SANDIA REPORT
SAND2016-5284
Unlimited Release
Printed June 2016

Procedure to Determine Coefficients for the Sandia Array Performance Model (SAPM)

Bruce H. King, Clifford W. Hansen, Daniel Riley, Charles D. Robinson and Larry Pratt

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2016-5284
Unlimited Release
Printed June 2016

Procedure to Determine Coefficients for the Sandia Array Performance Model

Bruce H. King, Clifford W. Hansen, Daniel Riley, Charles D. Robinson, Larry Pratt
Photovoltaics and Distributed Systems Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0951

Abstract

The Sandia Array Performance Model (SAPM), a semi-empirical model for predicting PV system power, has been in use for more than a decade. While several studies have presented comparisons of measurements and analysis results among laboratories, detailed procedures for determining model coefficients have not yet been published. Independent test laboratories must develop in-house procedures to determine SAPM coefficients, which contributes to uncertainty in the resulting models. Here we present a standard procedure for calibrating the SAPM using outdoor electrical and meteorological measurements. Analysis procedures are illustrated with data measured outdoors for a 36-cell silicon photovoltaic module.

ACKNOWLEDGMENTS

CFV Solar Test Labs of Albuquerque, New Mexico, contributed substantially to the development of this procedure.

Development of this procedure was supported by the U. S. Department of Energy SunShot Initiative.

CONTENTS

FIGURES

TABLES

NOMENCLATURE

AM	air mass
AOI	angle of incidence
DNI	direct normal irradiance
DOE	Department of Energy
GNI	global normal irradiance
GPOA	global plane of array irradiance
IV	current-voltage
MPP	Maximum Power Point
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Lab
POA	plane of array
PV	photovoltaic
RTD	Resistance Temperature Detector
SAM	System Advisor Model
SAPM	Sandia Array Performance Model
SNL	Sandia National Laboratories
SPA	Sun Position Algorithm
STC	standard test conditions
T/C	thermocouple

1. INTRODUCTION

1.1. Background

The Sandia Array Performance Model (SAPM) [1] is a semi-empirical model for predicting PV system power output and several other key performance parameters. Developed between 1991 and 2003, the SAPM is a component of the System Advisor Model (SAM) [2] distributed by NREL and forms the basis for a number of commercial and private performance models. Recently, code for SAPM has been released in both Matlab [3] and Python [4]. However, methods to generate coefficients for SAPM from performance measurements of modules have not been formally published by Sandia.

Prior efforts to transfer model calibration capability to third-party labs have resulted in only limited dissemination of Sandia's measurement and analysis methods. In 2006, Fanney et al. [5] compared measured performance parameters for three modules tested outdoors at the National Institute of Standards and Technology (NIST) and Sandia. They described the equipment used to collect the experimental data, the test procedures and resulting performance parameters for each of the three modules. However, Fanney et al. [5] did not directly address the question of independent SAPM coefficient generation and did not present a stepwise procedure for performing the analysis.

In 2011, Granata, et al. [6] reported on a more extensive effort to transfer this capability to TÜV Rheinland PTL. This study included two round-robin tests on two sets of three modules each. The results from this round of testing were used to independently develop SAPM coefficients at each lab. A comparison of annual energy yield predictions demonstrated prediction accuracy of less than 2%. While the transfer was deemed a success, the paper did not address the methodology in a way that was useful to other test labs; rather it served as objective proof of TÜV-PTL's ability to independently test modules and develop SAPM coefficients.

Prior to this work, Sandia published summaries describing how SAPM coefficients can be determined from measurements [7], [8]. However, these summary descriptions lacked the step-by-step details necessary to clearly describe the process for the measurements and data analysis. More recently, Peng [9] presented a set of indoor and outdoor methods to determine coefficients for amorphous silicon modules.

In response to requests from commercial laboratories and module manufacturers, Sandia is formally documenting the measurement and analysis methods. This procedure is accompanied by the data set used to illustrate each analysis step, available online at https://pvpmc.sandia.gov.

1.2. Sandia Array Performance Model Overview

The Sandia Array Performance Model consists of four primary equations describing short circuit current, open circuit voltage, current at MPP and voltage at MPP. These primary equations are supported by up to nine auxiliary equations. The equation for short circuit current is the core component of the model as it is used to calculate Effective Irradiance, which is used in all remaining equations.

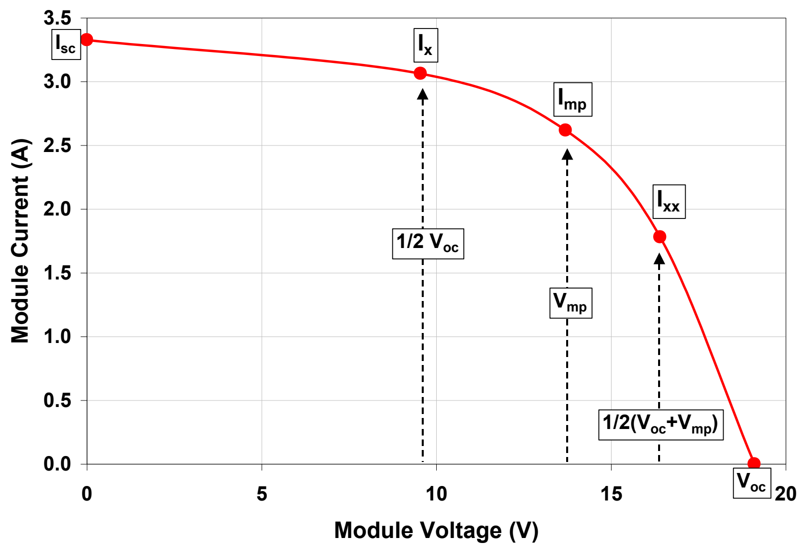

Figure 1. Model points on the IV curve described by the Sandia Array Performance Model (reproduced from [1]).

The equation for I_{sc} is given by;

$$I_{sc} \ = \ I_{sco} f_1(AM) \left[\frac{G_{poa}}{G_0}\right] [1 + \hat{\alpha}_{Isc}[T_c - T_0]]$$

where the function $f_1(AM)$ is a polynomial function linking the influence of air mass to photo-generated current.

$$f_1(AM) = a_0 + a_1(AM) + a_2(AM)^2 + a_3(AM)^3 + a_4(AM)^4$$

G_{poa} may be decomposed into beam and diffuse components

$$G_{poa} = G_b f_2(\theta) + f_d G_{diff}$$

where $f_2(\theta)$ is a polynomial function describing the reflection losses from the front surface of the module due to the angle of incidence between the module and the sun.

$$f_2(\theta) = b_0 + b_1(\theta) + b_2(\theta)^2 + b_3(\theta)^3 + b_4(\theta)^4 + b_5(\theta)^5$$

Substituting G_{poa} into the equation for I_{sc} gives the classical formulation presented in King [1].

$$I_{sc} \ = \ I_{sco} f_1(AM) \left[\frac{G_b f_2(\theta) + f_d G_{diff}}{G_0}\right] [1 + \hat{\alpha}_{Isc}[T_c - T_0]]$$

Effective irradiance, used for all remaining calculations, is given by

$$E_e = \frac{I_{sc}}{I_{sco}\left[1 + \hat{\alpha}_{Isc}[T_c - T_0]\right]}$$

The remaining primary equations then are;

$$V_{oc} = V_{oco} + N_s \delta(T_c) \ln(E_e) + \beta_{Voc}[T_c - T_0]$$

$$I_{mp} = I_{mpo}[C_0 E_e + C_1 E_e^2]\left[1 + \hat{\alpha}_{Imp}[T_c - T_0]\right]$$

$$V_{mp} = V_{mpo} + C_2 N_s \delta(T_c) \ln(E_e) + C_3 N_s [\delta(T_c)\ln(E_e)]^2 + \beta_{Vmp}[T_c - T_0]$$

where $\delta(T_c)$, the thermal voltage per cell, is given by

$$\delta(T_c) = \frac{nk[T_c + 273.15]}{q}$$

Two additional equations may be used to find intermediate points along the IV curve. These points were originally included to support modeling of battery-based systems in which PV modules may operate off of the MPP. I_x is defined as the current at the point on the IV curve where the voltage is one half the open circuit voltage. I_{xx} is defined as the current at the point on the IV curve where the voltage is halfway between maximum power and open circuit voltages.

$$I_x = I_{xo}[C_4 E_e + C_5 E_e^2]\left[1 + \left[\frac{\hat{\alpha}_{Isc} + \hat{\alpha}_{Imp}}{2}\right][T_c - T_0]\right]$$

$$I_{xx} = I_{xxo}[C_6 E_e + C_7 E_e^2]\left[1 + \hat{\alpha}_{Imp}[T_c - T_0]\right]$$

In the original model, temperature sensitivity of I_x was accounted for using α_{Isc}, the temperature coefficient for I_{sc}. This was subsequently changed to use the average of the temperature coefficients for I_{sc} and I_{mp}, however this change was never formally published. Use of the average value of the two temperature coefficients for current can in rare cases lead to calculated I_x exceeding calculated I_{sc}, which has no physical basis. A forthcoming revision to the model is anticipated to address this by replacing the use of an average temperature coefficient with a temperature coefficient generated specifically for I_x.

Finally, cell temperature, T_c is rarely known, whereas module temperature T_m is readily measurable. A simple one-dimensional thermal conduction model is used to calculate cell temperature from module temperature.

$$T_c = T_m + \frac{G_{POA}}{G_0}\Delta T$$

where ΔT is the temperature difference between a cell and module back surface at solar irradiance of 1000 W/m^2 (typically assumed to be 3°C). In addition, module temperature may be linked to ambient temperature T_a through the "wind speed" equation,

$$T_m = T_a + G_{POA} e^{a+bW}$$

1.3. Measurement and Analysis Procedure Overview

The measurement procedures largely follow the methodology described in [5]. Characterization is performed outdoors on a two-axis Azimuth-Elevation tracker. Modules are instrumented with thermocouples attached to the back sheet (or glass) of the module, and then mounted on the tracker. The majority of measurements are performed with the module held normal to the sun. After an appropriate light-soaking period, a thermal characterization is performed to determine temperature coefficients for voltage, current and maximum power. Electrical performance is characterized by measuring IV curves at two-minute intervals under clear and cloudy conditions, ideally across multiple days to determine the module's response to changing irradiance and spectrum. Finally, the angle of incidence behavior of the module is determined by measuring short circuit current at prescribed incident angles between the sun and the module normal. Terms used in this procedure are summarized in Tables 1 - 5. The complete set of module coefficients is summarized in Section 7.

A. Thermal Test to Determine PV Module Temperature Coefficients

Thermal characterization is performed to determine temperature coefficients for I_{sc}, I_{mp}, V_{oc}, and V_{mp}. This procedure requires no prior knowledge regarding the electrical performance characteristics of the module being tested, although the module voltage and current at STC are useful when expressing the temperature coefficient in terms of percent per degree Celsius and are used to calculate temperature coefficients for P_{mp}.

B. Electrical Performance Test and Analysis

Electrical performance testing and analysis produces the majority of the coefficients for the SAPM. In addition to STC values for I_{sc}, I_{mp}, V_{oc}, and V_{mp}, and the cell diode factor, the electrical performance test produces a function describing the response of module short circuit current to variations in solar spectrum, usually indexed by air mass, a function describing cell temperature, and secondary coefficients (the so-called "C" coefficients) relating various points on the IV curve to effective irradiance. Module temperature coefficients must be determined prior to performing the electrical performance analysis.

C. Angle of Incidence Testing

Angle of Incidence (AOI) testing characterizes reflection losses. In [1] the reflection loss function is modeled as a polynomial in AOI; however, the measured data can be fit to other model forms. AOI testing may be considered as optional for modules utilizing a plain glass cover sheet lacking antireflective coating or texture because an accurate general-purpose model is available. The AOI test is the most difficult test to perform due to the requirements for tracker articulation. Most commercial two-axis solar trackers do not have a range of motion substantially beyond what is required to keep a module normal to the sun throughout the day.

