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

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Model Basics

Short Circuit Current is central to the model

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

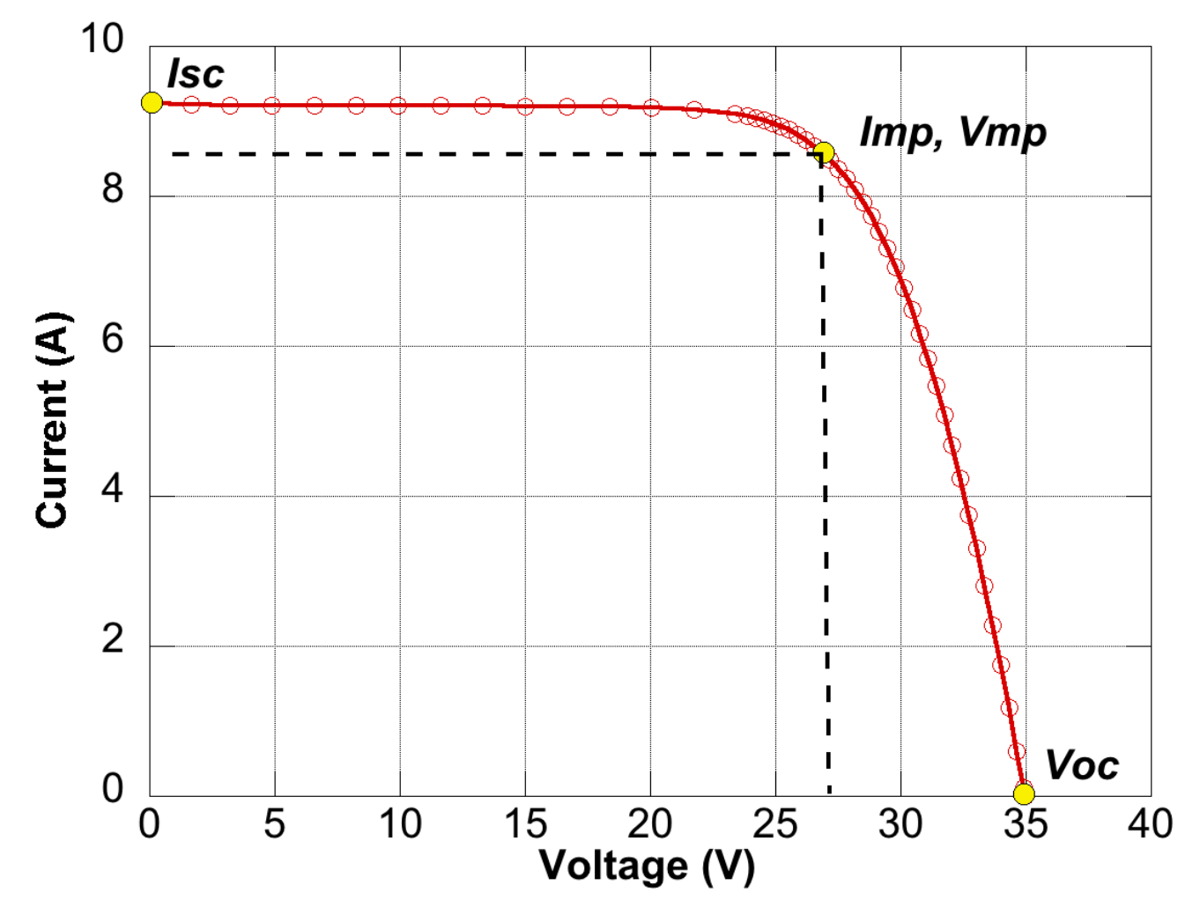
$$f_1(AM) = a_0 + a_1(AM) + a_2(AM)^2 + a_3(AM)^3 + a_4(AM)^4$$

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

Temperature Models

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

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



Remaining primary functions dependent on E_e, not G_{poa}

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

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

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

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

Equipment

- Azimuth-Elevation solar tracker capable of AOI range between 0° and 90°.
- AOI-corrected pyranometer measuring global POA irradiance (G_{POA}), mounted in the module test plane
- Pyranometer measuring the diffuse POA irradiance (G_{diff}), mounted in the module test plane
- Pyrheliometer measuring DNI (G_{DNI}), mounted on separate weather tracker
- Short circuit current and module temperature measurement
- Wind speed, ambient air temperature, barometric pressure
- Mitsubishi PV-UE125MF5N 36-Cell Polycrystalline Module (~2008)

