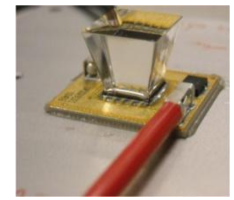
Sandia PV Array Performance Model

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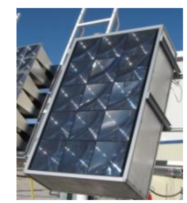


Sandia PV Modeling Workshop
September 22, 2010




Sandia Array Performance Model

Objective

- Develop a module and array performance model for detailed system engineering as well as system production (energy) analysis, for both grid-connected and stand-alone PV systems. Model was to be based on fundamental cell performance characteristics, but requiring only routine outdoor I-V measurements and meteorological data to determine performance coefficients.

Sandia's Unique PV Test Facility (1976 to Present)

- Cell, module, and array I-V measurements with associated solar resource and meteorological data since 1976; experience with every imaginable PV technology
- Dozens of arrays and thousands of modules tested, millions of I-V curves recorded, along with 20+ years of high resolution solar resource and weather data

Approaches Considered

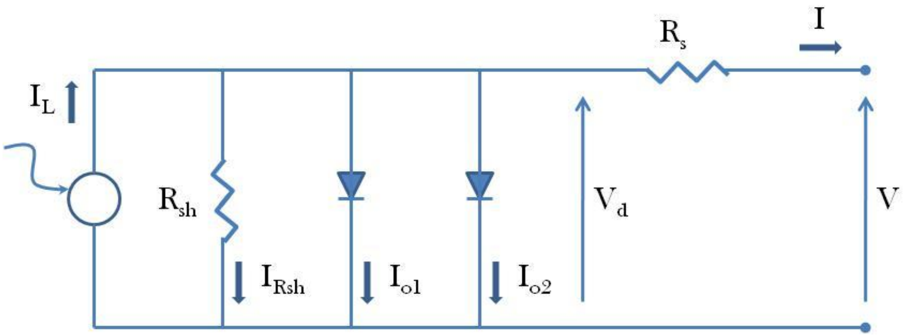
- Early multi-linear regression models versus irradiance and module temperature led to PVFORM model (Menicucci), and subsequent evolution in PVWatts model.
- Cell equivalent circuit models using parameters determined from light I-V and dark I-V measurements used extensively, but ruled out for modules and array modeling.
- Empirical sub-models, based on specific testing procedures, that isolate performance characteristics: module I-V parameters, temperature coefficients, operating temperature, solar spectral influence, optical and AOI effects, tracking error sensitivity, inverter performance, system derates. (PVMOD, PVDesignPro, SAM)

Models Within Models

- PV electrical performance model (I_{sc}, V_{oc}, I_{mp}, V_{mp}, P_{mp}, α_{Isc}, α_{Imp}, β_{Voc}, β_{Vmp}, δ_{Pmp}, series x parallel cells and modules, bypass diodes)
- Solar spectral model (irradiance, atmosphere, spectral response)
- Optical and AOI model (reflectance loss, AR coating, texture, lenses, etc.)
- Thermal model (cell and module operating temperature vs. environment)
- Solar irradiance on tilted surface (Perez, HDKR, Hay/Davies, Gueymard, Skartveit/Olseth, Liu/Jordan, …)
- Solar tracking algorithms (fixed, 1-axis, 2-axis, angle limits)
- Inverter performance model (voltage, power, temperature)
- Solar resource data (components, hourly TMY, measured)
- Application (Energy prediction, performance monitoring, diagnostics)
- System derate factors (soiling, shading, wiring, transformers, alignment, tracking error, availability, degradation, etc.)
- Economic models

Cell Equivalent Circuit Model

Basic Limitation: Appropriate for single-junction cells and for limited irradiance and temperature range, but not for series-connected cells or multi-junction cells.