Table 1. Measured values required for analysis

Symbol	Definition
I_{sc}	Short circuit current (A)
V_{oc}	Open Circuit Voltage (V)
I_{mp}	Current at maximum power (A)
V_{mp}	Voltage at maximum power (V)
I_x	Current at V= 0.5*V_{oc}, (A)
I_{xx}	Current at V= 0.5*(V_{oc}+V_{mp}), (A)
T_m	Module back surface temperature, (°C)
T_a	Ambient temperature (°C)
P	Barometric pressure, (Torr)
W	Wind speed, (m/s)
E_{poa}	Irradiance in plane of the array (W/m^2), typically a reference cell
G_{poa}	Broadband irradiance in plane of the array (W/m^2), typically a pyranometer
G_{DNI}	Direct normal irradiance (W/m^2), typically a pyrheliometer
G_{diff}	Diffuse component of irradiance (W/m^2),
Z_s	Zenith angle of sun, measured from vertical (degrees)
AZ_s	Azimuthal angle of Sun from North, (degrees)
Z_m	Zenith angle of module, measured from vertical (degrees)
AZ_m	Azimuthal angle of module normal from North, (degrees)

Table 2. Constants and reference conditions

Symbol	Definition
A	Module area (m^2)
E_0, G_0	Irradiance at STC, 1000 W/m^2
h	Elevation at which characterization is performed (m)
k	Boltzmann's constant, 1.38066 $\times 10^{-23}$ (J/K)
N_s	Number of series-connected cells in a module cell-string
P_0	Reference barometric pressure, 760 (Torr)
q	Elementary charge, 1.60218 $\times 10^{-19}$ (Coulomb)
T_o	Temperature for reporting, typically 25°C
T_r	Reference Temperature for analysis, typically 50°C.
ΔT	Temperature difference between a cell and the module's back surface at 1000 W/m^2 (°C), typically assumed to be 3°C

Table 3. Intermediate calculated values

Symbol	Definition
T_c	Cell temperature (°C)
AM	Pressure adjusted air mass
E_e	Effective Irradiance in suns, calculated from I_{sc} (dimensionless)
θ	Incident angle between the module and the sun

Table 4. Calculated values from the analysis

Symbol	Definition
$\alpha_{Isc}, \hat{\alpha}_{Isc}$	Temperature coefficient for I_{sc} (A/°C), (1/°C)
$\alpha_{Imp}, \hat{\alpha}_{Imp}$	Temperature coefficient for I_{mp} (A/°C), (1/°C)
$\beta_{Voc}, \hat{\beta}_{Voc}$	Temperature coefficient for V_{oc} (V/°C), (1/°C)
$\beta_{Vmp}, \hat{\beta}_{Vmp}$	Temperature coefficient for V_{mp} (V/°C), (1/°C)
$\gamma_{Pmp}, \hat{\gamma}_{Pmp}$	Temperature coefficient for P_{mp} (W/°C), (1/°C)
I_{sco}, I_{scr}	Reference short-circuit current at T_0, T_r (A)
V_{oco}, V_{ocr}	Reference open-circuit voltage at T_0, T_r (V)
I_{mpo}, I_{mpr}	Reference current at maximum power at T_0, T_r (A)
V_{mpo}, V_{mpr}	Reference voltage at maximum power at T_0, T_r (V)
I_{xo}, I_{xr}	Reference current at V= 0.5*V_{oc} at T_0, T_r (A)
I_{xxo}, I_{xxr}	Current at V= 0.5*(V_{oc}+V_{mp}) at T_0, T_r (A)
$f_1(AM)$	4^{th} order polynomial relating air mass to short circuit current
$f_2(\theta)$	5^{th} order polynomial representing the reflection losses from the front surface of the module
n	Diode (ideality) factor for the module's cells (dimensionless)
C_0, C_1	Coefficients relating E_e to I_{mp}
C_2, C_3	Coefficients relating E_e to V_{mp}
C_4, C_5	Coefficients relating E_e to I_x
C_6, C_7	Coefficients relating E_e to I_{xx}
a, b	Coefficients relating T_a and W to T_m

2. TEST EQUIPMENT

Characterization is performed outdoors on a two-axis Azimuth-Elevation tracker. Modules are instrumented with thermocouples attached to the back sheet (or glass) of the module, and then mounted on the tracker.

Figure 2. Modules under test on a two-axis tracker at Sandia

2.1. Equipment

The following equipment is required to conduct this test procedure:

1. Solar tracker
   a. Situated such that shading and reflection from other structures are negligible during the entire test.
   b. Test plane for mounting the module and reference irradiance sensors
   c. Tracking system capable of keeping the module normal to the sun throughout the measurement process
   d. Off-tracking capability to controllably steer the tracker during Angle of Incidence (AOI) characterization (optional – only used for measuring AOI response). The tracker must have enough range of motion to allow for a 0 - 90 degree AOI between the module POA and the sun. Preferably the full range in AOI can be achieved exclusively through changes in elevation to minimize effects of ground reflections.
   e. Capability for determining the angle between the plane of array and the sun position associated with each I-V scan (optional – only used for measuring AOI response). The AOI typically is calculated from the known tracker position and the known sun position.
2. Irradiance sensors mounted on the test plane (±0.5°)
   a. Reference cell for measuring global plane of array irradiance (typically silicon)
   b. Broadband instrument for measuring global plane of array irradiance (typically a pyranometer), preferably calibrated for angle of incidence response.
   c. Broadband instrument for measuring the diffuse POA irradiance (typically a shaded pyranometer). Optional, refer to Section 2.2 for details.
3. Weather Station
   a. Pyrheliometer measuring DNI, typically mounted on a separate two axis tracker
   b. Wind speed and direction at 10 meter height

   c. Ambient air temperature
   d. Barometric pressure (optional, for use in calculating absolute, pressure adjusted air mass)

4. Capability for measuring and logging module current-voltage (I-V) characteristics in rapid succession, at a rate of 2 scans/minute and preferably at 4 scans/minute or faster. Ensure that the measuring equipment is sufficient to measure V_{oc} at the fully shaded condition as well as I_{sc} at full irradiance.

   Note: POA Irradiance should be inspected immediately before and after each IV scan. If these values differ by more than 3%, the curve should be discarded. This check typically is performed during data collection, but may be performed as part of data quality checks at the conclusion of the test, prior to analysis.

5. Means of measuring the average temperature of the PV module under test to ±1°C. Average temperature is typically determined from measurements of three or four temperature sensors, typically either Type-T thermocouples or RTDs. However, care should be taken to determine whether the resulting data represent the average over the module's cells.
6. Data logging system to simultaneously record IV scans, DNI, POA irradiance, module temperature, ambient temperature, barometric pressure, wind speed, sun position and tracker position. If this data is measured with separate data acquisition systems, ensure the time stamps between each system are synchronized to within a few seconds.
7. Opaque material to shade the module (thermal test only). This allows the module to cool to near ambient temperature prior to the start of the measurements. The test is initiated when the shade is removed. Ideally, a 25 to 50 mm air gap can be maintained between the material and the module to improve convective cooling. Rigid, reflective material such as white foam core board is preferred. The foam should be cut to be 50 - 100 mm larger than the size of the module.
8. Insulation to be added to the back surface of the module (thermal test only). Insulation improves the temperature uniformity across the module and increases the temperature range that can be achieved during the test. "Double bubble" reflective foil insulation has been found to be particularly effective. If testing a framed module, the insulator should be cut to precisely fit within the module frame. It is recommended to have prepared the insulator beforehand using the same or a similar module as a template.

2.2. Plane of Array Irradiance Measurements

The SAPM comprises a set of equations that translate plane-of-array (POA) irradiance, air temperature and wind speed to electrical output of a PV module. A set of model coefficients is estimated using POA measurements obtained with a particular instrument (e.g., pyranometer, reference cell) and thus the instrument type and accuracy is implicit in the SAPM model coefficients. Conceptually, any type of irradiance instrument can be used to develop coefficients as long as measurements from a similar instrument are used for prediction.

The irradiance instrument type used to develop model coefficients is rarely specified. Instead, the usual assumption is that POA irradiance is a broadband measurement. Thus we recommend a broadband thermopile based pyranometer as the model general choice. However, if it is known in advance that model predictions will be referenced to irradiance from an alternate instrument, e.g., a reference cell or silicon photodiode, then model coefficients should be developed with that type of instrument in mind.

The majority of the measurements necessary to calibrate the SAPM are made with the module and irradiance equipment held normal to the sun. For a small subset of measurements, those for the AOI response, the test plane is necessarily taken off sun. This presents a challenge in that pyranometers do not exhibit perfect cosine response to solar AOI and variation can exceed 10%. Global plane of array (POA) pyranometers used for AOI characterization must therefore be appropriately calibrated to obtain accurate results.

Here, we present a novel method of measuring the AOI response of a module [10]. Using a customized tracker with extended travel, the module can be articulated through the full range of 0-90° AOI by rotating only the elevation axis while the azimuthal axis continues to track the sun. This enables the use of a simple method to use measured diffuse irradiance rather than calculated diffuse irradiance (global POA minus cosine adjusted DNI) during analysis. This has several advantages. First, the uncertainty of the POA diffuse measurement is smaller than the uncertainty in a calculated POA diffuse. Second, calculating global POA from measured diffuse POA and direct normal irradiance (DNI) removes the need for an AOI correction for a global POA pyranometer.

Figure 3. Diffuse POA irradiance measurement for elevation-only rotations

3. TEST PROCEDURE

3.1. Environmental Conditions

A broad range of weather conditions is required over the test period. For the electrical performance analysis, weather conditions during the test should include periods of clear sky conditions ideally spanning from sunrise to sunset, as well as the equivalent of several days with non-clear sky conditions (partly cloudy or overcast). In the event that full, clear days are not available, the clear sky data set should be assembled from the equivalent of three days of data from partly clear days. Clear sky data should be from continuous spans of several hours or longer rather than filtered from partly cloudy data. Ideally, test conditions will include AM1.5, but this is not possible at all times of the year. Stable, overcast conditions are preferred for non-clear sky data. Preferred environmental conditions are listed in Tables 6 and 7.

Table 5. Clear Sky environmental conditions during the procedure.

Parameter	**Required**	**Preferred**
Global Normal Irradiance (GNI)	800 - 1050 W/m^2	600 - 1200 W/m^2
DNI/GNI	> 0.85	> 0.90
Air Mass (Absolute, pressure adjusted)	1.5 – 5.0	1.0 – 7.0
Wind Speed	0 - 4 m/s	0 - 10 m/s
Minimum Test duration	600 minutes/2 days	1200 minutes/3 days

Table 6. Cloudy Sky environmental conditions during the procedure.

Parameter	**Required**	**Preferred**
Global Normal Irradiance (GNI)	200 - 400 W/m^2	100 - 500 W/m^2
DNI/GNI*	0 – 0.85 (< 0.05)	
Minimum Test Duration	200 minutes/1 day	1200 minutes/3 days

* a range of conditions are preferred, however the bulk of the measurements should occur at DNI/GNI < 0.05

For measurement of temperature coefficients and AOI response, stable weather conditions are required during the test, which will typically last 30-60 minutes. These measurements are best performed on clear days with minimal haze and low wind speed. The tests are typically performed close to solar noon when spectral irradiance is relatively stable. Ideally the tests are performed close to AM1.5, but this is not possible at all times of the year. For AOI testing, there should be no visible clouds or hazy conditions within a ±45° view angle of the sun during the test period. Jet contrails close to the sun may also influence the measurement. Preferred environmental conditions are listed in Table 8.

Table 7. Environmental conditions during measurement of temperature coefficients and AOI response.

Parameter	Required	Preferred
Global Normal Irradiance (GNI)	800 - 1200 W/m^2	950 - 1050 W/m^2
Variation in GNI	± 2.5%	± 0.5%
DNI/GNI	> 0.85	> 0.90
Air Mass (Absolute, pressure adjusted)	1 - 2	1.4 - 1.6
Wind Speed	< 4 m/s	< 2 m/s
Ambient Temperature	> 0°C	> 10°C

3.2. Module Preparation and Test Setup

The module must be sufficiently pre-conditioned before beginning the test so that changes in the I-V characteristics are a function of environmental or imposed conditions experienced during the test and not from some other phenomenon such as light-induced degradation or meta-stability. Preconditioning should follow the recommended insolation provided in IEC 61215 [11] for crystalline silicon modules (> 5 kWh/m^2) or for thin-film modules, a stabilization procedure similar to that described in [12]. In practice, the module is installed on the tracker without pre-conditioning and the first few days of data collection are excluded from analysis.