Test Conditions

Parameter	Required	Preferred
Clear Sky Conditions		
GNI	800 - 1050 W/m²	600 - 1200 W/m²
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 minutes/2 days	1200 minutes/3 days
Cloudy or All-Sky Conditions		
GNI	200 - 400 W/m²	100 - 500 W/m²
DNI/GNI*	0 – 0.85 (< 0.05)	
Min. Test duration	200 minutes/1 day	1200 minutes/3 days
Thermal and AOI Measurements		
GNI	800 - 1200 W/m²	950 - 1050 W/m²
Variation in GNI	± 2.5%	± 0.5%
DNI/GNI	> 0.85	> 0.90
Air Mass	1 - 2	1.4 - 1.6
Wind Speed	< 4 m/s	< 2 m/s
Ambient Temperature	> 0°C	> 10°C

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

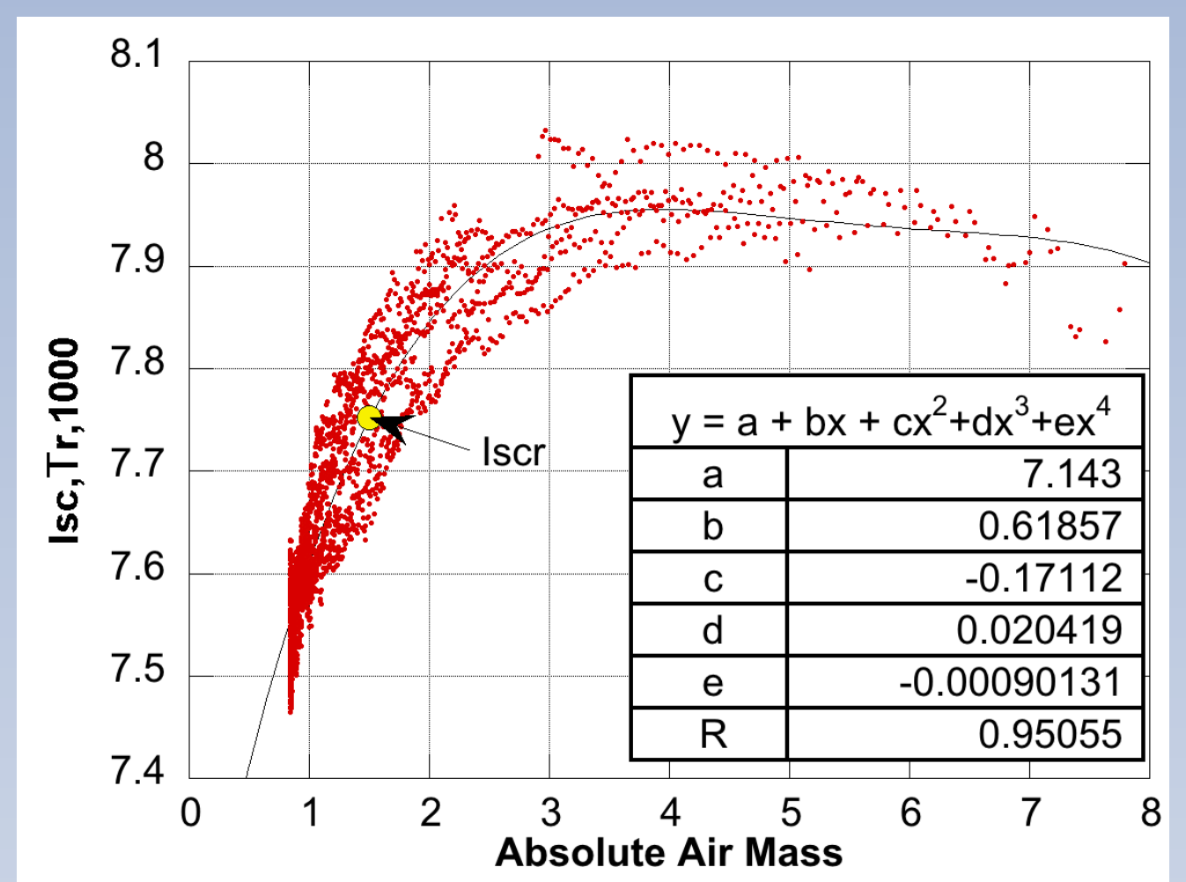
Abstract

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 industry, Sandia has formally documented the measurement and analysis methods as a supplement to the original model description.