Circuit Equations

$I = I_L - I_{Rsh} - I_{d1} - I_{d2}$

$I_L = \int SR(\lambda) \cdot E(\lambda)\, d\lambda \approx I_{sc}$

$V_d = V + I \cdot R_s$ ('Diode' voltage)

$I_{Rsh} = V_d / R_{sh}$

$I_{d1} = I_{o1} \cdot \{\exp[(q \cdot V_d)/(n \cdot k \cdot T_c)] - 1\}$ (For 'ideal' diode with n=1)

$I_{d2} = I_{o2} \cdot \{\exp[(q \cdot V_d)/(n_2 \cdot k \cdot T_c)] - 1\}$ (For 'non-ideal' diode with n > 1)

$I_o = A \cdot \{(q \cdot D_e \cdot \eta_i^2)/(L_e \cdot N_A) + (q \cdot D_h \cdot \eta_i^2)/(L_h \cdot N_D)\}$ (Saturation currents)

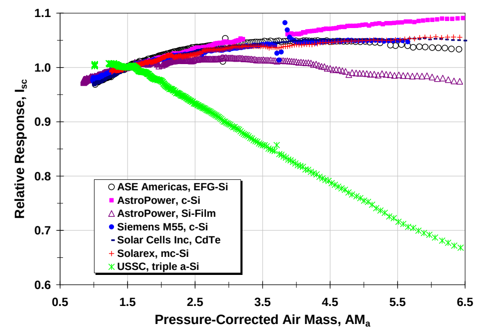
Fundamentals: Every term in equations varies with temperature and/or irradiance! Only exceptions (constants) are k and q and cell area, A. Second diode is needed in the model for low efficiency cells at low irradiance.

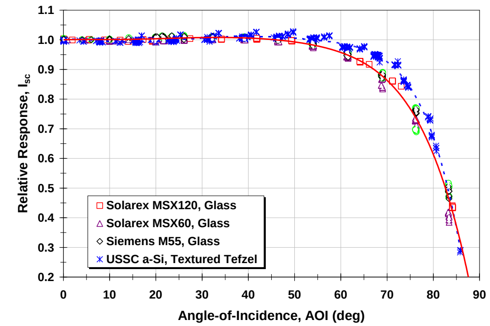
Partial Remedy: Determine parameters (I_{sc}, R_s, R_{sh}, I_{o1}, I_{o2}, n_2) at two temperature extremes (25, 75 C) and use interpolation for other temperatures, as done in Sandia PVSIM program.[1]

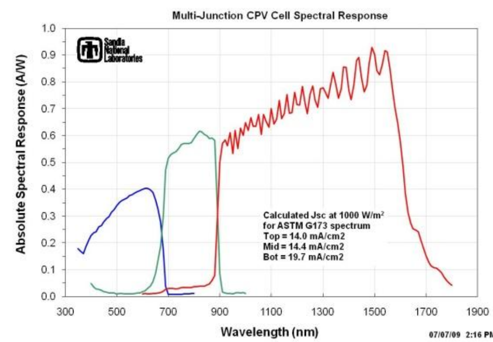
[1] D. King, J. Dudley, W. Boyson, "PVSIM: A Simulation Program for Cells, Modules, Arrays," 25th IEEE PVSC, May 1996.

