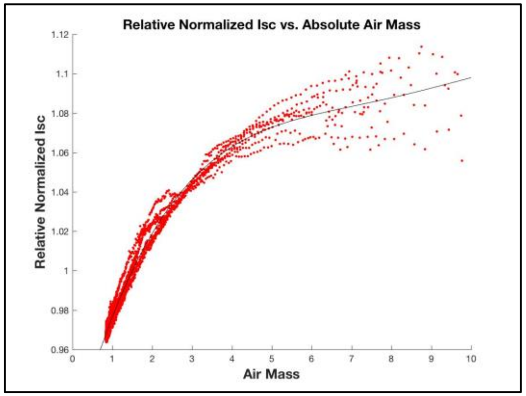

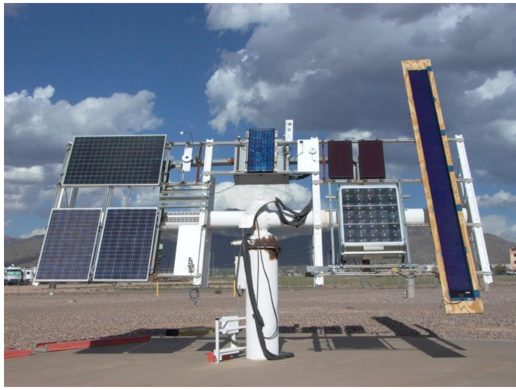

Simplifying methods to calibrate the Sandia Array Performance Model: elimination of the traditional thermal test

Bruce King and Charles Robinson

6th PV Performance Modeling Workshop
25 October, 2016
SAND2016-10541C

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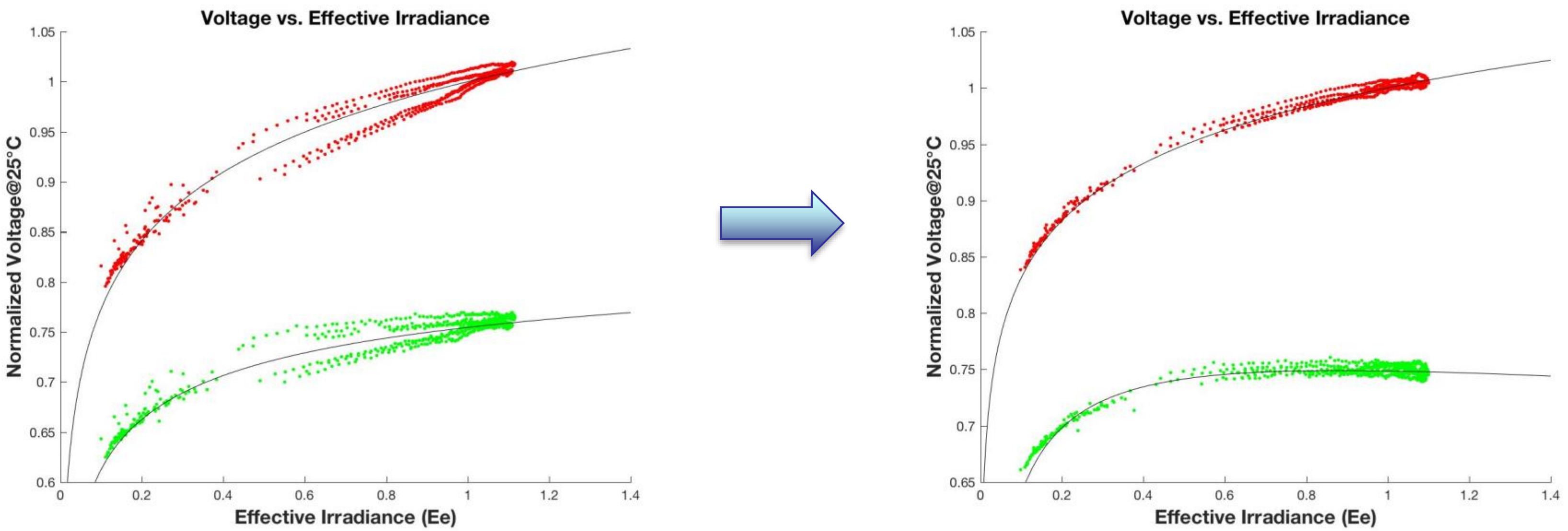
Overview