Example Analysis

- Thermal Test to measure temperature coefficients (not shown)
- Clear Sky Conditions are used to calibrate I_{sco} and Air Mass function
- Calibrated I_{sco} used to determine E_e as input to remaining functions
- All-Sky Conditions (Clear + Cloudy) are used to calibrate remaining primary functions
- Angle of incidence test to determine reflection losses (not shown)

Short Circuit Current at STC and Air Mass Function



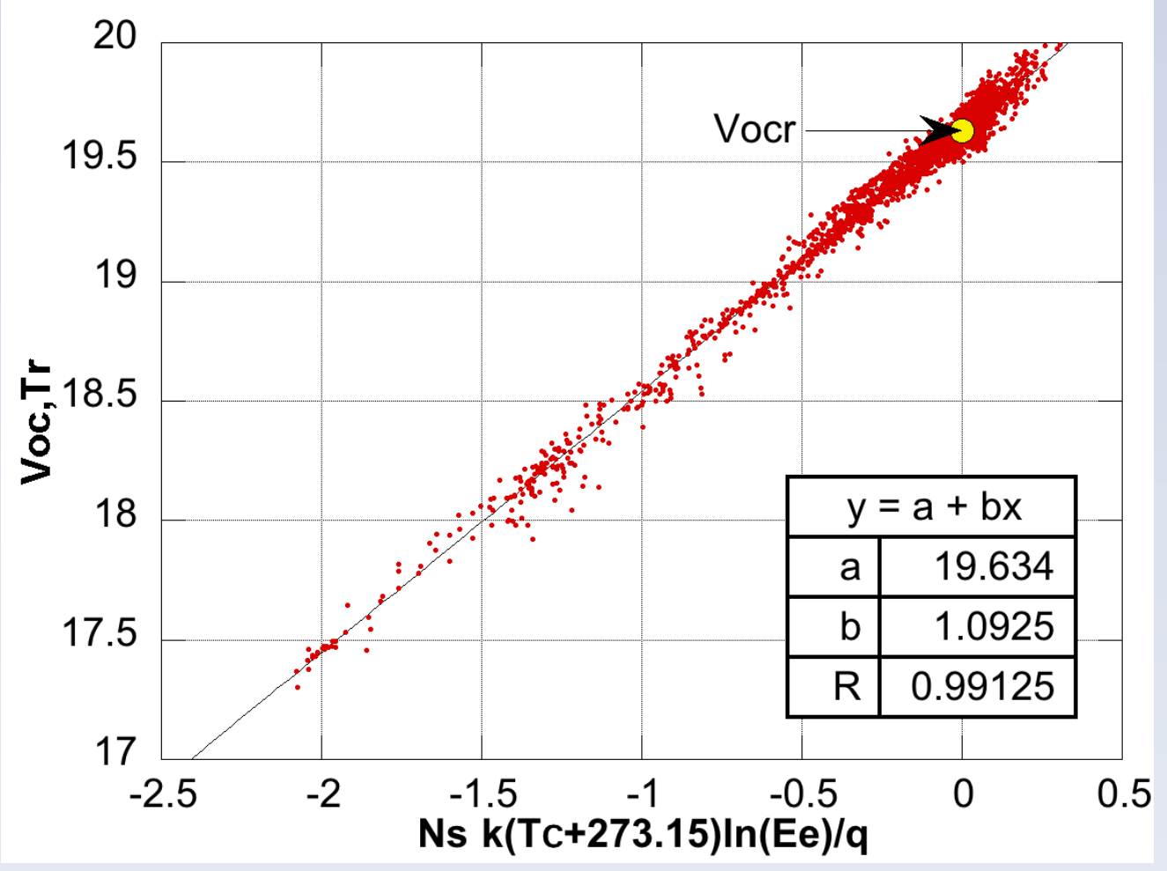
$$I_{sc,Tr,1000} = \frac{I_{sc}}{[1 + \hat{\alpha}_{Isc}[T_c - T_r]]} \left[\frac{G_0}{G_{poa}}\right]$$