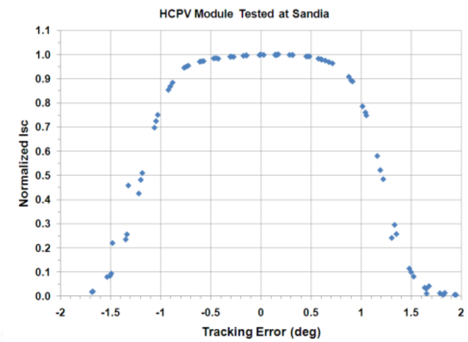
PV System Modeling Gets Complicated

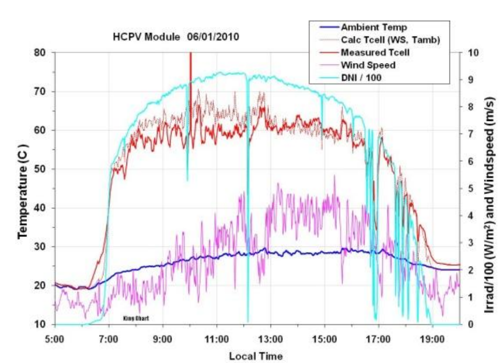
FACTORS INFLUENCING PV PERFORMANCE				
Factor	Cell	Module	Array	System
Solar irradiance	☼	☼	☼	☼
Cell temperature	☼	☼	☼	☼
Solar spectrum	☼	☼	☼	☼
Cell mismatch		☼	☼	☼
Cell stability		☼	☼	☼
Optics, AOI		☼	☼	☼
Temperature coefficients		☼	☼	☼
Bypass diodes		☼	☼	☼
Module materials		☼	☼	☼
Ambient temperature		☼	☼	☼
Wind speed		☼	☼	☼
Wind direction		☼	☼	☼
Mounting		☼	☼	☼
Surroundings		☼	☼	☼
Alignment			☼	☼
Module mismatch			☼	☼
Wiring			☼	☼
Tracking			☼	☼
Shading			☼	☼
Soiling			☼	☼
Inverter efficiency				☼
Transformers				☼
Availability				☼
Degradation				☼

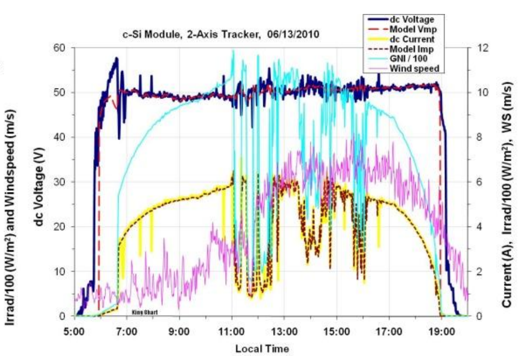












Module Temperature Coefficients

Historically temperature coefficients for I_{sc}, V_{oc}, P_{mp} were defined for individual cells at a specific irradiance level (1000 W/m^2) and a specific solar spectral irradiance (AM1.5). Several assumptions were often made:

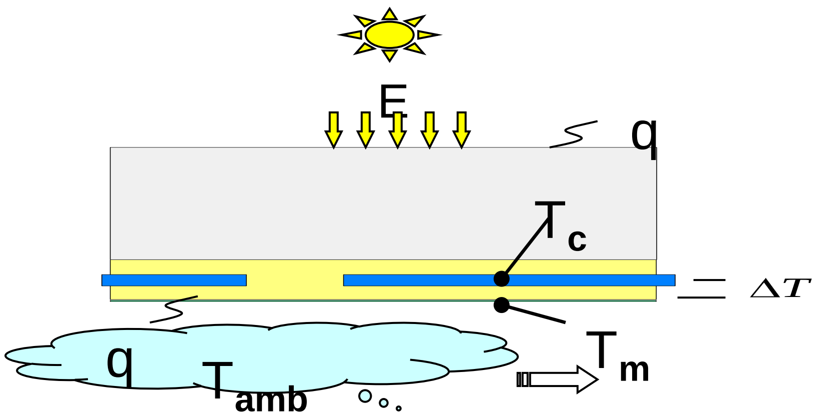
- current (I_{sc} and I_{mp}) varies linearly with temperature (usually ok),
- $\alpha_{Isc} = \alpha_{Imp}$ (typically not the case),
- voltage (V_{oc} and V_{mp}) varies linearly with temperature (usually ok),
- voltage coefficients do not vary with irradiance (usually ok),
- $\beta_{Voc} = \beta_{Vmp}$ (typically not the case),
- normalized power coefficient, δ_{Pmp} (%/ C), can be applied at all irradiance levels (not the case),
- $\delta_{Pmp} = V_{mp} \cdot \alpha_{Imp} + I_{mp} \cdot \beta_{Vmp}$ (V_{mp} and I_{mp} are irradiance dependent).

Years of module testing experience has led to the use of four separate temperature coefficients in the Sandia performance model.