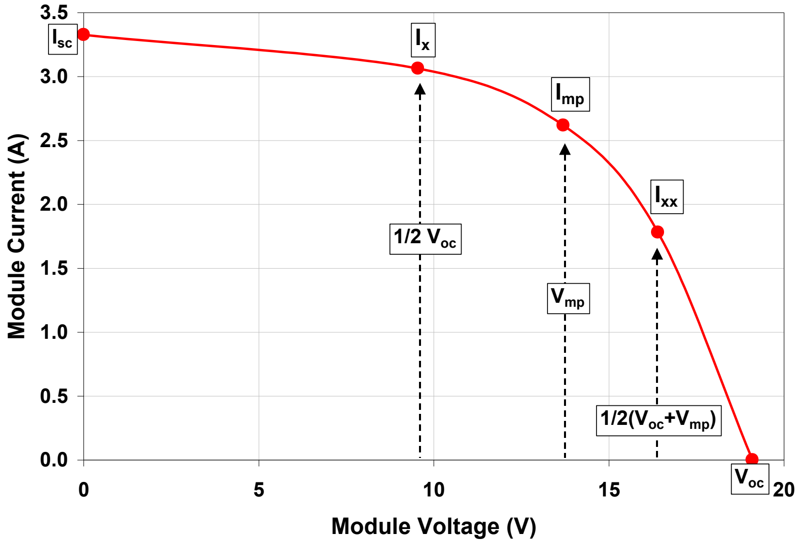
- Background
- Brief overview of Sandia Array Performance Model (SAPM) and calibration from outdoor tracker data
- Brief overview of alternative method to fit SAPM
- Example temperature coefficients and comparison to standard method
- Validation of method against multiple module types

Background

- Presented a new method of fitting the Sandia Model at the 5th PV Performance Modeling and Monitoring Workshop in San Jose
- Motivated by prototype CIGS module – problem with temperature coefficients (believable, but incorrect)
- New method eliminated problem
- New method is internally self-consistent – eliminates practice of using temperature coefficients measured for one module in the analysis of another
  - better for long-term performance and degradation studies in which individual modules are tracked for many years



Sandia Array Performance Model (SAPM)



$$I_{sc} = I_{sco} f_1(AM) \left[\frac{E_b f_2(\theta) + f_d E_{diff}}{E_0}\right] [1 + \hat{\alpha}_{Isc}[T_c - T_0]]$$

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

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

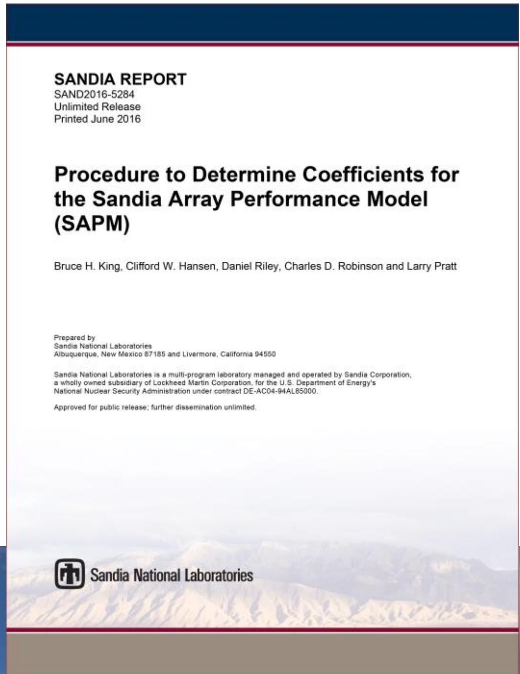
$$V_{mp} = V_{mpo} + C_2 N_s \delta(T_c) \ln(E_e) + C_2 N_s [\delta(T_c) \ln(E_e)]^2 + \beta_{Vmp}[T_c - T_0]$$

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

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

- Semi-empirical model that defines five points on the IV curve
- Full model consists of 4 primary constitutive equations, 37 coefficients
- Coefficients can be used with PV_Lib, SAM and other modeling packages to predict system performance

Standard Model Calibration


SANDIA REPORT
SAND2016-5284
Unlimited Release
Printed June 2016

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

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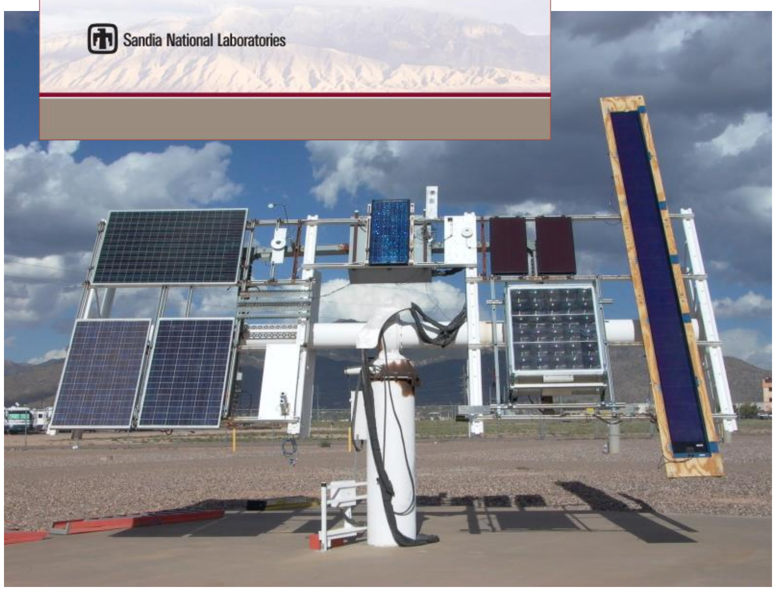


