Outdoor Test and Analysis Procedures for Generating Coefficients for the Sandia Array Performance Model

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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 laboratory intercomparisons of measurements and analysis, detailed procedures for determining model coefficients have never been published. Independent test laboratories must develop in-house procedures to determine SAPM coefficients, which contributes to uncertainty in the resulting models. In response to requests from commercial laboratories and module manufacturers, Sandia has formally documented the measurement and analysis methods as a supplement to the original model description. In this paper we present a description of the measurement procedures and an example analysis for calibrating the SAPM.

***Index Terms* — Sandia Array Performance Model, SAPM, outdoor testing, PV modules, angle of incidence, temperature coefficients, System Advisor Model, PV_LIB**

I. INTRODUCTION

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, the capability to generate coefficients for SAPM from performance measurements of modules has not been widely available outside of Sandia.

Prior efforts to transfer this 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 procedures necessary for independent laboratories to carry out 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 has formally documented the measurement and analysis methods as a supplement to the original model description. The procedure consists of measurement and analysis steps to develop a full set of SAPM coefficients for use with SAM or PV_Lib and is accompanied by a data set used to illustrate each analysis step [10, 11]. The example data set consists of thousands of IV measurements from a Mitsubishi 36-cell polycrystalline module (circa 2008) obtained across 5 days of testing. It also consists of data obtained from thermal and AOI testing for the same module.

In this paper, we present an overview of the procedure and example analysis for a subset of the model.

Fig. 1. Modules under test on a two-axis tracker at Sandia

II. SAPM OVERVIEW

The Sandia Array Performance Model consists of a set of equations that translate plane-of-array (POA) irradiance, air temperature and wind speed to electrical output of a PV module. Four primary equations describe 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 (E_e), which is used in all remaining equations.

Calibration of I_{sc} can in principle be done with any type of irradiance instrument (e.g., pyranometer, reference cell). However the instrument type and accuracy propagates into the model coefficients. We recommend a broadband thermopile-based pyranometer as the general choice for model calibration. 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 can be developed with that type of instrument in mind.

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

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

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

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

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 and measured irradiance.

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

Finally, module temperature may be linked to ambient temperature T_a through the "wind speed" equation,

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

Two additional equations may be used to find intermediate points along the IV curve, I_x and I_{xx}. These points were originally included to support modeling of battery-based systems in which PV modules may operate off of the MPP. For brevity, determination of these coefficients is not presented here, but may be found in the full procedure [10].

TABLE I
SUMMARY OF NOMENCLATURE

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)
T_m	Module back surface temperature, (°C)
T_a	Ambient temperature (°C)
W	Wind speed, (m/s)
G_{poa}	Broadband irradiance in plane of the array (W/m^2), typically a pyranometer
G_0	Reference irradiance, 1000 W/m^2
AM	Pressure adjusted air mass
θ	Incident angle between the module and the sun
T_c	Cell temperature (°C)
ΔT	Temp. difference between cell and the module back surface at 1000 W/m^2, typically 3°C
T_0, T_r	Ref temperatures, typically 25°C and 50°C
$\hat{\alpha}_{Isc}, \hat{\alpha}_{Imp}$	Temperature coefficients for I_{sc} and I_{mp} (1/°C)
β_{Voc}, β_{Vmp}	Temperature coefficients for V_{oc} and V_{mp} (V/°C)
I_{sco}, I_{scr}	Ref. short-circuit current at T_0, T_r (A)
V_{oco}, V_{ocr}	Ref. open Circuit Voltage at T_0, T_r (V)
I_{mpo}, I_{mpr}	Ref. current at maximum power at T_0, T_r (A)
V_{mpo}, V_{mpr}	Ref. voltage at maximum power at T_0, T_r (V)
$f_1(AM)$	Polynomial relating AM to I_{sc}
$f_2(\theta)$	Polynomial relating reflection losses to I_{sc}
n	Diode ideality factor (dimensionless)
C_x	Coefficients relating E_e to I_{mp} and V_{mp}
a, b	Coefficients relating T_a and W to T_m
E_e	Effective Irradiance (dimensionless)
G_{diff}	Diffuse component of irradiance (W/m^2),
G_b	Beam component of irradiance (W/m^2)
N_s	Number of series-connected cells in a module cell-string
k	Boltzmann's constant, 1.38066×10^{-23} (J/K)
q	Elementary charge, 1.60218×10^{-19} (Coulomb)

III. Overview and 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. The majority of measurements are performed with the module held normal to the sun.

The following equipment is used for conducting these tests;

1. Solar tracker
   a) Test plane for mounting the module and reference irradiance sensors
   b) Tracking system capable of keeping the module normal to the sun during the measurement procedure.
   c) Off-tracking capability to controllably steer the tracker over a range of 0° – 90° AOI between the module POA and the sun during Angle of Incidence (AOI) characterization
2. Irradiance sensors mounted on the test plane
   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) [10], (optional, see Section IV. C. for more 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.
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.
6. 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.
7. 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.