Empirical Thermal Model: Tm and Tc

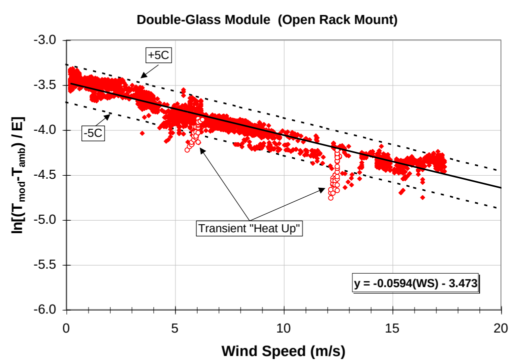
$$T_m = E \cdot \{e^{a+b \cdot WS}\} + T_{amb}$$

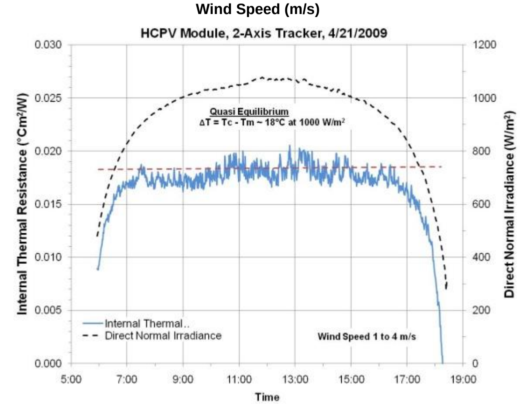
$$T_c = T_m + \frac{E}{1000} \cdot \Delta T_{1000}$$



A rigorous thermal modeling capable of addressing all module technologies, mounting methods, orientations, field layouts, and environmental conditions would be great; however, unlikely to be practically implemented.

Sandia model now uses a simple empirical relationship that works reasonably well for quasi-equilibrium conditions, and is adaptable to all module technologies and system configurations.



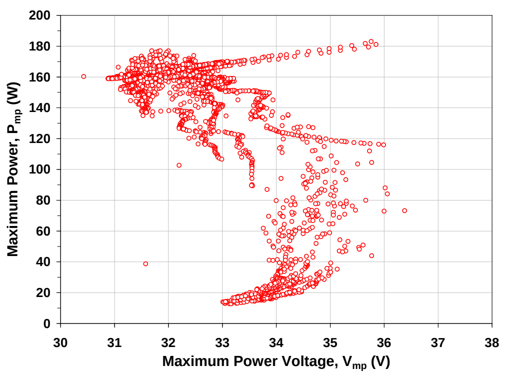


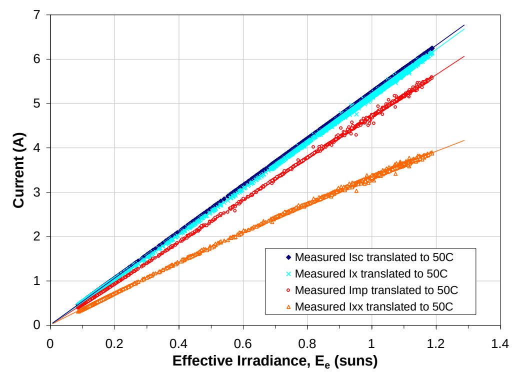
1^{st} Principle of I-V Curve Shape
(Effective Irradiance, E_e)

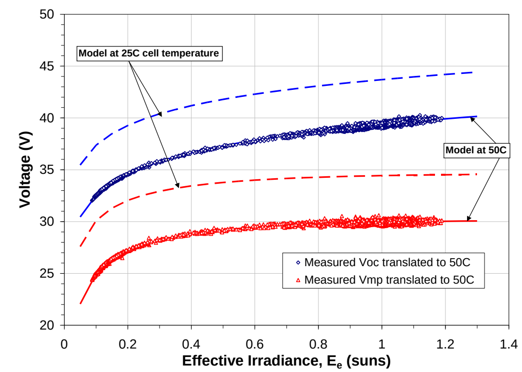
If cell (module) I_{sc} and cell temperature (T_c) are established, then the I-V curve shape (V_{oc}, V_{mp}, I_{mp}, FF) is defined for

- all solar spectra,
- all environmental conditions.

This "practical principle" leads to the concept of "effective irradiance, E_e" based on a reference short-circuit current value, I_{sco}. After translation for temperature, measured I-V data become self consistent and well behaved.