- Characterization is performed outdoors on a two-axis solar tracker.
- Full characterization takes two weeks or longer
  - Exact length of testing depends on local weather conditions
- Historical calibration method utilizes data restricted to tight bounds (e.g. AM1.4-1.6) coupled with "piece-wise" regression analysis

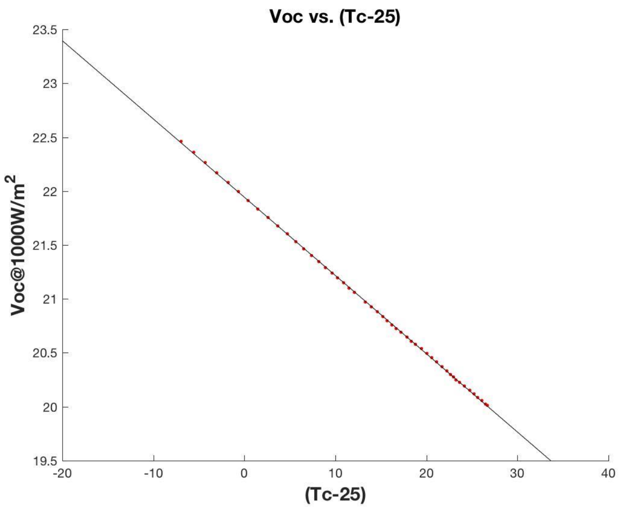
Three components

- **Electrical performance test**
  - Tracker held on sun from sunrise to sunset, multiple days, clear and cloudy conditions
  - IV curves measured at 2 minute intervals
  - Approximately 1000 IV curves minimum
- **Thermal test**
  - IV curves measured as module heats rapidly
  - Temperature coefficients for I_{sc}, I_{mp}, V_{oc} and V_{mp}
- **Angle of incidence (AOI) response**
  - IV curves measured as module is indexed off-sun

Traditional Outdoor Thermal Test to determine temperature coefficients

Procedure (consistent with IEC 60891, 61853)

- Module is covered with an opaque sheet and allowed to cool to ambient temperature
- Cover is removed; IV curves and module temperatures are measured rapidly (~2 samples/minute) while temperature rises
- Temperature coefficients are determined from linear regression analysis of I_{sc}, V_{oc}, I_{mp}, V_{mp} against measured temperature



Challenges:

- Temperature uniformity
- Time-consuming
- Reduces amount of "clear-sky" data available for other analyses

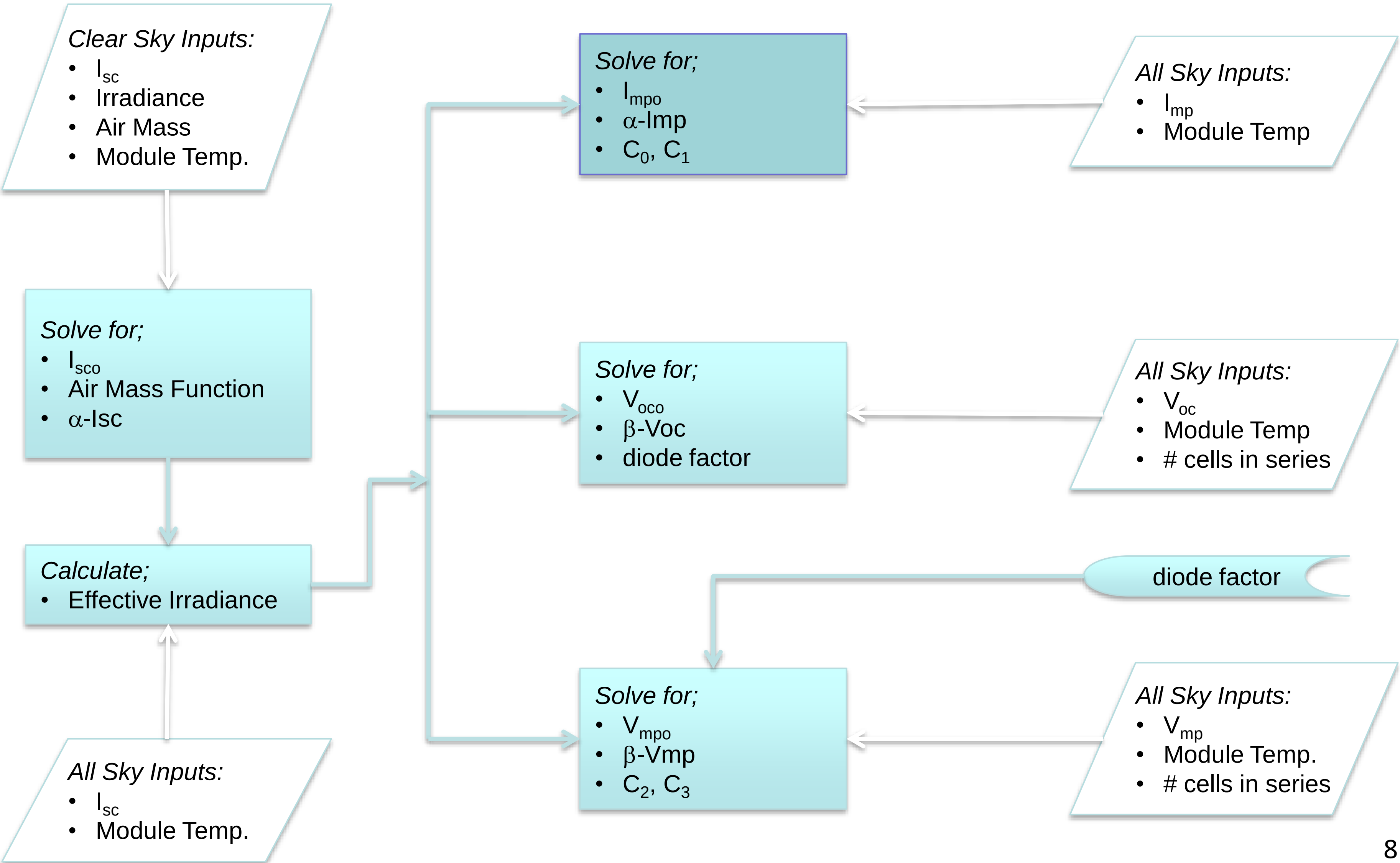
Because of these challenges, coefficients are often measured on only a single module of a given type