IV. Procedure Description

Step-by step details of the measurement procedure are too lengthy to present here and are instead presented in Reference [10]. Individual 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.

The module is instrumented with 3 or 4 temperature sensors (historically Type-T thermocouples) prior to installation on the tracker. The module is then mounted in the plane-of-array on the tracker and IV measuring equipment is attached to the module's electrical connectors.

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. Stable ambient conditions are required during the test (Table II).

TABLE II
AMBIENT CONDITIONS FOR THERMAL AND AOI TESTS

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

The module is covered with an opaque sheet and allowed to cool to ambient temperature. Once at ambient (to within ~ 6°C) the back of the module is thermally insulated to improve temperature uniformity and increase the maximum temperature reached during the test. IV curves and module temperatures are then measured rapidly (~ 4 scans/minute) with the tracker normal to the sun. The cover is removed and heated to an equilibrium temperature. A typical test requires approximately 30 minutes once the cover has been removed. Linear regression analysis is then performed to determine voltage and current temperature coefficients.

B. Electrical Performance Test and Analysis

Electrical performance testing and analysis results in the majority of the coefficients for the SAPM. In addition to STC values for I_{sc}, I_{mp}, V_{oc}, and V_{mp}, it produces a polynomial function describing the response of module short circuit current to air mass, cell diode factor, a wind speed function, 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 this analysis.

Unlike the thermal test, the electrical performance test is best performed over a wide range of weather conditions. When clear sky conditions (Table III) do not occur for full days, data from multiple days may be merged. For crystalline silicon modules, this practice is generally acceptable. However, care must be exercised when characterizing any module type that displays significant relaxation overnight or light-soaking behavior. In addition to data collected during clear sky conditions, the equivalent of several days of data during all sky conditions is required (Table IV). Preferably, these data represent both overcast conditions in which the irradiance is stable, as well as transient partly cloudy conditions.

TABLE III
CLEAR SKY AMBIENT CONDITIONS

Parameter	Required	Preferred
GNI	800 - 1050 W/m^2	600 - 1200 W/m^2
DNI/GNI	> 0.85	> 0.90
Air Mass	1.5 – 5.0	1.0 – 7.0
Wind Speed	0 - 4 m/s	0 - 10 m/s
Min. Test duration	600 min./2 days	1200 min./3 days

TABLE IV
CLOUDY OR ALL-SKY AMBIENT CONDITIONS

Parameter	Required	Preferred
GNI	200 - 400 W/m^2	100 - 500 W/m^2
DNI/GNI*	0 – 0.85 (< 0.05)	
Min. Test Duration	200 min./1 day	1200 min./3 days

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

The module is held normal to the sun for the duration of the electrical performance test and IV curves are recorded every two minutes. Irradiance is checked before and after each IV sweep to ensure that irradiance was stable over the IV sweep time. The IV curve is discarded when irradiance is determined to have changed during the IV curve sweep. The module is held at maximum power between IV curves.

C. Angle of Incidence Testing

Angle of Incidence (AOI) testing characterizes reflection losses, which in the SAPM is modeled with a polynomial in function. Other model forms [13] can be fit to the AOI test data. AOI testing may be considered optional for modules utilizing a plain glass cover sheet lacking antireflective coating or texture because an accurate general-purpose model is available [14], [15]. 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 the POA normal to the sun throughout the day.

The weather conditions required for this test are identical to those required for a thermal test. In practice, a thermal test is often performed just before solar noon and an angle of incidence test is performed just after solar noon. The module should be on sun for a minimum of 30 minutes before initiating an angle of incidence test to ensure thermal stability at the beginning of the test.

The module is initially tracked normal to the sun for 10 minutes while IV curves and module temperature are recorded (~ 4 scans/minute). The tracker is then gradually indexed to a range of incidence angles from 0° to 90°. Ideally, the tracker will have a deterministic control system such that prescribed incidence angles can be achieved (i.e. 0°, 5°, 10°, etc). Often this is not the case and incidence angle must be calculated from recorded sun position and tracker position. Tracker rotation is preferably towards and beyond zenith rather than across the horizon, to minimize irradiance variation from ground reflections [10].

V. ANALYSIS

After completion of the full test procedure, three data sets are assembled; one each for determination of temperature coefficients, electrical performance and angle of incidence response. Procedurally, measurement of temperature coefficients may occur at the conclusion of outdoor testing, however, analytically, they must be determined before performing any other analysis. Determination of AOI response relies on both temperature coefficients and in the most general case, the air mass function. In practice, this analysis is performed last.

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.

The full analysis procedure, including determination of temperature coefficients and AOI response, is too lengthy to present here. The remaining analysis will focus on electrical performance.