In preparation for the measurements;

1. Attach at least three small gauge thermocouples to the back surface of the module (directly behind cells) in the locations shown in Figure 3. For other modules (e.g. monolithic thin-film), thermocouples should be placed in similar locations. Note that the recommended positions are a slight deviation from IEC 60891 [13] (four positions) and IEC 61853 [14] (three positions). Additional thermocouples can be used to reduce uncertainty in the average module temperature or provide redundancy in the measurements.
2. Mount the module in the plane-of-array on the tracker.
3. Attach I-V measuring equipment to the module’s electrical connectors and verify operation.

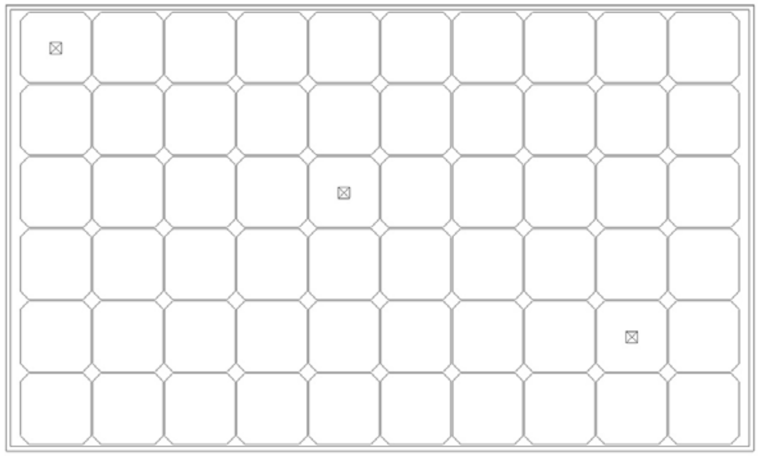

Figure 4. Preferred locations for temperature measurement

3.3. Test procedures

Test procedures may be performed in any logical order, as long as the module has been suitably preconditioned. Since a broad range of environmental conditions over multiple days are desired for the Electrical Performance analysis, the module is typically installed on the tracker with little regard for the current weather. Temperature coefficients and AOI response are typically measured opportunistically during the test when environmental conditions are appropriate.

A. Electrical Performance

1. Clean the front surface of the module. It is recommended to clean the module periodically throughout the duration of the test. Typically, the module will be cleaned a minimum of twice a week. More frequent cleaning may be required after rain or heavy wind.
2. Clean and check the irradiance sensors. This is typically performed at the same time that the module is cleaned.
3. Ensure the tracker is tracking normal to the sun.
4. Initiate IV sweeps. A rate of one scan every two minutes is typical. The module should be held at the maximum power point in between scans if the IV sweep hardware has this capability.
5. Allow the test to operate continuously during daylight hours until a minimum equivalent of 3 clear sky days and 1-2 cloudy sky days are obtained. In aggregate, a minimum of 600 data points (1200 minutes) should be obtained. In practice, a period of 1-4 weeks may be required to obtain sufficient data across the relevant environmental conditions.
6. As necessary perform Thermal Test and Angle of Incidence Tests during the testing period.

B. Thermal Test

1. Clean the front surface of the module.
2. Shade the module from illumination, ensuring that the irradiance sensor remains unshaded. Under typical conditions, the module may have been operational for several hours prior to performing this step and must cool to near ambient. Wait until the module

is within 5°C or less of ambient temperature before proceeding to Step 3. This step may take 30 – 120 minutes depending on ambient conditions.

*Failure to allow the module to cool adequately before applying insulation may result in excessive cooling time and a missed window of appropriate environmental conditions for performing the thermal test***.**

3. Apply the insulation to the module's back surface. It is recommended to have prepared the insulator beforehand using the same or a similar module as a template. The insulation should be installed flush with the back surface of the module with minimal air gaps. Tape is typically used around the perimeter of the module to secure the insulation and further reduce convection.
4. Initiate IV scans and record at a rate of 2 scans/minute or faster. Sandia's standard practice is to use a scan rate 4 scans/minute. The module should be held at the maximum power point in between scans if the IV sweep hardware has this capability.
5. Remove the shade and allow the module to heat naturally.
6. Terminate the test after the module back surface temperatures have reached steady values. The module back-surface temperature should increase to least 30°C above ambient and preferably above 60°C absolute during the test. The total time required to complete this step is typically 30 – 60 minutes but depends on the mass and heat capacity of the module.

Figure 5. Module prepared for thermal test. Insulated back surface (left) and module shade (right).

C. Angle of Incidence

1. Determine AOI values for measurement. Suggested values are listed in Table 9.
2. Clean the front surface of the module

3. Initiate IV scans and record at a rate of 2 scans/minute or faster. Sandia's standard practice is to use a scan rate 4 scans/minute. The module should be held at the maximum power point in between scans if the IV sweep hardware has this capability.
4. Remove the shade and allow the module to heat naturally.
5. Hold the module normal to the sun for a minimum of 10 minutes. The module temperature and I_{sc} should be stable over this time period.

   Note: The average value of I_{sc} determined during the last 1-2 minutes of this period is used to calculate I_{scr}, a temporary value in the subsequent analysis. Errors in this measurement will propagate throughout the analysis.

6. Index the tracker off sun to the first AOI value according to the planned movement.
7. Hold the tracker for a minimum of one minute at each AOI step. A dwell at each position ensures the pyranometers and module temperature stabilize and allows multiple measurements to be averaged, providing a smoother data set for fitting the AOI functions. Obtain a minimum of three curves at each angle.
8. Index the tracker to each AOI in the planned sequence, repeating Step 6 at each angle.
9. At the completion of the measurement, it is recommended to return the tracker to an on sun condition and remeasure I_{sc}. Note any significant discrepancies between this value and the value of I_{scr} determined at the beginning of the test. If this value differs from the initial Isc measurement by more than 3%, it may be necessary to repeat the test.

Table 8. Suggested incidence angles for measurement of AOI response

0°	20°	40°	56°	70°	82°
5°	25°	44°	60°	73°	85°
10°	30°	48°	64°	76°	87°
15°	35°	52°	67°	79°	89°

3.4. Recorded Data Sets

At the completion of the tests, assemble a data set from each curve and associated measurements. If necessary, merge the data from multiple data acquisition systems, ensuring that time stamps are synchronized. The data should be quality checked and filtered prior to analysis. Additional data filtering may be required as each scatterplot is generated and viewed in the course of the analysis. Graphical analysis at each step of the analysis is highly encouraged. The data sets used to illustrate each analysis step in this procedure are available online at https://pvpmc.sandia.gov.

A. Extracted Data from IV Curves

Prior to analysis, key points must be extracted from each IV curve.

1. Standard electrical parameters, I_{sc}, V_{oc}, I_{mp} and V_{mp}.
2. I_x (optional). I_x is the measured current at module $V = 0.5V_{oc}$
3. I_{xx} (optional). I_{xx} is the measured current at module $V=0.5(V_{oc}+V_{mp})$

B. Data Quality Checks

Prior to filtering or analysis, the data should be quality checked to exclude mismatches between measured IV curves and the environmental measurements.

1. Stable Irradiance during IV sweep – If not inspected during data collection, POA Irradiance should be inspected immediately before and after each IV scan. If these values differ by more than 3%, the curve should be discarded.
2. Module Temperature readings – due to the duration of the test, it is not uncommon for a temperature sensor to come loose. Module temperature readings should generally track to within ±2°C of the mean over the course of the test, although larger differences of ±5°C of the mean may be observed at high operating temperatures >50°C. Temperature channels should be inspected for systematic deviations that may indicate loose sensors. Any channels that display significant deviation (particularly lower) from the others should be excluded from analysis.
3. Reasonable Limits – data should exclude measurements outside reasonable limits, for example POA irradiance < 50W/m^2 or > 1400 W/m^2.

C. Clear Sky Data Set

A calendar plot of DNI or POA irradiance can be used to identify candidate clear days or clear periods. If available, select three or more full days (sunrise to sunset) in which variation due to clouds is minimal or non-existent. If such conditions do not exist, select clear periods spanning both morning and afternoon hours over a minimum of three days that satisfy all minimum conditions in Table 2. The clear sky data are used to determine the spectral response function, $f_1(AM)$, I_{sco}, and cell temperature coefficients a and b. Historically, the clear sky analysis has been performed prior to merging the clear sky data with cloudy sky data to create the data set used to estimate the remaining model coefficients. Often additional "hand-filtering" of the data is required to remove outliers, and performing the clear sky analysis before merging the two sets of data eliminates the need to perform this filtering twice.

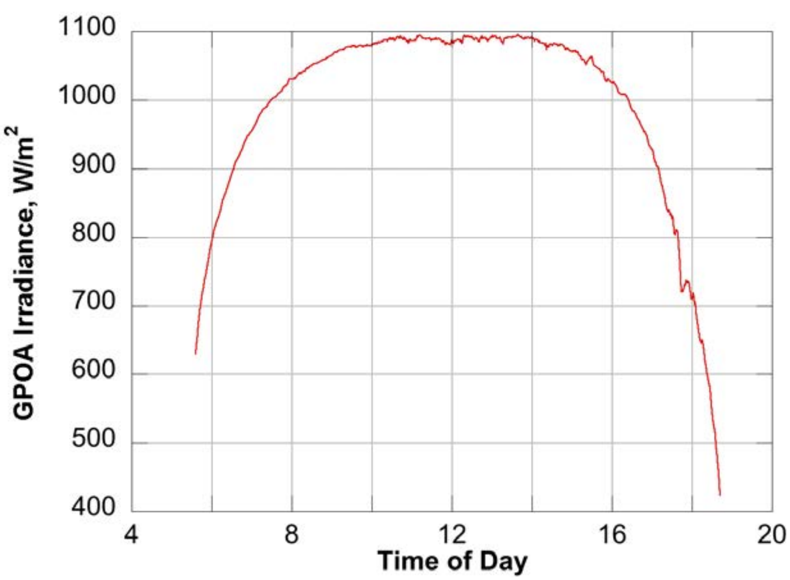

Figure 6. Example clear-sky irradiance profile

D. Cloudy Sky Data Set

A calendar plot of DNI or POA irradiance can be used to identify candidate cloudy days or cloudy periods. If available, select two or more full days (sunrise to sunset) in which there is significant cloud cover and low irradiance for a majority of hours. If such conditions do not exist, select cloudy periods spanning a minimum of three days in which all minimum conditions in Table 3 are met. If using data from partly cloudy days, it is generally not necessary to remove high irradiance, clear periods. This data will be merged with the Clear Sky Data Set to create the All-Sky Data Set following the determination of $f_1(AM)$, I_{sco}, and the a and b coefficients. The All-Sky data set is used to determine all remaining coefficients, including V_{oco}, I_{mpo}, V_{mpo}, I_{xo}, I_{xxo} diode factor n and the C_x coefficients associated with I_{mp}, V_{mp}, I_x and I_{xx}.

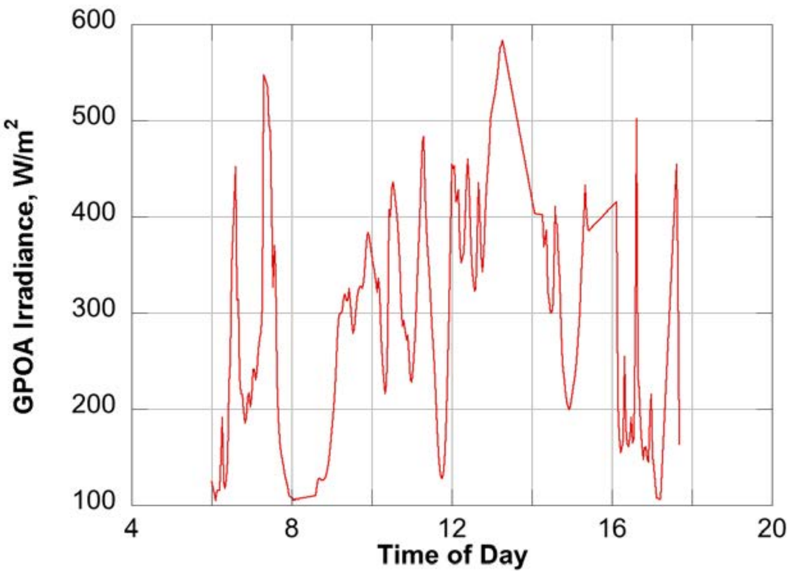

Figure 7. Example cloudy-sky irradiance profile

4. DETERMINATION OF TEMPERATURE COEFFICIENTS

After completion of the measurements, the following analytical procedures should be used to calculate the temperature coefficients. Procedurally, measurement of temperature coefficients may occur at the conclusion of outdoor testing. However, analytically, they must be determined before performing any other analysis. Both the Electrical Performance Analysis and AOI Analysis depend on measured temperature coefficients. The analysis can also provide estimates for the basic module performance parameters (I_{sco}, I_{mpo}, V_{oco}, V_{mpo}) at STC, however accurate values for these performance parameters should be reported from the Electrical Performance Analysis (Section 5).