Alternate analysis method* eliminates need to directly measure temperature coefficients

- Simultaneously solve each SAPM constitutive equation for fundamental parameters, e.g. STC electrical parameters, airmass function, temperature coefficients, etc.
- Does not use temperature coefficients from a discrete test – eliminates need to perform test
- Uses all IV data collected over a test interval
- Eliminates use of data restricted to tight bounds (e.g. AM1.4-1.6) coupled with “piece-wise” regression analysis

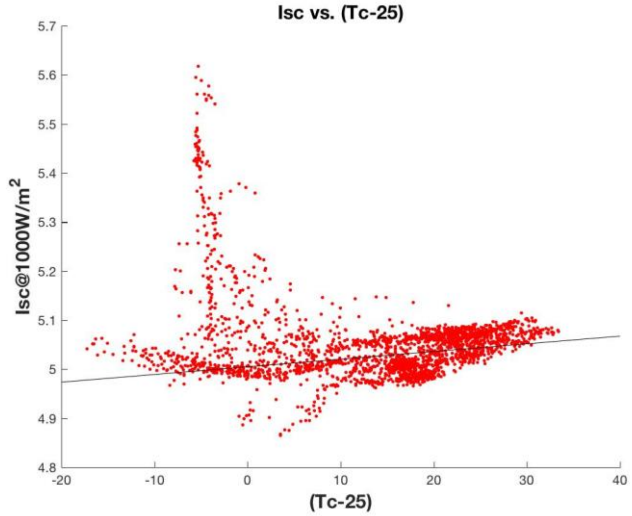
Presented at 5th PV Performance Modeling Workshop, 9 May, 2016, San Jose, CA
https://pvpmc.sandia.gov/download/5240/

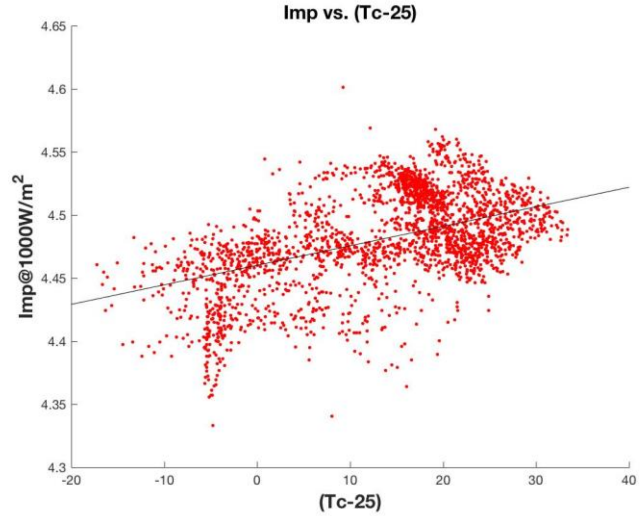
Alternate Method – Simultaneous Solution