A. Clear Sky Analysis (Determination of $f_1(AM)$ 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. This portion of the analysis utilizes Clear Sky conditions, as indicated in Table III.

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

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

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

$$I_{scr} = \bar{f}_1(AM = 1.5)$$

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

$$f_1(AM) = \frac{\bar{f}_1(AM)}{I_{scr}}$$

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

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

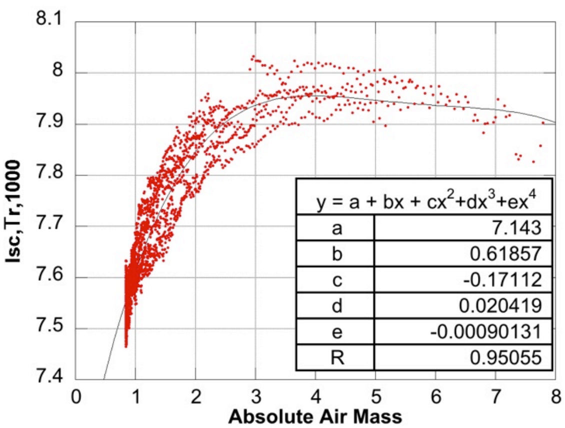

Fig. 2. Determination of f_1(AM) and I_{scr}.

B. All-Sky Analysis

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

i). Effective Irradiance: 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.

ii). Open Circuit Voltage (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}

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

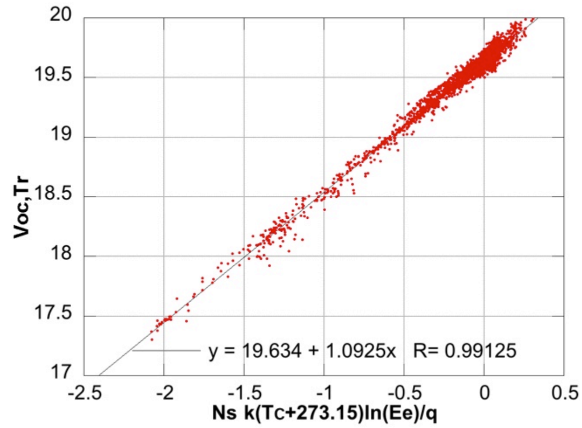

Fig. 3. Determination of V_{ocr} and diode factor, n.

iii). Maximum Power Current (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}

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

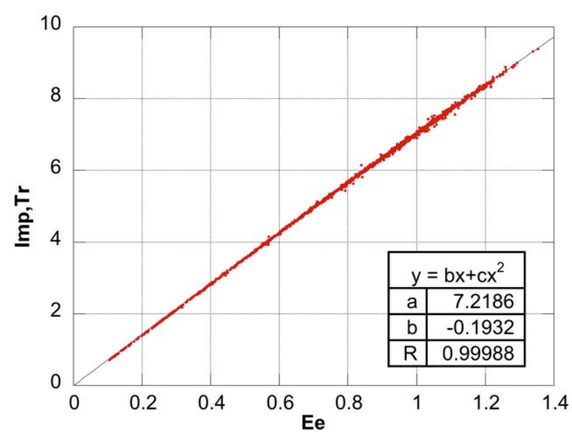

Fig. 4. Determination of I_{mpr}, C_0 and C_1

iii). Maximum Power Voltage (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}

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

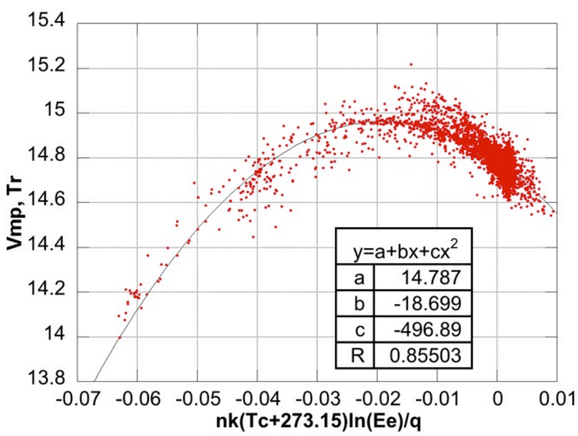

Fig. 5. Determination of V_{mpr}, C_2 and C_3.

VI. Summary

Prior efforts to transfer the measurement and analysis procedures for the Sandia Array Performance Model to third-party labs have resulted in only limited dissemination. In response to requests from commercial laboratories and module manufacturers, Sandia has formally documented the measurement and analysis methods as a supplement to the original model description. In this paper we have presented a description of the measurement procedures and an example analysis for calibrating the SAPM.

The procedure consists of measurement and analysis steps to develop a full set of SAPM coefficients for use with SAM or PV_Lib and is accompanied by a data set used to illustrate each analysis step. The procedure and data set are freely available for download from a variety of sources, including Sandia's website.

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