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

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

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

Open Circuit Voltage at STC and diode factor



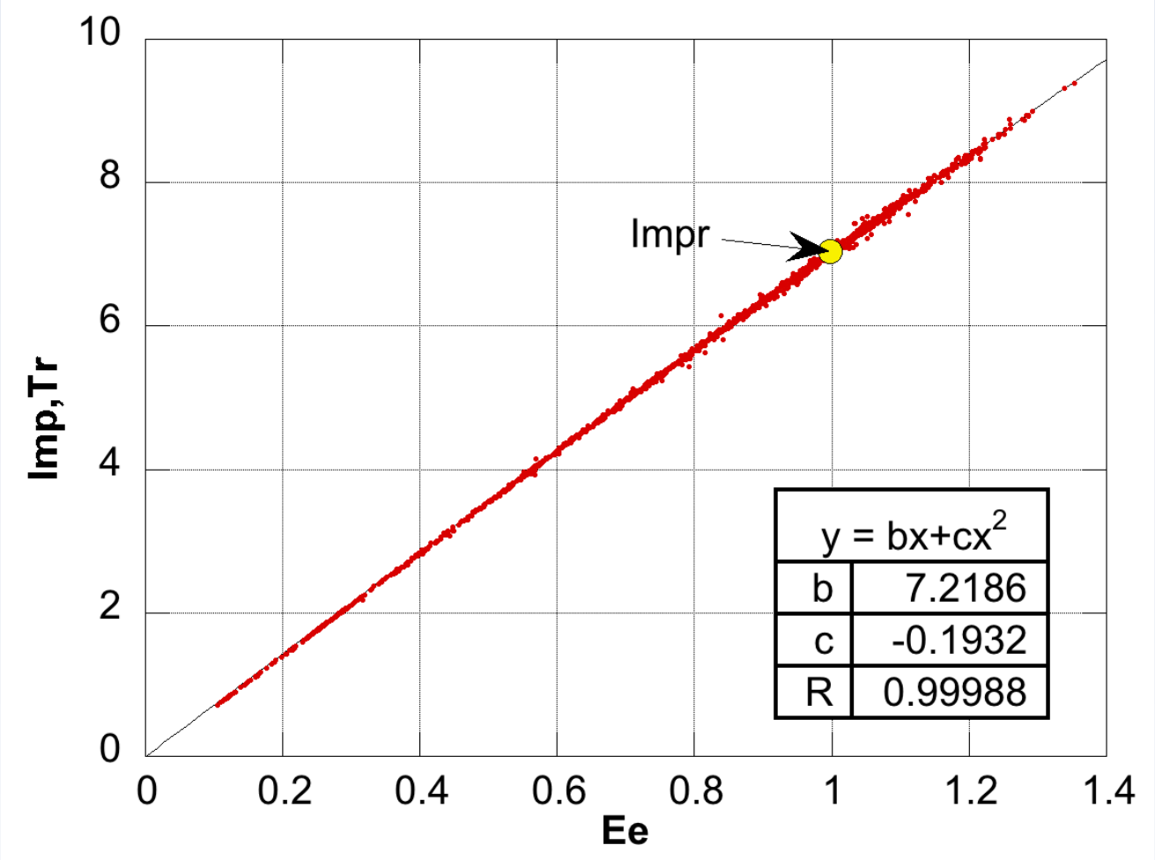
$$V_{oc,Tr} = V_{oc} - \beta_{Voc}[T_c - T_r]$$