3300 I-V measurements, 5 days, clear and cloudy, 165-W mc-Si module

Versatility of Effective Irradiance Concept

$$I_{sc} = I_{sco} \cdot E_e \cdot \{1+\alpha_{Isc} \cdot (T_c - T_o)\}$$

Basic E_e Equation

= 1 PV
= 0.7 LCPV
= 0 HCPV

$$E_e = f_1(AM_a) \cdot \{(E_{DNI} \cdot \cos(AOI) \cdot f_2(AOI) + f_d \cdot E_{diff}) / E_o\}$$

--- usable --- ---------------------------------- available -----------------------------------

where: $E_{diff} = E_{POA} - E_{DNI} \cdot \cos(AOI)$

Bifacial Module Example

$$E_e = f_1(AM_a) \cdot \{(E_{DNI} \cdot \cos(AOI) \cdot f_2(AOI) + f_d \cdot E_{diff} + f_{bck} \cdot E_{bck}) / E_o\}$$

Determining appropriate E_e relationship is module technology, site, and system design dependent; thus, the most difficult task in system performance modeling.

Sandia Module Performance Model

$$I_{sc} = I_{sco} \cdot E_e \cdot \{1+\alpha_{Isc} \cdot (T_c - T_o)\}$$

$$I_{mp} = I_{mpo} \cdot \{C_0 \cdot E_e + C_1 \cdot E_e^2\} \cdot \{1 + \alpha_{Imp} \cdot (T_c\text{-}T_o)\}$$

$$V_{oc} = V_{oco} + N_s \cdot \delta(T_c) \cdot \ln(E_e) + \beta_{Voc} \cdot (T_c\text{-}T_o)$$

$$V_{mp} = V_{mpo} + C_2 \cdot N_s \cdot \delta(T_c) \cdot \ln(E_e) + C_3 \cdot N_s \cdot \{\delta(T_c) \cdot \ln(E_e)\}^2 + \beta_{Vmp} \cdot (T_c\text{-}T_o)$$

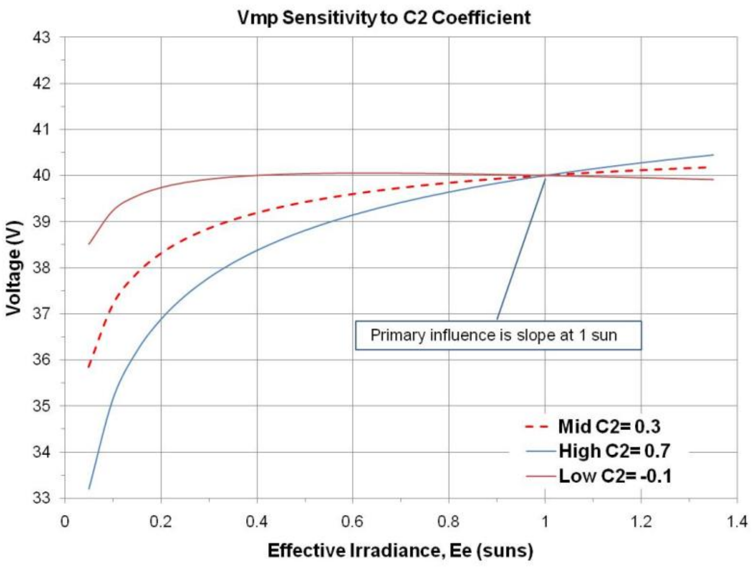
$$P_{mp} = I_{mp} \cdot V_{mp}$$

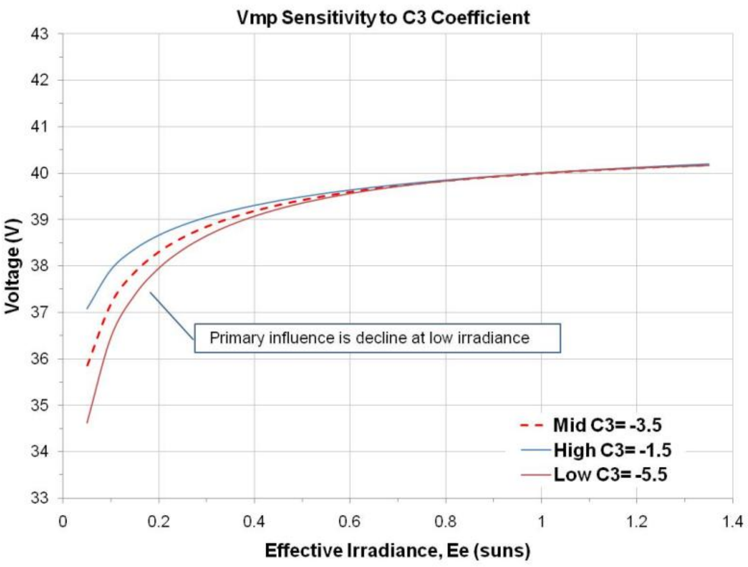
where: $\delta(T_c) = n \cdot k \cdot (T_c+273) / q$

