrum and Angle of Incidence Effects

Use of SAPM to predict outdoor performance requires the empirical function $f_1\left(AM_a\right)$ that corrects I_{SC} for the variation in solar spectrum throughout the day, and the empirical function $f_2\left(AOI\right)$ that corrects E_b to account for reflection at the module's surface. At present, we do not have a method to propose to obtain $f_1\left(AM_a\right)$ from indoor measurements, and indeed, it may be impractical to do so. Measurement using a flash tester would require methods to adjust the spectrum of the flash to represent different air masses. Instead, we are investigating methods for obtaining the necessary outdoor measurements of I_{SC} that will permit estimation of $f_1\left(AM_a\right)$ without using an automated two-axis tracker, and that can be completed within one day. We have found promising results by manually-orienting a module toward the sun at intervals throughout an afternoon but more measurement, and validation, must be completed.

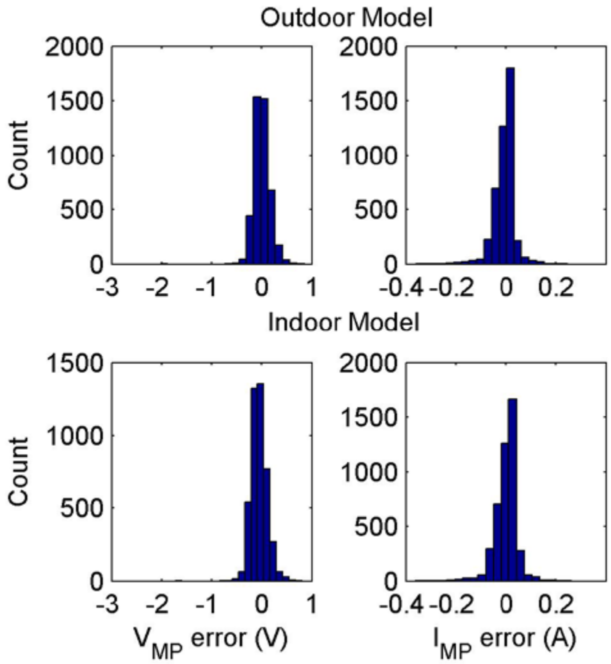

Fig 4. Error in predicted V_{MP} (V) and I_{MP} (A) for outdoor and indoor models.

Empirical determination of $f_2(AOI)$ requires measurements of I_{SC} over a range of incidence angles, and concurrent measurements of E_b. With an appropriately configured flash tester, in which the module could be rotated through a wide range of angles, it appears feasible to obtain the appropriate measurements during indoor testing. We have not yet made the attempt. However, when $f_2(AOI)$ has not been measured, it is common practice to substitute a function that has been measured for a module of similar construction. This practice appears reasonable, because reflection losses for typical front-surface materials are small over a wide range of AOI [1], and because reflection losses are primarily determined by the front-surface material itself, rather than by other aspects of a module's components or construction. Consequently, we view the use of surrogates for $f_2(AOI)$ as acceptable.

VII. Conclusion

We have developed and demonstrated measurement techniques and methods for parameter estimation to obtain the majority of parameters for the SAPM from indoor measurements. Currently, we do not offer a method to determine the empirical function that represents the effects of variation in solar spectrum but we are actively investigating potential methods. We also do not offer a method to estimate the empirical function that quantifies reflection losses, but we view the use of surrogates in place of an empirically-determined function as an acceptable practice.

Validation of the method with one SunPower 305W crystalline silicon module showed that outdoor performance can be predicted with equal accuracy for models obtained from either indoor or outdoor measurements. With practice and appropriately configured equipment, these methods may reduce the time required for testing from many days to several hours.

However, our validation was carried out with only a single module for which the SAPM provides an excellent representation of its performance. Additional validation should be conducted with other modules of similar manufacture, and with modules employing different technology (e.g., CdTe, amorphous silicon, CIGS).

Finally, our methods for estimating parameters permit investigation of the relationship between the number of measured I-V curves and the uncertainty in predictions from the resulting model. Additional I-V curves allow model parameters to be estimated with greater precision, and if an insufficient number of measured I-V curves are available, the lack of precision would produce a model with unacceptable accuracy. However, the pertinent question is "how many I-V curves are enough, and at which combinations of temperature and irradiance should these curves be measured?" We intend to explore this question in future research.

Acknowledgement

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References

[1] D. L. King, W. E. Boyson, J. A. Kratochvil, *Photovoltaic Array Performance Model*, SAND2004-3535, Sandia National Laboratories, Albuquerque, NM.

[2] C. Hansen, J. Stein, S. Miller, W. Boyson, J. Kratochvil, D. King, "Parameter Uncertainty in the Sandia Array Performance Model for Flat-Plate Crystalline Silicon Modules," in *37th IEEE Photovoltaic Specialist Conference*, 2011, p. 3138 – 3143.

[3] International Electrotechnical Commission (IEC), International Standard 61853-1 Ed. 2, 2011.

[4] International Electrotechnical Commission (IEC), International Standard 60891 Ed. 2, 2009.