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

$$V_{ocr} = a \qquad n = \mathrm{b}$$

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

MPP Current at STC and “C” Coefficients



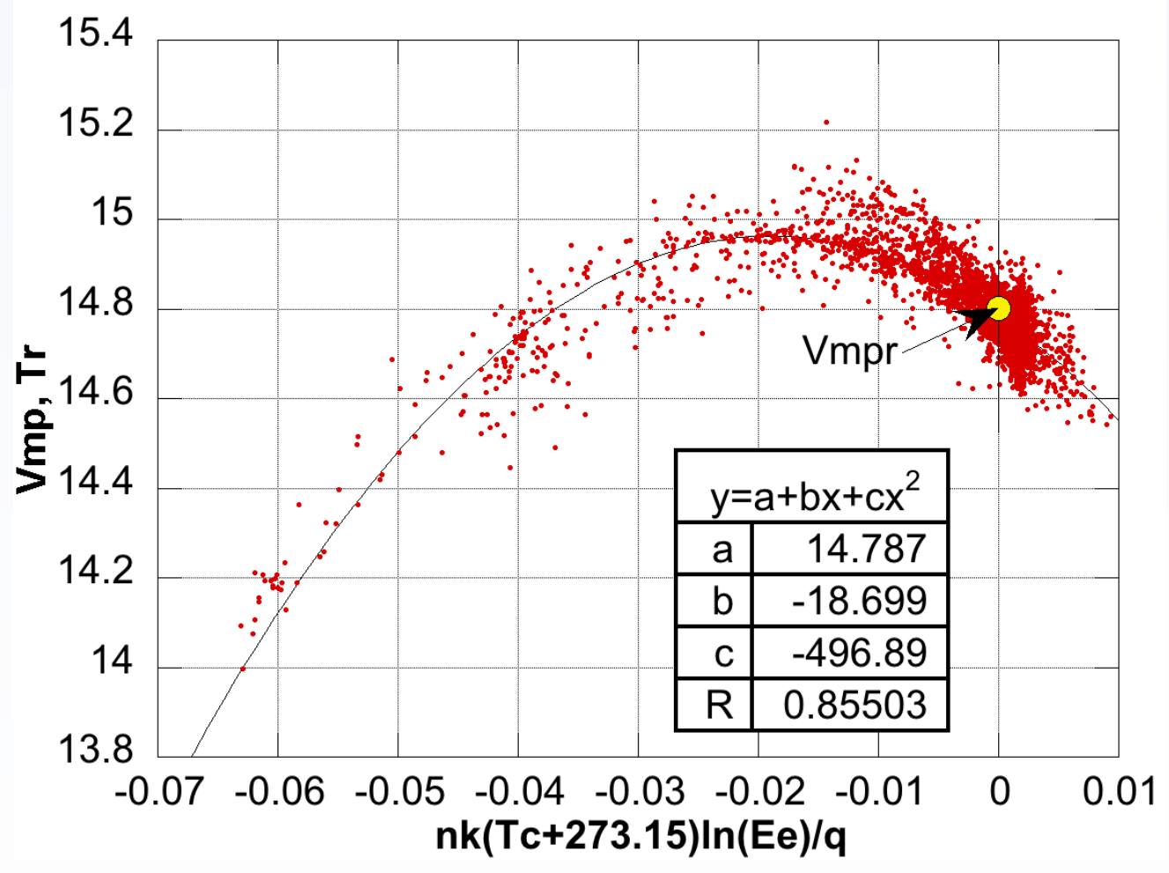
$$I_{mp,Tr} = \frac{I_{mp}}{\left[1 + \hat{\alpha}_{Imp}[T_c - T_r]\right]}$$