Basic electrical performance model is actually very simple. Complexity is in the determination of effective irradiance (spectral and AOI effects) and cell temperature.

D. King, W. Boyson, J. Kratochvil, "Photovoltaic Array Performance Model," Sandia National Laboratories Report, SAND2004-3535, Aug. 2004.

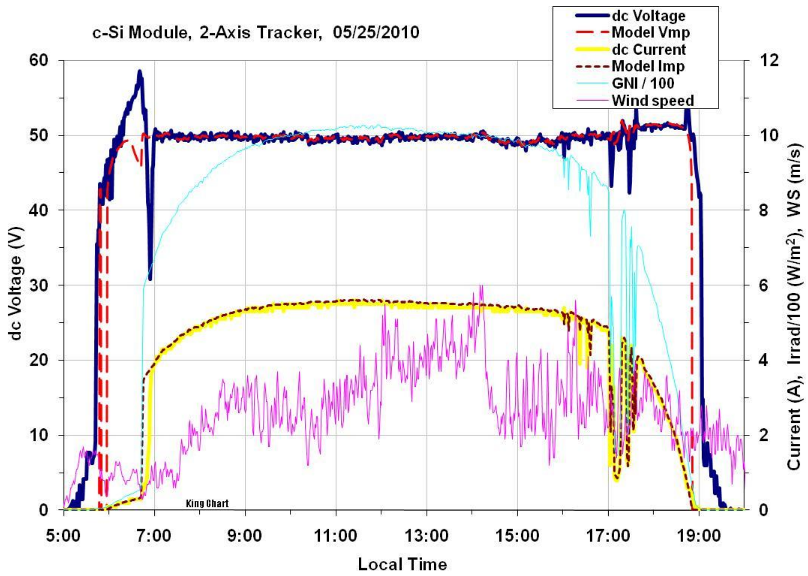
Sensitivity of Vmp to Coefficients

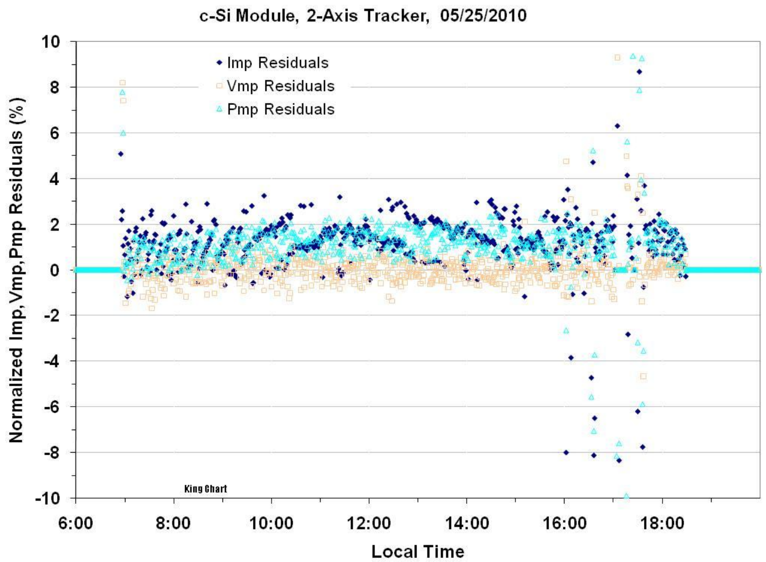




Basic understanding of the influence of performance coefficients makes it possible to tailor module coefficients to better match array or system performance, also aiding in long-term monitoring and the diagnosis of abnormal performance.