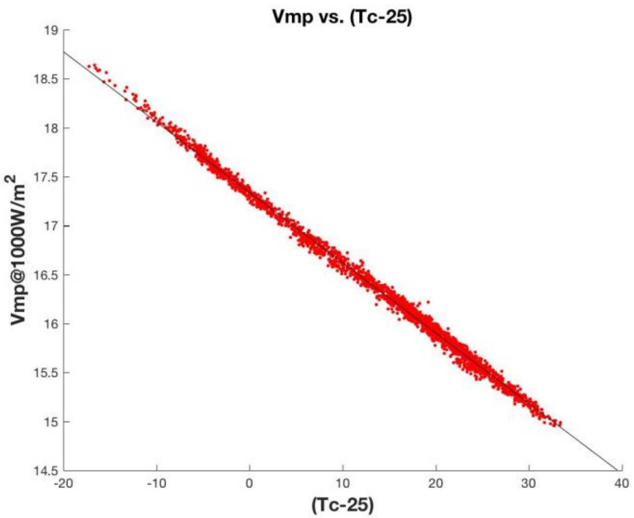


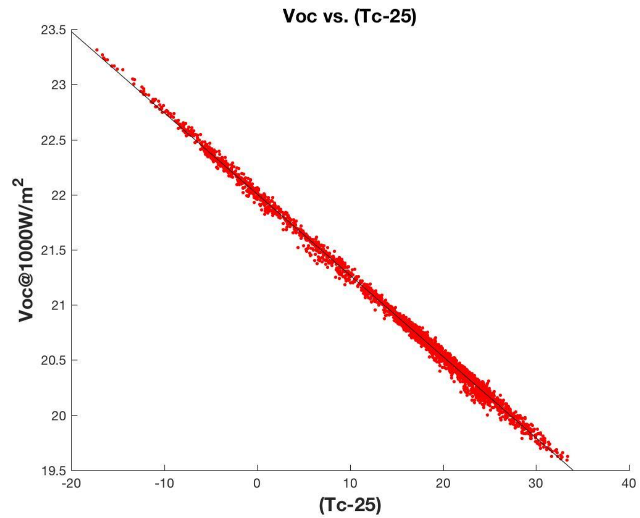
Example: monocrystalline silicon module

Sandia National Laboratories

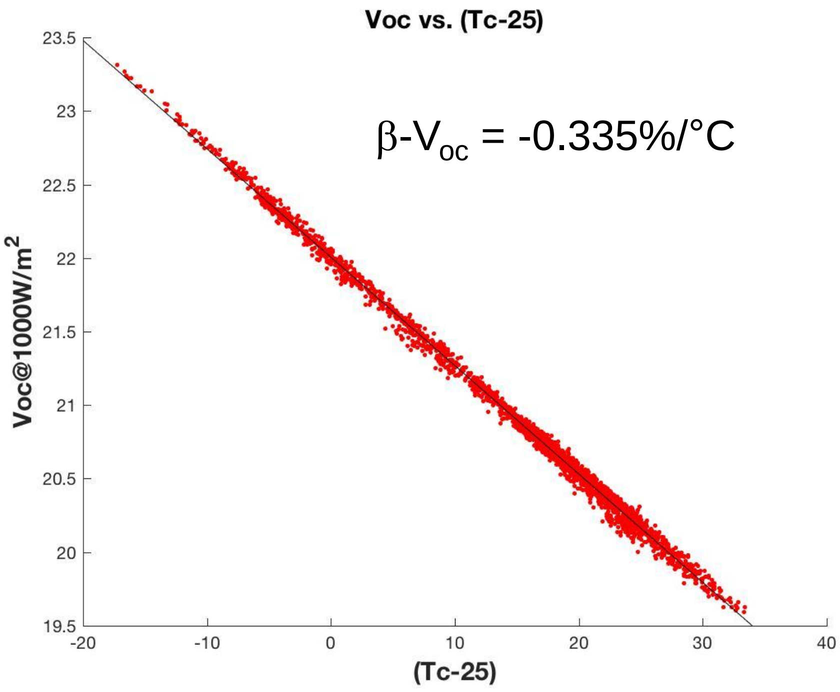




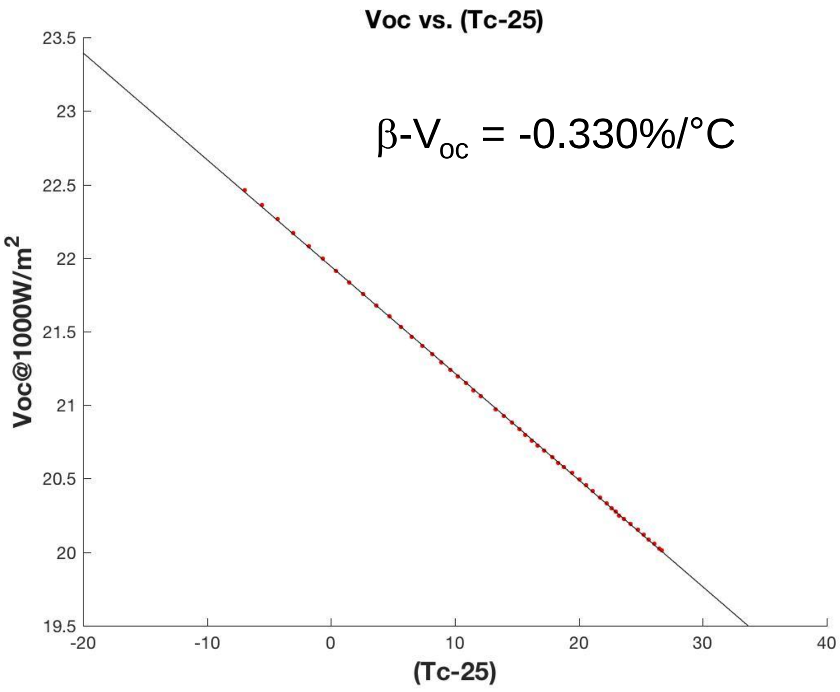




Temperature Coefficients – β-V_{oc} comparison



Calculated



Measured

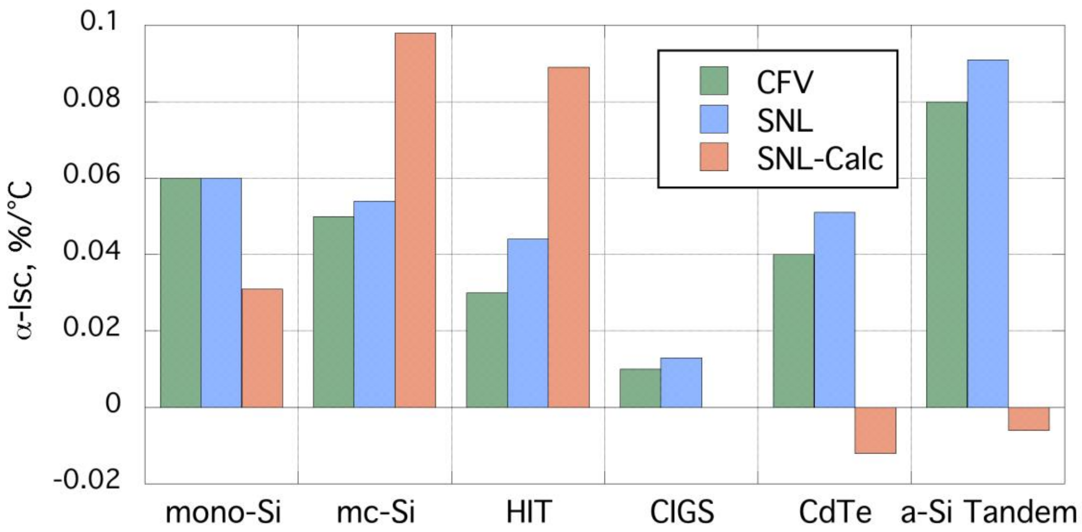
Validation against multiple module types

- Leverage MPERT* data set published by Bill Marion
  - Open data set collected for 24 modules
  - Includes STC performance, temperature coefficients, SAPM model parameters, IV curve data for multiple years, multiple climates
  - Crystalline Silicon – mono, multi, HIT
  - Thin Film – CIGS, CdTe, a-Si (tandem, triple junction)