$$I_{mpr} = b + c$$

$$C_0 = \frac{b}{I_{mpr}} \qquad C_1 = \frac{c}{I_{mpr}}$$

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

MPP Voltage at STC and “C” Coefficients



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

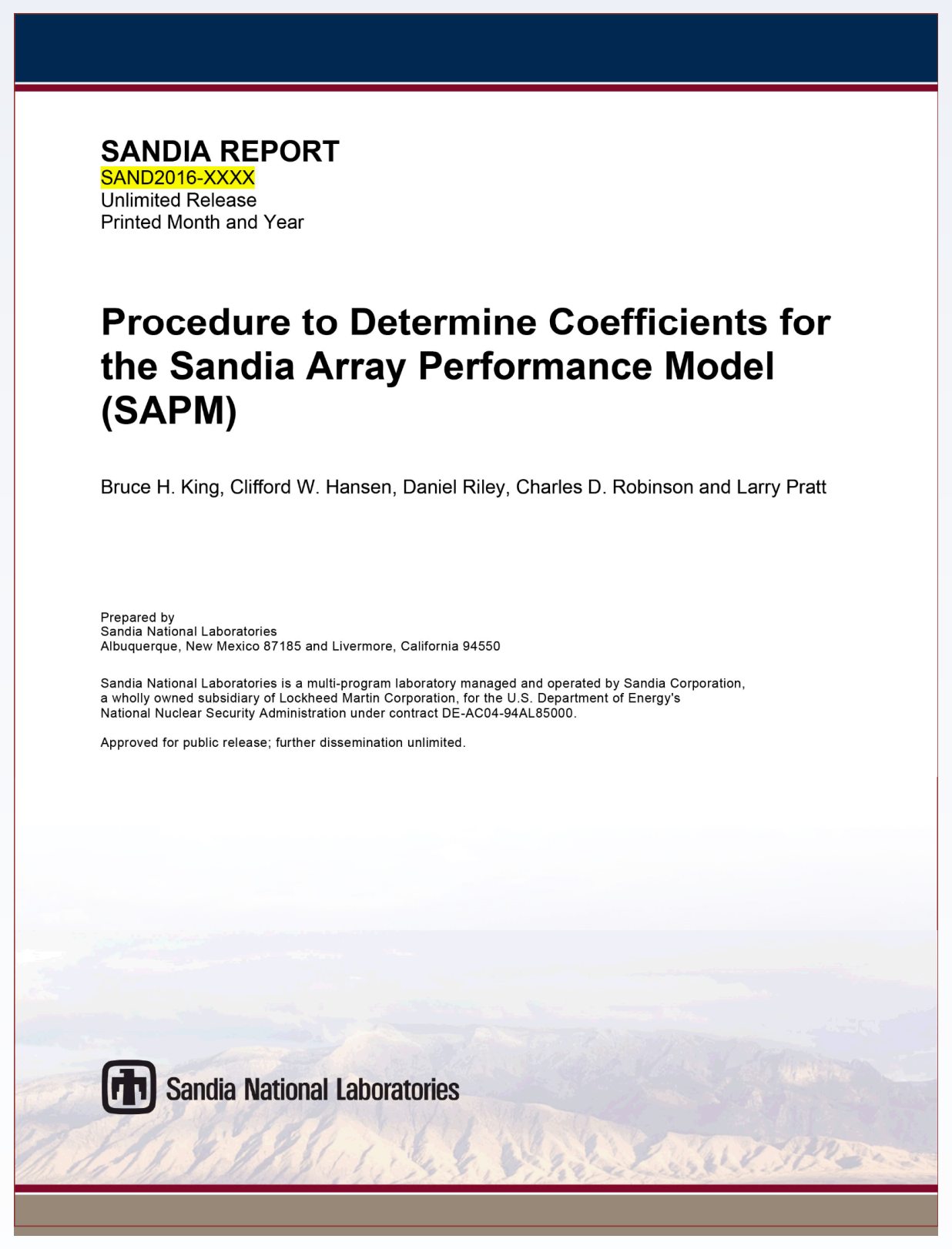
$$\frac{nk[T_c + 273.15]\ln(E_e)}{q}$$

$$V_{mpr} = a \qquad C_2 = \frac{b}{N_s} \qquad C_3 = \frac{c}{N_s}$$

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

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/m²), typically a pyranometer
G_0	Reference irradiance, 1000 W/m²
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/m², typically 3°C
T_0, T_r	Ref temperatures, typically 25°C and 50°C
α_{Isc}, α_{Imp}	Temperature coefficients for I_{sc} and I_{mp} (1/°C)
β_{Voc}, ®$_{Vmp}$	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/m²),
G_b	Beam component of irradiance (W/m²)
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)

Summary



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

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- In response to request by industry, Sandia has formally documented the measurement and analysis procedures to determine SAPM coefficients
- The procedure - along with example data sets – will be released at https://pvpmc.sandia.gov
- Coefficients generated using this procedure can be used with PV_LIB or SAM
- An example analysis is shown here for the primary SAPM equations
- Full analysis including temperature coefficients and AOI response is presented in the procedure

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