4.1. Data Preparation

The data sets used to illustrate each analysis step in this procedure are available online at https://pvpmc.sandia.gov.

Assemble a data set from each curve and associated measurements.

For each data record in both data sets, calculate:

1. Module temperature, T_m, calculated as the average of temperatures from the multiple temperature sensors.
2. Average cell temperature, T_c. For typical flat-plate modules with the insulating blanket attached to the back surface ΔT = 1°C is a reasonable value. For flat-plate modules with open back surface and without the insulating blanket ΔT = 3°C is a reasonable value.

$$T_c = T_m + \frac{G_{POA}}{G_0}\Delta T$$

3. Calculate the temperature difference, (T_c – 25).

4.2. Temperature Coefficients

A. Short-Circuit Current (α_{Isc})

1. For each data record, translate measured I_{sc} to E_0 (typically 1000 W/m^2).

$$I_{sc,1000} = I_{sc}\left[\frac{E_0}{E_{poa}}\right]$$

2. Plot $I_{sc,1000}$ vs. (T_c-25) and fit a linear equation of the form y = a+bx.
3. Record α_{Isc}, with units of A/°C and $\hat{\alpha}_{Isc}$ with units of 1/°C.

$$\alpha_{Isc} = b \quad \text{and} \quad \hat{\alpha}_{Isc} = \frac{b}{a}$$

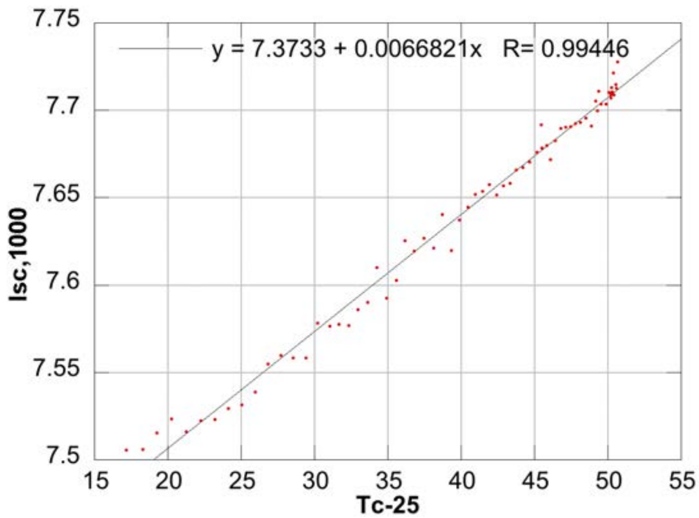

Figure 8. Determination of α_{Isc}

B. Open Circuit Voltage (β_{Voc})

1. For each data record, translate measured V_{oc} to E_0 (typically 1000 W/m^2). Note that diode factor n is typically not known at this point and is assumed to be unity.

$$V_{oc,1000} = V_{oc} - \frac{N_s n k [T_c + 273.15] \ln\left(\frac{E_{POA}}{E_0}\right)}{q}$$

2. Plot $V_{oc,1000}$ vs. (T_c-25) and fit a linear equation of the form y = a+bx.
3. Record β_{Voc}, with units of V/°C and $\hat{\beta}_{Voc}$ with units of 1/°C.

$$\beta_{Voc} = b \quad \text{and} \quad \hat{\beta}_{Voc} = \frac{b}{a}$$

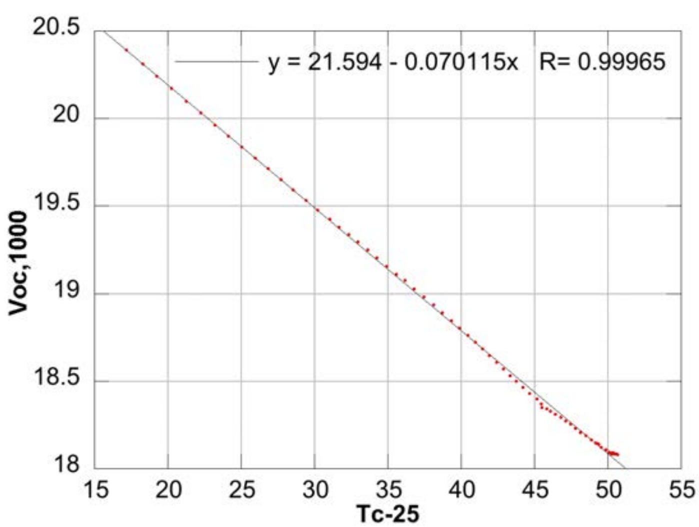

Figure 9. Determination of β_{Voc}

C. Current at MPP (α_{Imp})

1. For each data record, translate measured I_{mp} to E_0 (typically 1000 W/m^2).

$$I_{mp,1000} = I_{mp}\left[\frac{E_0}{E_{poa}}\right]$$

2. Plot $I_{mp,1000}$ vs. (T_c-25) and fit a linear equation of the form y = a+bx.
3. Record α_{Imp}, with units of A/°C and $\hat{\alpha}_{Imp}$ with units of 1/°C.

$$\alpha_{Imp} = b \quad \text{and} \quad \hat{\alpha}_{Imp} = \frac{b}{a}$$

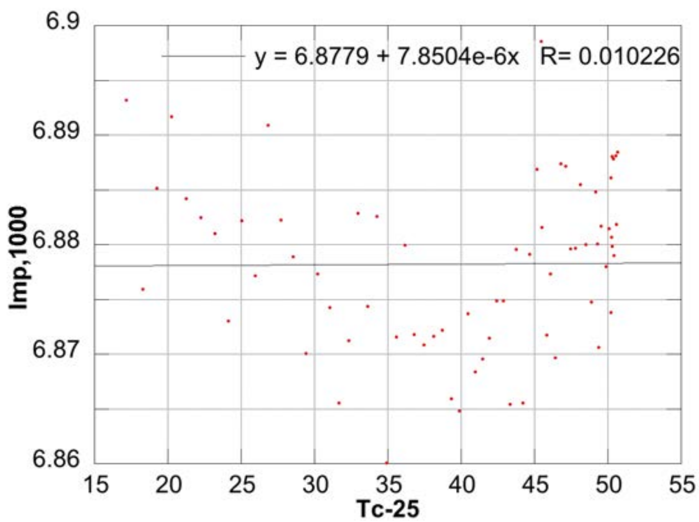

Figure 10. Determination of α_{Imp}

D. Voltage at MPP (β_{Vmp})

1. For each data record, translate measured V_{mp} to E_0 (typically 1000 W/m^2). Note that diode factor n is typically not known at this point and is assumed to be unity.

$$V_{mp,1000} = V_{mp} - \frac{N_s n k[T_c + 273.15]\ln\left(\frac{E_{POA}}{E_0}\right)}{q}$$

2. Plot $V_{mp,1000}$ vs. (T_c-25) and fit a linear equation of the form y = a+bx.
3. Record β_{Vmp}, with units of V/°C and $\hat{\beta}_{Imp}$ with units of 1/°C.

$$\beta_{Vmp} = b \quad \text{and} \quad \hat{\beta}_{Vmp} = \frac{b}{a}$$

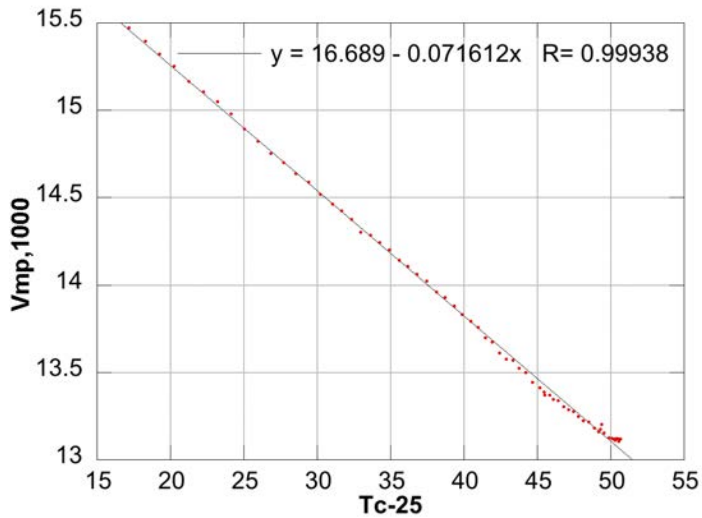

Figure 11. Determination of β_{Vmp}

E. Maximum Power - optional

1. For each data record, calculate $P_{mp,1000}$

$$P_{mp,1000} = I_{mp,1000} V_{mp,1000}$$

2. Plot $P_{mp,1000}$ vs. (T_c-25) and fit a linear equation of the form y = a+bx.
3. Record γ_{Pmp} with units of W/°C and $\hat{\gamma}_{Pmp}$ with units of 1/°C.

$$\gamma_{Pmp} = b \quad \text{and} \quad \hat{\gamma}_{Pmp} = \frac{b}{a}$$

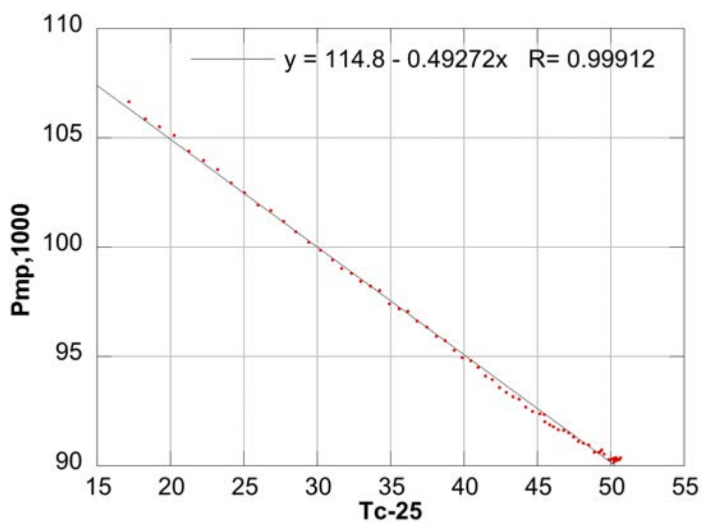

Figure 12. Determination of γ_{Pmp}

4.3. Additional Notes

Values of $\hat{\alpha}_{Isc}$, β_{Voc}, $\hat{\alpha}_{Imp}$ and β_{Vmp} are used unmodified in the remaining analysis sections. Values of α_{Isc}, $\hat{\beta}_{Voc}$, α_{Imp} and $\hat{\beta}_{Vmp}$ are not used in the analysis, but should be retained for consistent reporting rather than recalculating these values from the coefficients that are used in the electrical performance analysis.

The intercepts in each of the analyses above may be interpreted as estimates for the basic module performance parameters (I_{sco}, I_{mpo}, V_{oco}, V_{mpo}) at STC, however accurate values for these performance parameters should be reported from the Electrical Performance Analysis (Section 5).

Temperature coefficients in %/°C, consistent with current data sheet reporting practice, may be obtained by simply multiplying coefficients with units of 1/°C by 100.

5. ELECTRICAL PERFORMANCE ANALYSIS

After completion of the test and data acquisition and determination of temperature coefficients, the following analytical procedures should be used to calculate the remaining SAPM coefficients, with the exception of $f_2(\theta)$ (calculated below in Section 6). Procedurally, measurement of temperature coefficients may occur at the conclusion of outdoor testing. However, analytically, they must be determined before performing this analysis.

Historically, all Clear Sky analysis at Sandia has been performed prior to merging with Cloudy data to create the All Sky Data Set. The reason for this is that there is often additional "hand-filtering" of the data to remove outliers. Performing the clear sky analysis before merging the two sets of data eliminates the need to perform this filtering twice.

Prior to performing the analysis, common reference temperatures for both the analysis and reporting must established and used consistently throughout. Historically, Sandia has used a value of T_r = 50°C for analysis and T_0 = 25°C for reporting. If the reference temperature for analysis differs from that for reporting, care must be taken to translate temperature sensitive parameters to the reference temperature for reporting at the conclusion of the analysis. If the temperature chosen for analysis and reporting is the same, this step may be eliminated.