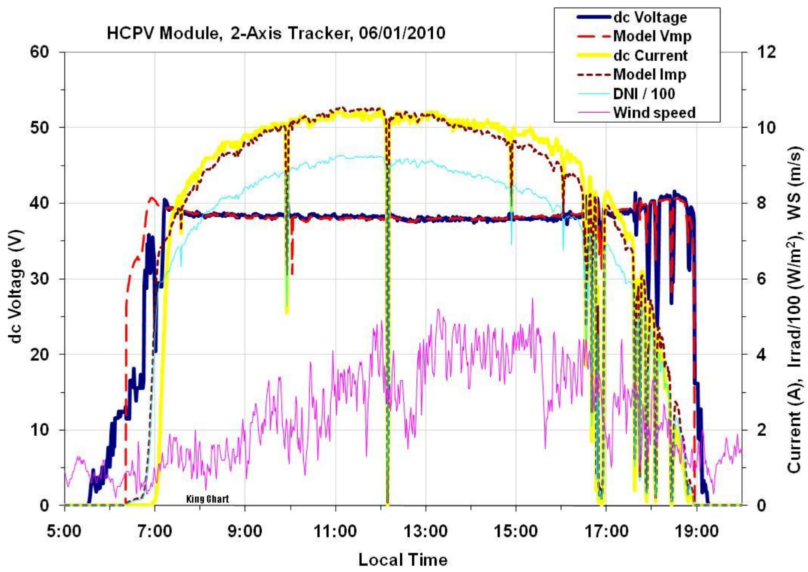
Example: Field Validation

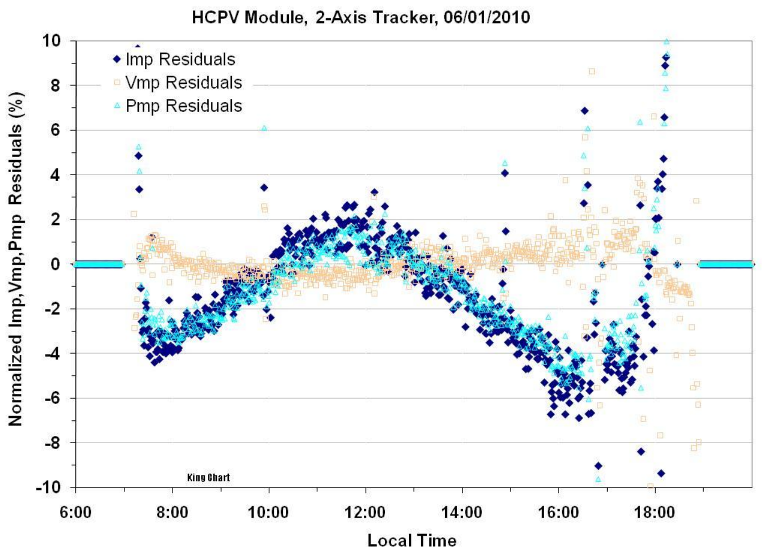




High resolution (1-min) performance data for grid-connected c-Si module mounted on 2-axis solar tracker. Morning shading present. First step in field validation is to confirm that I_{mp} and V_{mp} modeling equations match measured data for wide range of operating conditions. Normalized residuals for I_{mp}, V_{mp}, and P_{mp} provide relative magnitudes for errors as well as instructive trends.

Example: Field Validation





High resolution (1-min) performance data for grid-connected HCPV module mounted on 2-axis solar tracker. Morning shading present. In this case, the spectral model ($f_1(AM_a)$) was turned off to illustrate the effect on the I_{mp} residuals. As for the other coefficients, the spectral model can be tailored for the environmental conditions present at a particular site by using residual analysis.

Conclusions

- Sandia performance model has proven to be both versatile and accurate, and has been applied thousands of times for full variety of module and array technologies.
- Due to module production variation, mismatch, wiring losses, tracking errors, etc., array and system performance are best modeled by tailoring module coefficients based on system performance measurements (residuals).
- Accuracy of system performance models in predicting energy production will probably never match the expectations (wants) of the financial community.