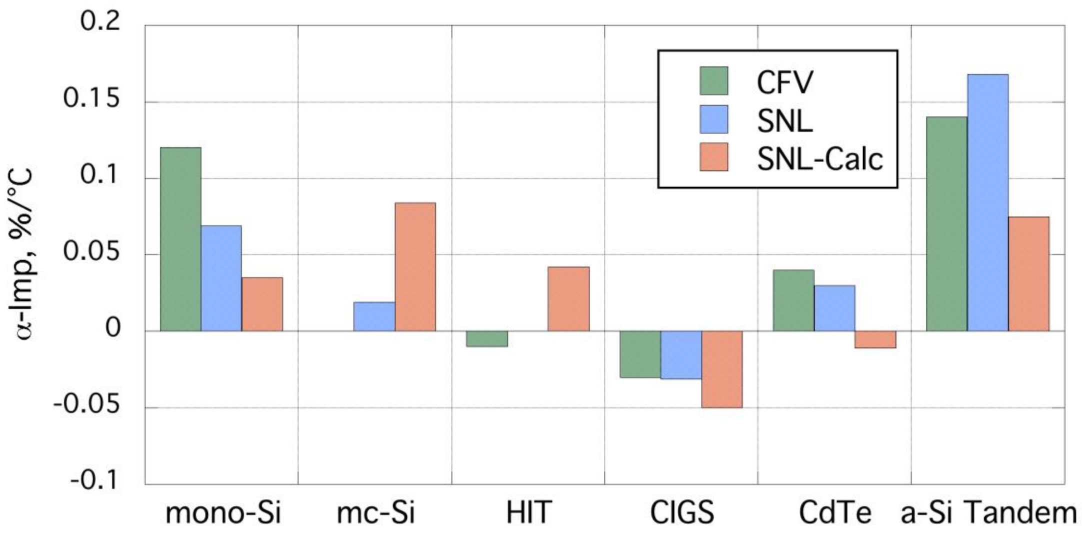
- Data leveraged for validation
  - Measured temperature coefficients
    - Sandia – measured outdoors on two-axis tracker using traditional method
    - CFV Solar - measured indoors with a h.a.l.m. flash solar simulator
  - Original IV curve data collected by Sandia
  - Down-select to six modules representing most major absorber types

* B. Marion, A. Anderberg, C. Deline, J del Cueto, M. Muller, G. Perrin, J. Rodriguez, S. Rummel, T. J. Silverman, F. Vignola, R. Kessler, J. Peterson, S. Barkaszi, M. Jacobs, N. Riedel, L. Pratt and B. King, “New Data Set for Validating PV Module Performance Models,” in *40th IEEE Photovoltaic Specialists' Conference*, Denver, CO, 2014.