5.1. Data Preparation

In preparation for analysis, it is useful to check the linearity of current as a first step. To accomplish this, fit a straight line to measured I_{sc} vs measured G_{POA}. Data should be excluded where measured I_{sc} differs significantly from the linear fit. For modules with crystalline silicon cells, a residual of ±6% of predicted I_{sc} is a reasonable threshold. The data sets used to illustrate each analysis step in this procedure are available online at https://pvpmc.sandia.gov.

A. Module to Cell Temperature

For each data record in both data sets, calculate:

1. Module temperature, T_m, calculated as the average of temperatures from the multiple temperature sensors.
2. Average cell temperature, T_c. For flat-plate modules installed on open racking, ΔT = 3°C is a typical value.

$$T_c = T_m + \frac{G_{POA}}{G_0}\Delta T$$

B. Pressure Adjusted Absolute Air Mass

Pressure adjusted absolute air mass may be found from [15].

$$AM = \frac{P}{P_0}\left[\cos(Z_s) + 0.5057\,[96.080 - Z_s]^{-1.634}\right]^{-1}$$

Historically, local pressure P is measured on site. In the event that this measured pressure is not available, the P/P_o can be estimated by the Barometric formula or other methods [16].

$$\frac{P}{P_0} = e^{-0.00011856h}$$

For each data record in both data sets:

1. Determine solar zenith angle, Z_s. This may be determined from the solar tracker's position log, separate calculation (e.g. SPA [17]) or lookup table that is merged with the data records.
2. Determine whether measured or calculated local pressure is to be used.
3. Calculate and record AM.

5.2. Clear Sky Analysis

All steps in this analysis utilize the Clear Sky Data set assembled above in Section 3.4.

A. Air Mass function, $f_1(AM)$ and I_{sco}

Determination of I_{sco} is one of the most crucial steps in the analysis, as this value will be used to establish the effective irradiance, E_e, used in the remainder of the analysis. The air mass function is an empirically determined polynomial that is a proxy for solar spectral influence on I_{sc}. It is dimensionless and defined to be 1 at AM1.5

$$f_1(AM) = a_0 + a_1(AM) + a_2(AM)^2 + a_3(AM)^3 + a_4(AM)^4$$

1. For each data record, translate measured I_{sc} to T_r and 1000 W/m^2

$$I_{sc,Tr,1000} = \frac{I_{sc}}{\left[1 + \hat{\alpha}_{Isc}[T_c - T_r]\right]} \left[\frac{G_0}{G_{poa}}\right]$$

2. Plot $I_{sc,Tr,1000}$ vs. AM and fit a fourth-order polynomial as shown above to the data. This gives a function $\overline{f}_1(AM)$ in units of amps.
3. Evaluate $\overline{f}_1(AM)$ at AM1.5 to find I_{scr}

$$I_{scr} = \overline{f_1}(AM = 1.5)$$

4. Normalize each coefficient of $\overline{f}_1(AM)$ by I_{scr} to find the dimensionless coefficients for $f_1(AM)$

$$f_1(AM) = \frac{\overline{f_1}(AM)}{I_{scr}}$$

5. If $T_r \neq T_0$, translate I_{scr} to I_{sco}

$$I_{sco} = \frac{I_{scr}}{\left[1 + \hat{\alpha}_{Isc}[T_r - T_0]\right]}$$

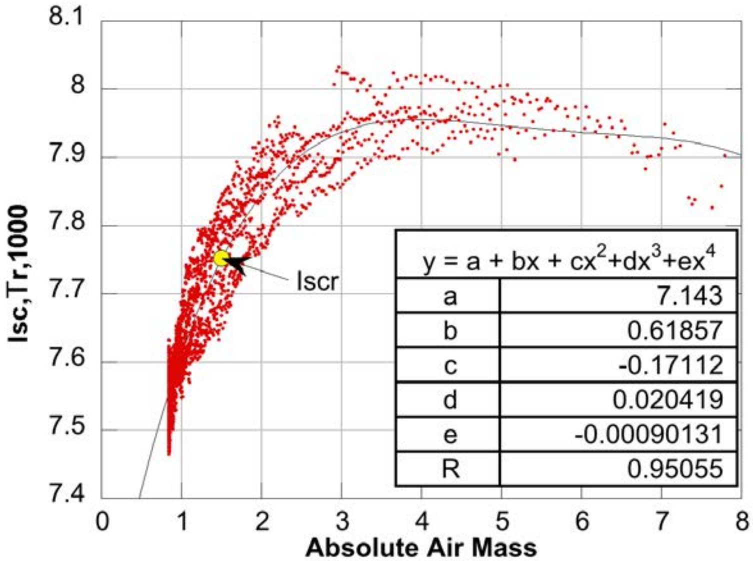

Figure 12. Determination of $f_1(AM)$ and I_{scr}.

B. Wind Speed and Module Temperature - optional

The wind speed function provides a method to estimate module temperature from measured ambient temperature and wind speed.

$$T_m = T_a + G_{POA} e^{a+bW}$$

1. For each data record, calculate

$$\ln\left(\frac{T_m - T_a}{G_{POA}}\right)$$

2. Plot this value vs wind speed W and fit a linear equation of the form y = a+bx
3. Record the coefficients a and b

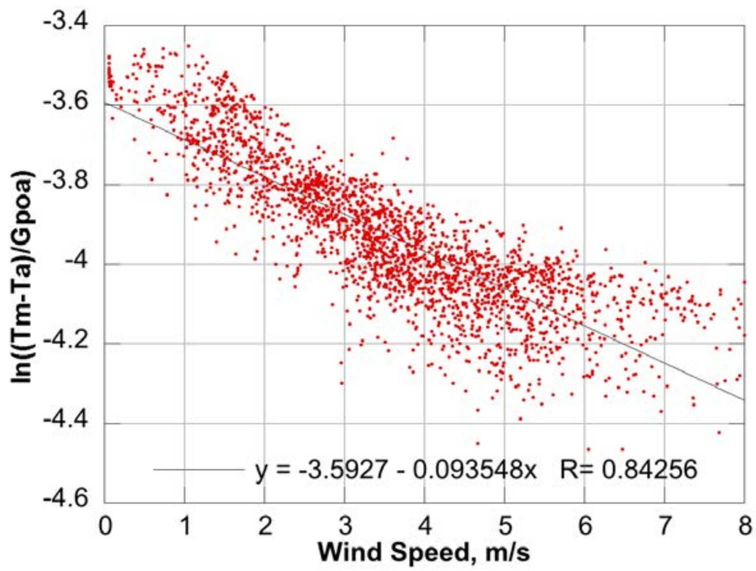

Figure 13. Determination of Wind Speed coefficients, a and b.

5.3. All-Sky Analysis

In preparation for this analysis, merge the Cloudy Sky Data set with the final data set from the Clear Sky Analysis.

A. Effective Irradiance (E_e)

For the remainder of the analysis, calculated effective irradiance, E_e, is used in place of measured irradiance, G_{POA}/G_0. E_e is calculated for each data record simply as;

$$E_e = \frac{I_{sc}}{I_{sco}\left[1 + \hat{\alpha}_{Isc}[T_c - T_0]\right]}$$

B. Open Circuit Voltage at STC (V_{oco}) and diode factor, n

1. For each data record, translate measured V_{oc} to T_r.

$$V_{oc,Tr} = V_{oc} - \beta_{Voc}[T_c - T_r]$$

2. For each data record, calculate the independent variable,

$$\frac{N_s k[T_c + 273.15]\ln(E_e)}{q}$$

3. Plot $V_{oc,Tr}$ vs the independent variable and fit a linear equation of the form y = a+bx
4. Solve the linear fit at E_e=1 to find V_{ocr}. Note that this is simply the intercept a.
5. Record the slope b as the diode factor, n.
6. If $T_r \neq T_0$, translate V_{ocr} to V_{oco}

$$V_{oco} = V_{ocr} - \beta_{Voc}[T_r - T_0]$$

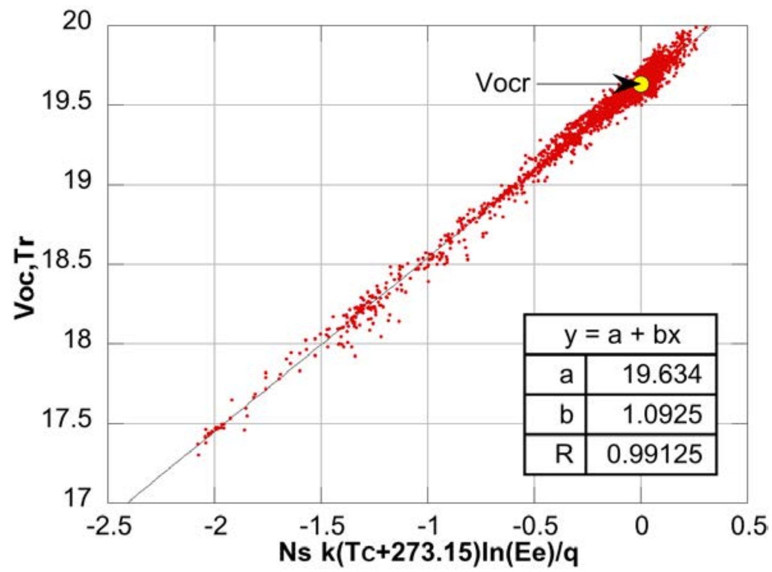

Figure 14. Determination of V_{ocr} and diode factor, n.

C. Maximum Power Current at STC (I_{mpo}), C_0 and C_1

1. For each data record, translate measured I_{mp} to T_r.

$$I_{mp,Tr} = \frac{I_{mp}}{\left[1 + \hat{\alpha}_{Imp}[T_c - T_r]\right]}$$

2. Plot $I_{mp,Tr}$ vs E_e and fit a second order polynomial of the form $y=bx+cx^2$ to the data.
3. Solve the fit at E_e=1 to find I_{mpr}. Note that this is simply the addition of the two coefficients b and c.
4. By definition, the sum of C_0 and C_1 must equal 1, however the coefficients b and c have units of amps. To find the unitless coefficients,

$$C_0 = \frac{b}{I_{mpr}} \quad \text{and} \quad C_1 = \frac{c}{I_{mpr}}$$

5. If $T_r \neq T_0$, translate I_{mpr} to I_{mpo}

$$I_{mpo} = \frac{I_{mpr}}{\left[1 + \hat{\alpha}_{Imp}[T_r - T_0]\right]}$$

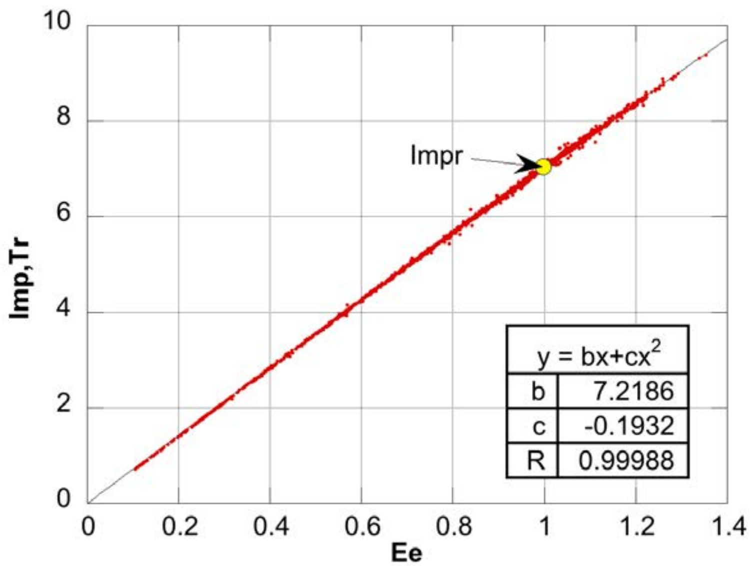

Figure 15. Determination of I_{mpr}, C_0 and C_1

D. Maximum Power Voltage at STC (V_{mpo}), C_2 and C_3

1. For each data record, translate measured V_{mp} to T_r.

$$V_{mp,Tr} = V_{mp} - \beta_{Vmp}[T_c - T_r]$$

2. For each data record, calculate the independent variable, where n is diode factor calculated above in the determination of V_{oco}

$$\frac{nk[T_c + 273.15]\ln(E_e)}{q}$$

3. Plot $V_{mp,Tr}$ vs the independent variable and fit a second order polynomial of the form $y=a+bx+cx^2$ to the data.
4. Solve the fit at Ee=1 to find V_{mpr}. Note that this is simply the intercept a.
5. The coefficients b and c must be adjusted to be on a per cell basis. To find the coefficients C_2 and C_3,

$$C_2 = \frac{b}{N_s} \quad \text{and} \quad C_3 = \frac{c}{N_s}$$

6. If $T_r \neq T_0$, translate V_{mpr} to V_{mpo}

$$V_{mpo} = V_{mpr} - \beta_{Vmp}[T_r - T_0]$$

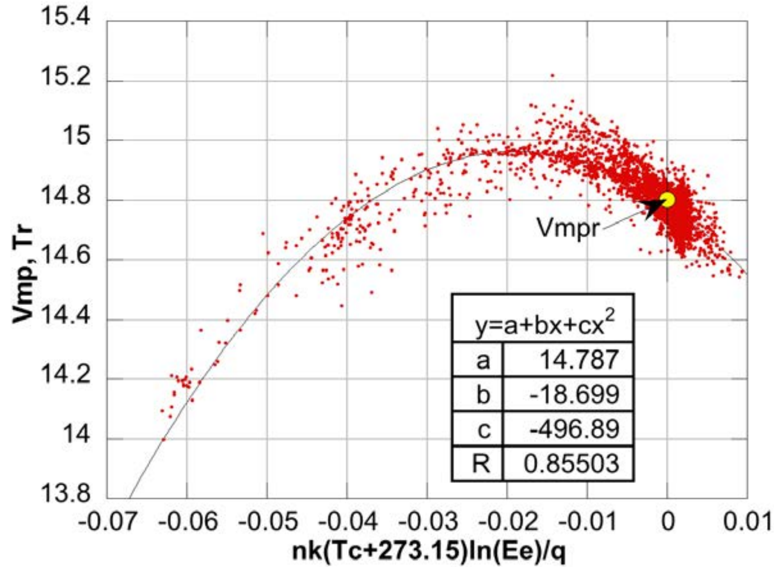

Figure 16. Determination of V_{mpr}, C_2 and C_3.

E. I_x at STC (I_{xo}), C_4 and C_5 - optional

I_x is defined as the current at the point on the IV curve where the voltage is one half the open circuit voltage. This analysis is virtually identical to the determination of I_{mpo}. It should be noted that use of an average temperature coefficient can lead to inconsistent behavior in the model. In the data set presented here, calculated I_x will exceed calculated I_{sc} at low temperatures. This has no physical basis and is a limitation of the model. A forthcoming revision to the model is anticipated to address this by replacing the use of an average temperature coefficient with a temperature coefficient generated specifically for I_x.

1. For each data record, translate measured I_x to T_r.

$$I_{x,Tr} = \frac{I_x}{\left[1 + \left[\frac{\hat{\alpha}_{Isc} + \hat{\alpha}_{Imp}}{2}\right][T_c - T_r]\right]}$$

2. Plot $I_{x,Tr}$ vs E_e and fit a second order polynomial of the form $y=bx+cx^2$ to the data.
3. Solve the fit at E_e=1 to find I_{xr}. Note that this is simply the addition of the two coefficients b and c.
4. By definition, the sum of C_4 and C_5 must equal 1, however the coefficients b and c have units of amps. To find the unitless coefficients,

$$C_4 = \frac{b}{I_{xr}} \quad \text{and} \quad C_5 = \frac{c}{I_{xr}}$$

5. If $T_r \neq T_0$, translate I_{xr} to I_{xo}

$$I_{xo} = \frac{I_{xr}}{\left[1 + \left[\frac{\hat{\alpha}_{Isc} + \hat{\alpha}_{Imp}}{2}\right][T_r - T_0]\right]}$$

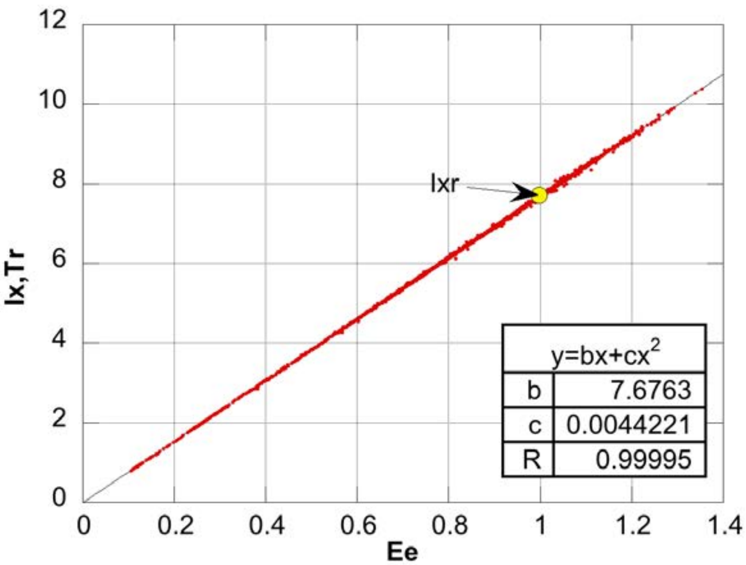

Figure 17. Determination of I_{xr}, C_4 and C_5

F. I_{xx} at STC (I_{xxo}), C_6 and C_7 - optional

I_{xx} is defined as the current at the point on the IV curve where the voltage is halfway between maximum power and open circuit voltages. This analysis is virtually identical to the determination of I_{mpo}.

1. For each data record, translate measured I_{xx} to T_r.

$$I_{xx,Tr} = \frac{I_{xx}}{\left[1 + \hat{\alpha}_{Imp}[T_c - T_r]\right]}$$

2. Plot $I_{xx,Tr}$ vs E_e and fit a second order polynomial of the form $y=bx+cx^2$ to the data.
3. Solve the fit at E_e=1 to find I_{xxr}. Note that this is simply the addition of the two coefficients b and c.
4. By definition, the sum of C_6 and C_7 must equal 1, however the coefficients b and c have units of amps. To find the unitless coefficients,

$$C_6 = \frac{b}{I_{xxr}} \quad \text{and} \quad C_7 = \frac{c}{I_{xxr}}$$

5. If $T_r \neq T_0$, translate I_{xr} to I_{xo}

$$I_{xxo} = \frac{I_{xxr}}{\left[1 + \hat{\alpha}_{Imp}[T_r - T_0]\right]}$$

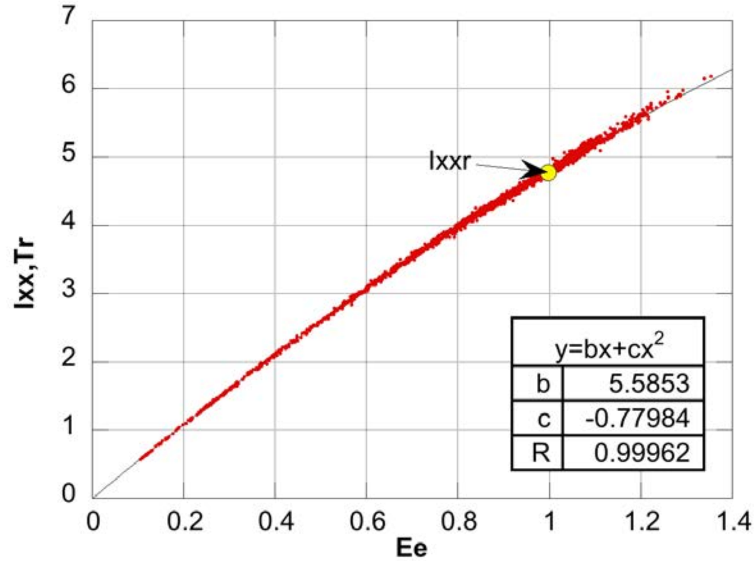

Figure 18. Determination of I_{xxr}, C_6 and C_7

5.4. Summary Plots and Model Validation

Following analysis, it is recommended to generate summary plots to display the model. It is also recommended to perform model validation.

A. Summary Plots

For each of the following plots, normalized values are calculated and plotted against model parameters.

1. Air Mass

$$I_{Rel.Norm} = \frac{1}{\left[1 + \hat{\alpha}_{Isc}[T_c - T_r]\right]} \left[\frac{I_{sc}}{I_{sco}}\right] \left[\frac{G_0}{G_{poa}}\right] = f_1(AM)$$

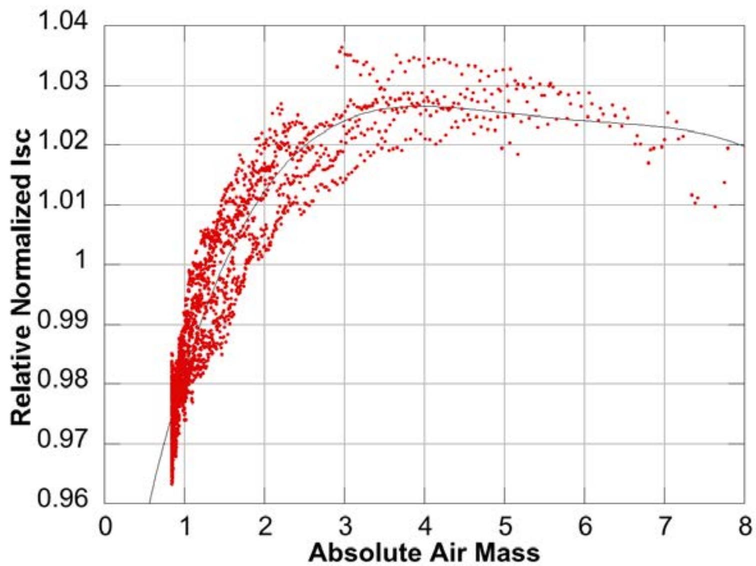

Figure 19. Relative Normalized I_{sc} as a function of Air Mass

2. Currents, I_{sc}, I_{mp}, I_x and I_{xx}

$$\frac{I_{sc}}{\left[1+\hat{\alpha}_{Isc}[T_c-25]\right]}=I_{sco}E_e$$

$$\frac{I_{mp}}{\left[1+\hat{\alpha}_{Imp}[T_c-25]\right]}=I_{mpo}[C_0E_e+C_1E_e^2]$$

$$\frac{I_x}{\left[1+\left[\frac{\hat{\alpha}_{Isc}+\hat{\alpha}_{Imp}}{2}\right][T_c-25]\right]}=I_{xo}[C_4E_e+C_5E_e^2]$$

$$\frac{I_{xx}}{\left[1+\hat{\alpha}_{Imp}[T_c-25]\right]}=I_{xxo}[C_6E_e+C_7E_e^2]$$

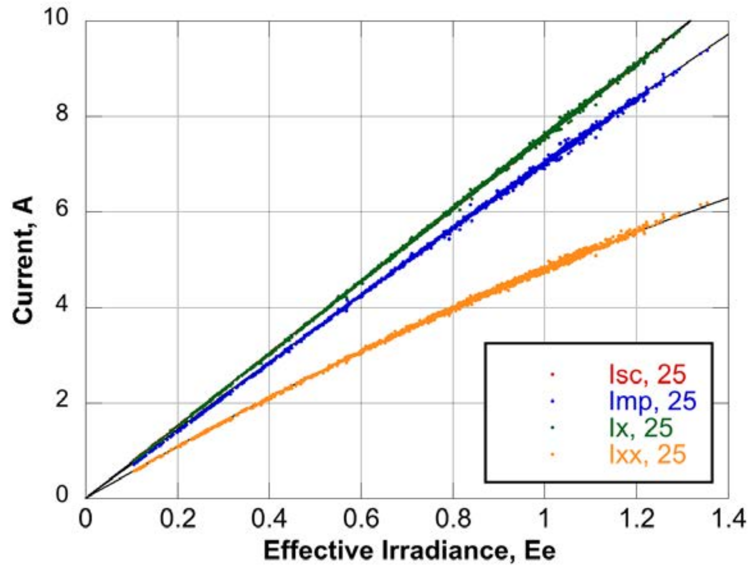

Figure 20. Currents adjusted to 25°C as a function of effective irradiance. Note that in this case, I_x overlays I_{sc}.