Currents

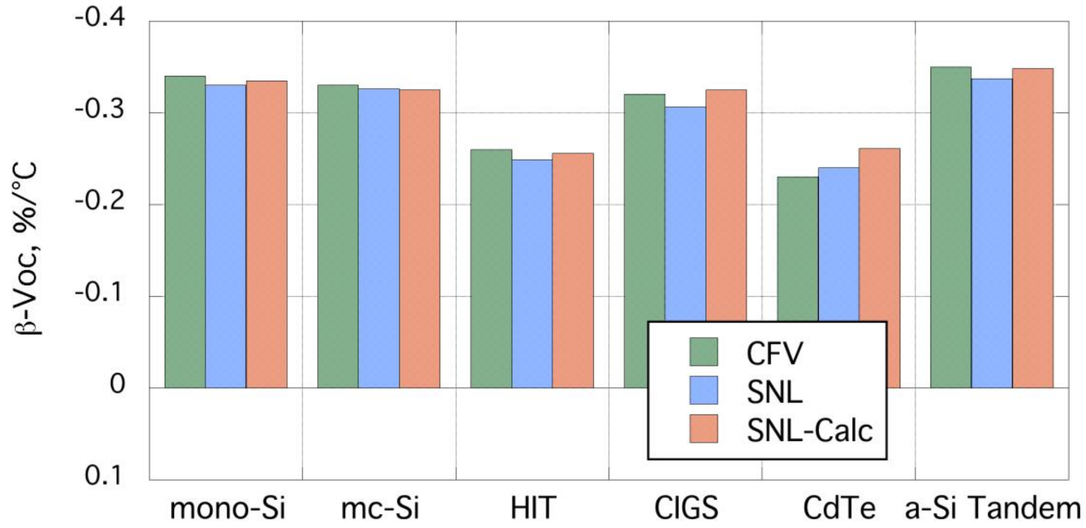


- Average absolute difference between Measured and Calculated was ~0.05%
- Maximum difference was 0.1% (a-Si)

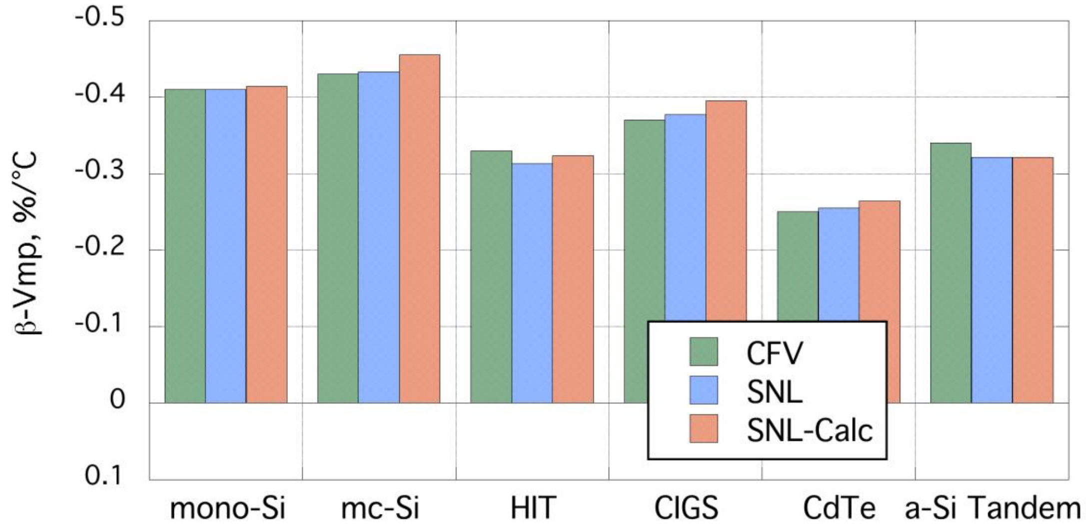


- Average absolute difference between Measured and Calculated was ~0.06%
- Maximum difference was 0.1% (a-Si)