3. Voltages, V_{oc} and V_{mp}

$$V_{oc} - \beta_{Voc}[T_c - 25] = V_{oc} + \frac{N_s n k [T_c + 273.15] \ln(E_e)}{q}$$

$$V_{mp} - \beta_{Vmp}[T_c - 25] = V_{mp} + C_2 N_s \frac{n k [T_c + 273.15] \ln(E_e)}{q} + C_3 N_s \left[\frac{n k [T_c + 273.15] \ln(E_e)}{q}\right]^2$$

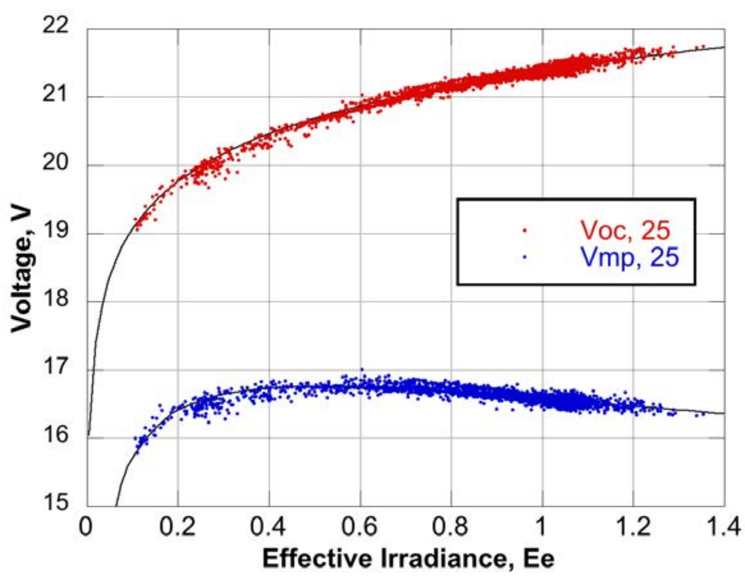

Figure 21. Voltages adjusted to 25°C as a function of Effective Irradiance.

B. Model Validation

A simple model validation can be performed by comparing measured values to model predictions. For each data record, calculate the predicted value using the Effective Irradiance E_e and measured module temperature, T_m as the inputs. Modeled I_{sc} predictions are determined using G_{POA} as in input instead of E_e. Note that for this particular case, V_{oc} displays a bias error. This can be attributed to an inaccurate temperature coefficient [18, 19] A forthcoming update to the SAPM and analysis methods is anticipated to address this deficiency.

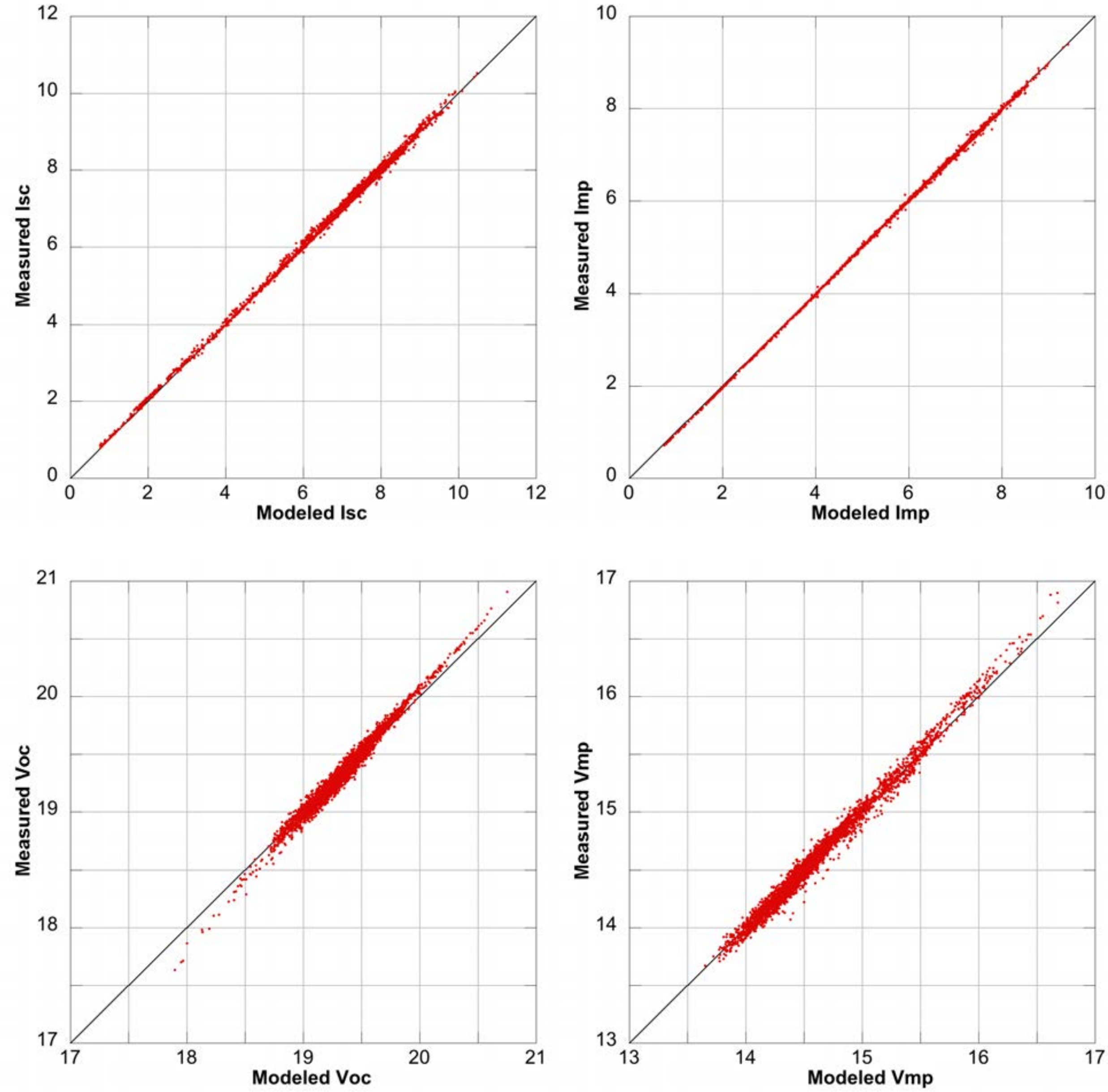

Figure 22. Measured vs. Modeled plots for I_{sc}, I_{mp}, V_{oc} and V_{mp}.

6. ANGLE OF INCIDENCE (AOI) ANALYSIS

After completion of the test and data acquisition and determination of temperature coefficients, the following analytical procedures should be used to calculate the $f_2(\theta)$ or AOI function. The AOI function is an empirically determined polynomial. It is dimensionless and defined to be 1 at normal incidence angle, $\theta = 0$

$$f_2(\theta) = b_0 + b_1(\theta) + b_2(\theta)^2 + b_3(\theta)^3 + b_4(\theta)^4 + b_5(\theta)^5$$

The AOI analysis depends on decomposition of the irradiance in the plane of the module (G_{POA}) into beam and diffuse components. Contribution of the diffuse component G_{diff} to I_{sc} is removed and the AOI function is developed around the beam component. Historically, this analysis utilized measured DNI from the weather tracker and G_{POA} in the test plane; G_{diff} was calculated from these two. More recently, a new method has been adopted in which the diffuse component is measured directly in the test plane. Here, measured DNI and G_{diff} are used to calculate G_{POA}. Both methods are presented here, with the older method being referred to as the Standard Method and the newer method being referred to as the Preferred Method.

6.1. Data Preparation

The data sets used to illustrate each analysis step in this procedure are available online at https://pvpmc.sandia.gov.

Assemble a data set from each curve and associated measurements as shown below in Table 3.

1. Merge the measured IV summary data (I_{sc}), module backsheet temperatures (T_m), irradiance measurements (G_{POA}, G_{DNI}, G_{diff}), sun azimuth and elevation (AZ_s, Z_s), and tracker plane of array position data (AZ_m and $Tilt_m$) into one time synchronized data set.
2. Remove points collected while the tracker was in motion. Depending on the measurement setup, this may or may not be required. If the IV scans occur at regular intervals regardless of the tracker movement, then it's important to remove these data points because the irradiance sensor may not have a fast enough response time to keep up with the tracker movement. If the setup only collects the IV scan after the tracker has stopped and enough time has passed to allow for the sensor to stabilize, then these data points may be kept.

A. Angle of Incidence

For each data record, calculate the angle of incidence between the module normal vector and the sun position.

$$\mathrm{AOI} = cos^{-1}[cos(\mathrm{Tilt_m})\, cos(\mathrm{Z_s}) + (sin(\mathrm{Tilt_m})\, sin(\mathrm{Z_s})\, cos(\mathrm{AZ_s} - \mathrm{AZ_m}))]$$

B. Pressure Adjusted Absolute Air Mass

Pressure adjusted absolute air mass may be found from [15]

$$AM = \frac{P}{P_0}[\cos(Z_s) + 0.5057\,[96.080 - Z_s]^{-1.634}]^{-1}$$

Historically, local pressure P is measured on site. In the event that this measured pressure is not available, the P/P_0 can be estimated by the Barometric formula or other means [16].

$$\frac{P}{P_0} = e^{-0.00011856h}$$

1. Determine whether measured or calculated local pressure is to be used.
2. Calculate and record AM.

C. Module to Cell Temperature

For each data record, calculate;

1. Average module temperature, T_m, as the average of temperatures from the multiple temperature sensors.
2. Average cell temperature, T_c. For flat-plate modules installed on open racking, $\Delta T = 3°C$ is a typical value.

$$T_c = T_m + \frac{G_{POA}}{G_0}\Delta T$$

D. Short Circuit Current at T_r and AM1.5

1. For each data record, translate measured I_{sc} to T_r (typically 50°C) and AM1.5

$$I_{sc,Tr,AM1.5} = \frac{I_{sc}}{f_1(AM)[1 + \hat{\alpha}_{Isc}[T_c - T_0]]}$$

6.2. Standard Method: Measured DNI and Global POA

In the standard method, G_{DNI} is measured using a pyrheliometer mounted on an independent weather tracker, G_{POA} is measured using a global pyranometer mounted in the test plane and G_{diff} is calculated.

A. Determination of I_{scr}

In the preceding sections, I_{sco} represents the short circuit current at STC conditions. However, for this analysis, it is preferred to use a local reference value, determined at the time of the measurement. The reference value is defined as I_{scr}.

1. Identify a minimum of 5 measurements made at AOI = 0, just before the module was taken off sun.
2. For each of the selected measurements, translate to G_0=1000 W/m^2.

$$I_{sc,Tr,AM1.5,1000} = I_{sc,Tr,AM1.5}\frac{G_0}{G_{POA}}$$

3. Calculate I_{scr} as the average of these values

$$I_{scr} = \frac{1}{n}\sum I_{sc,Tr,AM1.5,1000,n}$$

Note: Do not use the nameplate rating for I_{sc} or the measured I_{sco} at STC. I_{scr} must be based on the measured I_{sc} at the start of the AOI test procedure for this analysis to provide valid results.

B. Angle of Incidence Function, $f_2(\theta)$

1. For each data record, calculate $I_{sc,AOI}$

$$I_{sc,AOI} = \left[\frac{G_0}{G_{DNI}\cos\theta}\right]\left[\frac{I_{sc,Tr,AM1.5}}{I_{scr}} - \left[\frac{G_{POA} - G_{DNI}\cos\theta}{G_0}\right]\right]$$

2. Plot $I_{sc,AOI}$ vs. AOI (θ) and fit a fifth order polynomial to the data. This gives a dimensionless function $f_2(\theta)$.

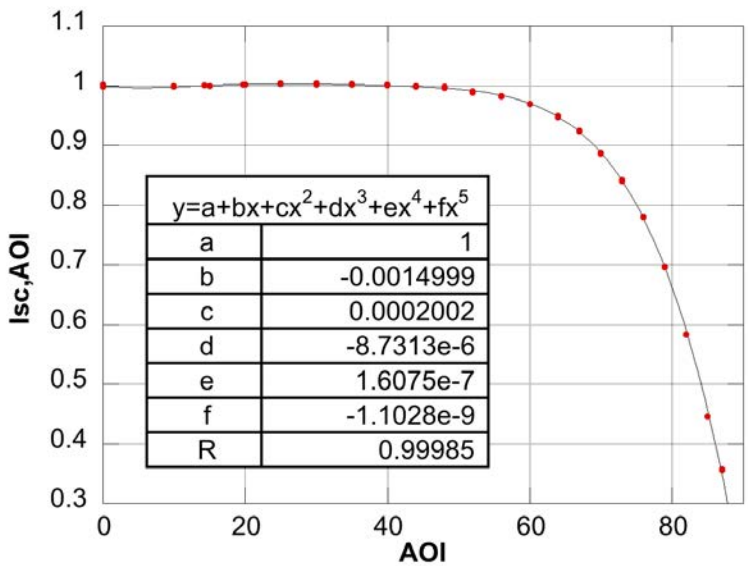

Figure 23. Determination of AOI function, $f_2(\theta)$

6.3. Preferred Method: Measured DNI and Diffuse POA

In the preferred method, G_{DNI} is measured using a pyrheliometer mounted on an independent weather tracker, G_{diff} is measured using a shaded global pyranometer mounted in the test plane and G_{POA} is calculated [10].