Voltages



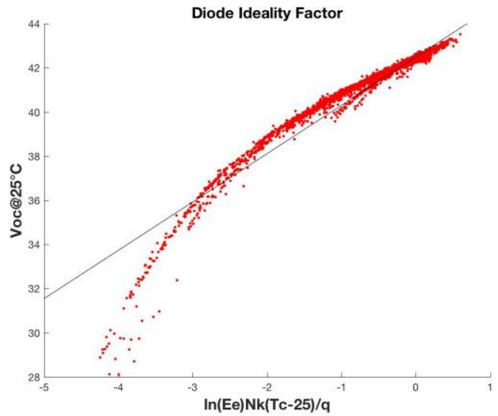
- Average absolute difference between Measured and Calculated was ~0.01%
- Maximum difference was 0.03% (CdTe)

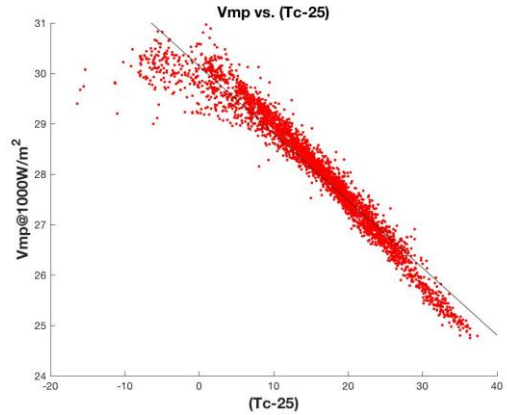


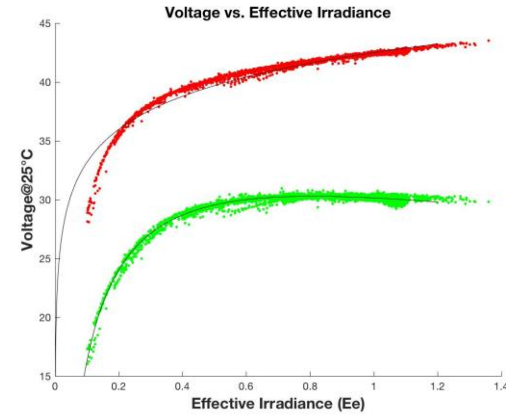
- Average absolute difference between Measured and Calculated was ~0.02%
- Maximum difference was 0.03% (mc-Si,CIGS)

Limitations - Voltage

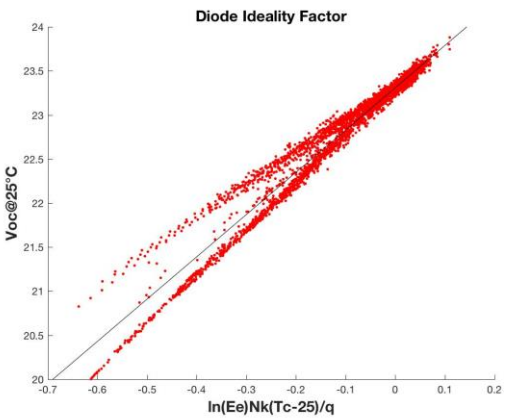
CIGS (CIGS39013)

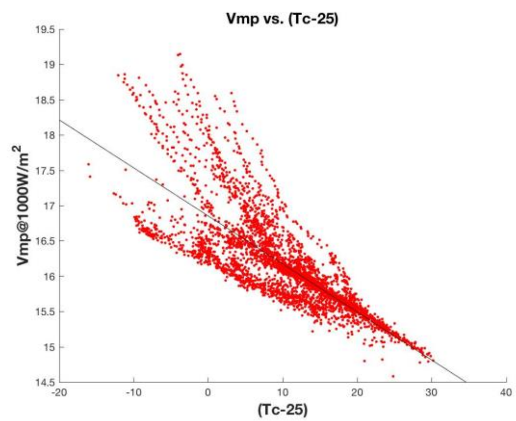


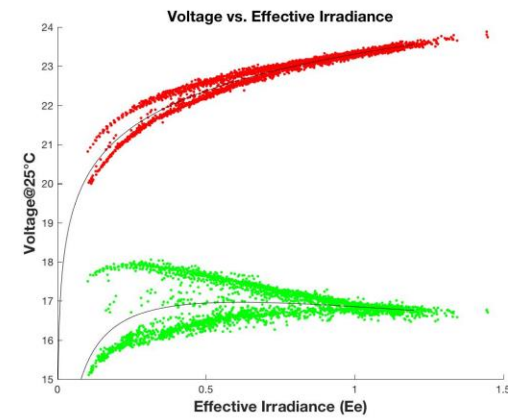




a-Si Triple Junction (aSiTriple28325)







SAPM doesn't describe everything!

Summary

- An alternate method to fit SAPM constitutive equations using measured IV curves was previously demonstrated
- The alternate method does not use temperature coefficients from a discrete test – eliminates need to perform test
- Eliminating the thermal test simplifies module characterization and can make more clear sky data available for analysis
- Better for long-term performance and degradation studies in which individual modules are tracked for many years
- Method was validated against historical data sets including most common flat-plate absorber types (both crystalline silicon and thin film)