A. Determination of I_{scr}

In the preceding sections, I_{sco} represents the short circuit current at STC conditions. However, for this analysis, it is preferred to use a local reference value, determined at the time of the measurement. The reference value is defined as I_{scr}.

1. Identify a minimum of 5 measurements made at AOI = 0, just before the module was taken off sun.
2. For each of the selected measurements, translate to G_0=1000 W/m^2.

$$I_{sc,Tr,AM1.5,1000} = I_{sc,Tr,AM1.5}\left[\frac{G_0}{G_{DNI}+G_{diff}}\right]$$

3. Calculate I_{scr} as the average of these values

$$I_{scr} = \frac{1}{n}\sum I_{sc,Tr,AM1.5,1000,n}$$

Note: Do not use the nameplate rating for I_{sc} or the measured I_{sco} at STC. I_{scr} must be based on the measured I_{sc} at the start of the AOI test procedure for this analysis to provide valid results.

B. Angle of Incidence Function, $f_2(\theta)$

1. For each data record, calculate $I_{sc,AOI}$

$$I_{sc,AOI} = \left[\frac{G_0}{G_{DNI}\cos\theta}\right]\left[\frac{I_{sc,Tr,AM1.5}}{I_{scr}} - \left[\frac{G_{diff}}{G_0}\right]\right]$$

2. Plot $I_{sc,AOI}$ vs. AOI (θ) and fit a fifth order polynomial to the data. This gives a dimensionless function $f_2(\theta)$.

7. SUMMARY PERFORMANCE COEFFICIENT TABLE

The individual module performance coefficients used in the Sandia Array Performance Model are summarized below.

Parameter	Value	Definition
Model	Mitsubishi PV-UE125MF5N	Module model
Year	2008	Year manufactured
Module Area	1.01	Total module area, (m^2)
Material	Polycrystalline Silicon	Solar cell material
Series Cells	36	# of cells in series per string
Parallel C-S	1	# of parallel cell-strings
I_{sco}	7.5785	I_{sc} at STC, (A)
V_{oco}	21.3869	V_{oc} at STC, (V)
I_{mpo}	7.0252	I_{mp} at STC, (A)
V_{mpo}	16.5773	V_{mp} at STC, (V)
α_{Isc}	9.0626E-04	I_{sc} temperature coefficient, normalized, (1/°C)
α_{Imp}	1.1414E-06	I_{mp} temperature coefficient, normalized, (1/°C)
C_0	1.0275	Coefficients relating I_{mp} to effective irradiance, (dimensionless)
C_1	-0.0275	
β_{Voco}	-0.070115	V_{oc} temperature coefficient at 1000 W/m^2, (V/°C)
$m\beta_{Voc}$	0	Irradiance dependence of β_{Voco}, typically 0, (V/°C)
β_{Vmpo}	-0.071612	V_{mp} temperature coefficient at 1000 W/m^2, (V/°C)
$m\beta_{Vmp}$	0	Irradiance dependence of β_{Vmpo}, typically 0, (V/°C)
n	1.0925	Cell diode factor (dimensionless)
C_2	-0.5194	Coefficients relating V_{mp} to Effective Irradiance, (C_2, dimensionless; C_3, 1/V)
C_3	-13.8025	
a_0	0.92165	Polynomial coefficients for spectral (Airmass), $f_1(AM_a)$
a_1	0.079813	
a_2	-0.022079	
a_3	0.0026347	
a_4	-0.00011630	
b_0	1.00000	Polynomial coefficients for AOI response, $f_2(\theta)$
b_1	-1.4999E-03	

Parameter	Value	Definition
b_2	2.0020E-04	
b_3	-8.7313E-06	
b_4	1.6075E-07	
b_5	-1.1028E-09	
ΔT	3	Temperature difference between cell & module @ 1000 W/m^2
f_d	1	Fraction of G_{diff} used by module
a	-3.5927	Coefficients relating Wind Speed (WS), Irradiance (G) and Ambient Temperature (T_a) to Module Temperature (T_m)
b	-0.0935	
C_4	0.9994	Coefficients relating I_x to effective irradiance (dimensionless)
C_5	0.0006	
I_{xo}	7.5946	Current at V= 0.5*V_{oc}, (A)
I_{xxo}	4.8053	Current at V= 0.5*(V_{oc}+V_{mp}), (A)
C_6	1.1623	Coefficients relating I_{xx} to effective irradiance (dimensionless)
C_7	-0.16228	

8. REFERENCES

1. King, D.L., E.E. Boyson, and J.A. Kratochvil, *Photovoltaic Array Performance Model*, SAND2004-3535, Sandia National Laboratories, Albuquerque, NM, 2004.
2. System Advisor Model (SAM) Version 2015.6.30, retrieved January 21, 2016 from http://sam.nrel.gov.
3. PV_LIB Toolbox for Matlab (Version 1.3.1), retrieved January 21, 2016 from http://pvpmc.sandia.gov.
4. R. W. Andrews, J. S. Stein, C. W. Hansen, D. Riley, "Introduction to the Open Source PV_LIB for Python Photovoltaic System Modeling Package," *40th IEEE Photovoltaic Specialists Conference*, 2014.
5. A. H. Fanney, M. W. Davis, B. P. Dougherty, D. L. King, W. E. Boyson, J. A. Kratochvil, "Comparison of Photovoltaic Module Performance Measurements," *Journal of Solar Energy Engineering*, Vol 128 (2), pp. 152-159, 2006.
6. J. E. Granata, et al., "Successful Transfer of Sandia National Laboratories' Outdoor Test technology to TÜV Rheinland Photovoltaic Testing Laboratory," *37th IEEE Photovoltaic Specialists Conference*, 2011.
7. C. W. Hansen, et al., "Parameter Uncertainty in the Sandia Array Performance Model for Flat-Plate Crystalline Silicon Modules," *37th IEEE Photovoltaics Specialists Conference*, 2011.
8. C. W. Hansen, D. Riley, and M. Jaramillo, "Calibration of the Sandia Array Performance Model Using Indoor Measurements," *38th IEEE Photovoltaic Specialists Conference*, 2012.
9. J. Peng, L. Lu, H. Yang, T. Ma, "Validation of the Sandia model with indoor and outdoor measurements for semi-transparent amorphous silicon PV modules," *Renewable Energy*, Vol. 80, pp. 316-323, 2015.
10. B. H. King, "Recent Advancements in Outdoor Measurement Techniques for Angle of Incidence Effects," *47th IEEE Photovoltaic Specialists Conference*, 2015.
11. IEC 61215:2005, "Crystalline Silicon Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval."
12. M. G. Deceglie, T. J. Silverman, B. Marion and S. R. Kurtz, "Robust Measurement of Thin-Film Photovoltaic Modules Exhibiting Light-Induced Transients," *Proceedings SPIE 9561*, 2015.
13. IEC 60891:2009, "Photovoltaic Devices – Procedures for Temperature and Irradiance Corrections to Measured I-V Characteristics."
14. IEC 61853-1:2011, "Photovoltaic (PV) Module Performance Testing and Energy Rating – Part 1: Irradiance and Temperature Performance Measurements and Power Rating."
15. F. Kasten and A. T. Young, "Revised Optical Air Mass Tables and Approximation Formula," *Applied Optics*, **28**, pp. 4735-4738, 1989.
16. "A Quick Derivation Relating Altitude to Air Pressure," *Portland State Aerospace Society, Version 1.03*, 2004.
17. I. Reda, A. Andreas, "Solar Position Algorithm for Solar Radiation Applications," *Solar Energy*, Vol. 76(5), pp. 577 – 589, 2004.
18. C. W. Hansen, K. A. Klise, J. S. Stein, Y. Ueda and K. Hakuta, "Photovoltaic System Model Calibration Using Monitored System Data," *6th World Conference on Photovoltaic Energy Conversion*, 2014.

19. B. H. King, “CIGS Performance Analysis: Alternative Method to Fit the Sandia Array Performance Model,” presented at *The 5th PV Performance Modeling Workshop*, SAND2016-4658C.

APPENDIX A: DERIVATION OF TRANSLATION EQUATIONS

Translation of the measured electrical parameters to 1000 W/m^2 is an intermediate step in the analysis and originates from the basic relationships between each parameter and its response to temperature and irradiance described by the SAPM. Each equation contains key coefficients of the SAPM that are not known at this point in the analysis. Since knowledge of the temperature coefficients is a prerequisite for performing the remainder of the analysis, several simplifying assumptions must be made. Each of the simplified equations is linear in form y=a+bx. In each equation, the independent variable is (T_c – T_o). The slope b of the regression line is the value of the temperature coefficient. The dependent term y in each equation is the value translated to 1000 W/m^2. E_e is not known at this point in the analysis, so the ratio of measured irradiance E_{POA} to reference irradiance E_0 is used in its place. While most of the analysis relies on the use of measured irradiance from a broadband pyranometer in the plane of array (G_{POA}), determination of temperature coefficients is best done using irradiance measured with a reference cell.

A. Short-Circuit Current

Starting with the general form,

$$I_{sc} = I_{sco} f_1(AM)\left[\frac{E_{poa}}{E_0}\right]\left[1 + \hat{\alpha}_{Isc}[T_c - T_0]\right]$$

It is assumed that the test is performed near solar noon when air mass is relatively stable and can be approximated by $f_1(AM) = 1$. The equation for I_{sc} can be simplified and rearranged, where α_{Isc} has units of A/°C.

$$I_{sc}\left[\frac{E_0}{E_{poa}}\right] = I_{sco}\left[1 + \hat{\alpha}_{Isc}[T_c - T_0]\right] = I_{sco} + \alpha_{Isc}[T_c - T_0]$$

B. Open-Circuit Voltage

Open circuit voltage requires no simplification,

$$V_{oc} = V_{oco} + N_s \delta(T_c)\ln\left(\frac{E_{poa}}{E_0}\right) + \beta_{Voc}[T_c - T_0]$$

and may simply be rearranged to give

$$V_{oc} - N_s \delta(T_c)\ln\left(\frac{E_{poa}}{E_0}\right) = V_{oco} + \beta_{Voc}[T_c - T_0]$$

C. Current at Max Power

$$I_{mp} = I_{mpo}\left[C_0\left[\frac{E_{poa}}{E_0}\right] + C_1\left[\frac{E_{poa}}{E_0}\right]^2\right]\left[1 + \hat{\alpha}_{Isc}[T_c - T_0]\right]$$

may be simplified by recognizing that in practice, $C_0 \approx 1$ and $C_1 \ll 1$. Then,

$$I_{mp}\left[\frac{E_0}{E_{poa}}\right] = I_{mpo}\left[1 + \hat{\alpha}_{Imp}[T_c - T_0]\right] = I_{mpo} + \alpha_{Imp}[T_c - T_0]$$

D. Voltage at Max Power

$$V_{mp} = V_{mpo} + C_2 N_s \delta(T_c) \ln\left(\frac{E_{poa}}{E_0}\right) + C_2 N_s \left[\delta(T_c) \ln\left(\frac{E_{poa}}{E_0}\right)\right]^2 + \beta_{Vmp}[T_c - T_0]$$

Since the test is preferably performed near E = 1000 W/m^2 (or $E/E_0 \approx 1$), then $\ln(E/E_0) >> [\ln(E/E_0)]^2$ and the equation for V_{mp} may be simplified and rearranged to

$$V_{mp} - N_s \delta(T_c) \ln\left(\frac{E_{poa}}{E_0}\right) = V_{mpo} + \beta_{Vmp}[T_c - T_0]$$

DISTRIBUTION

1	MS0899	Technical Library	9536 (electronic copy)

Sandia National Laboratories