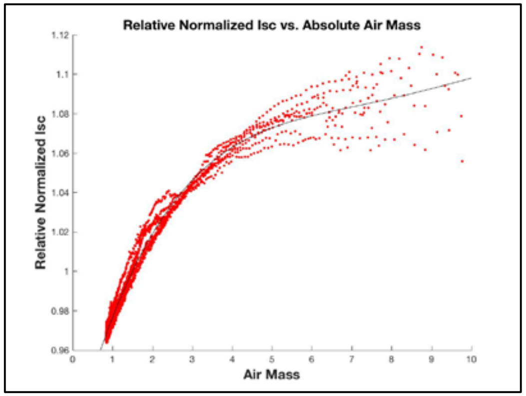


CIGS Performance Analysis:
Alternative Method to Fit the Sandia Array Performance Model

Bruce King

5th PV Performance Modeling Workshop

9 May, 2016

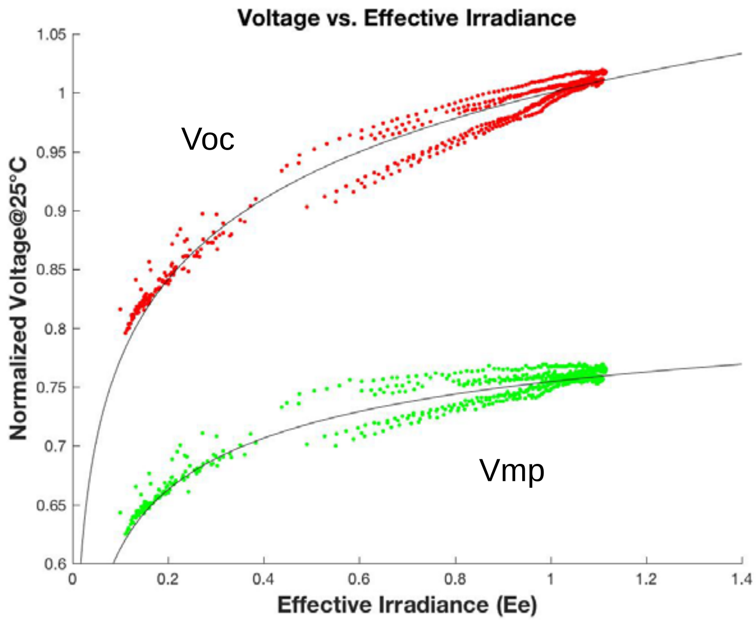
SAND2016-4658C

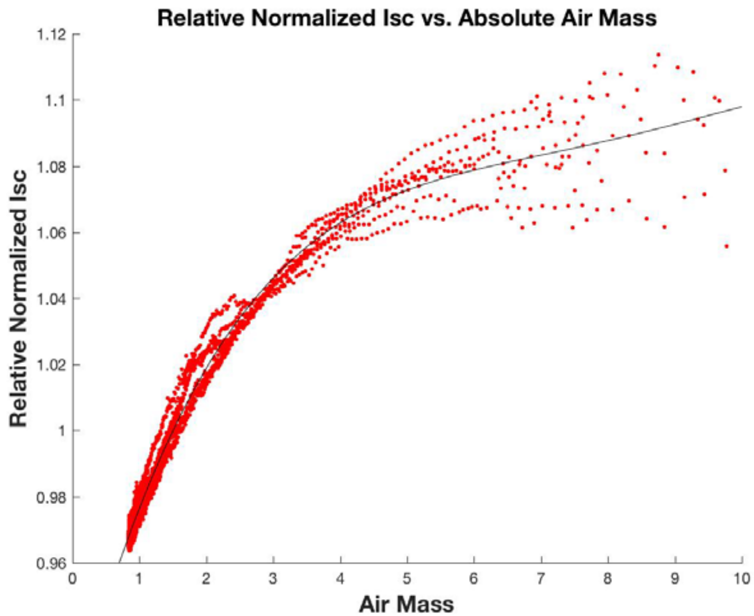
Outline

1. Challenges to Measuring and Modeling CIGS Performance
2. Overview of Outdoor Performance Measurements and Sandia Array Performance Model (SAPM)
3. Alternative Method to Fit SAPM
4. Summary

Challenges to Measuring and Modeling CIGS Performance

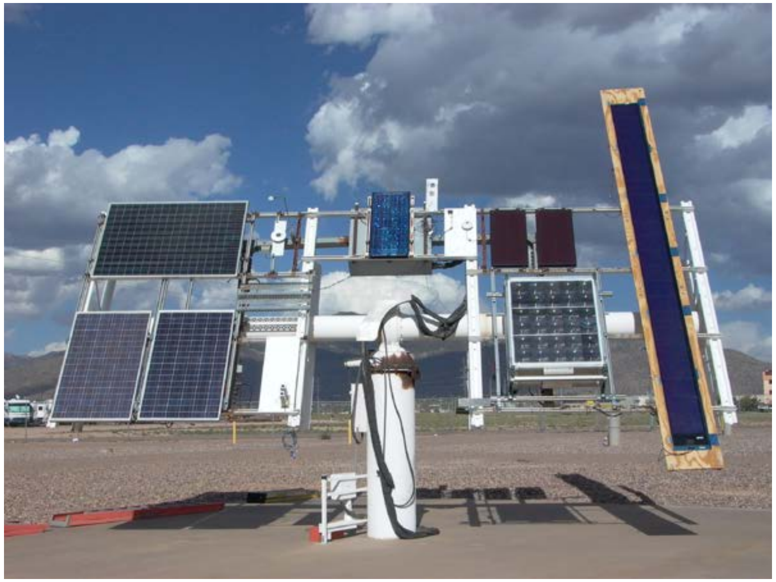
- Metastable performance
  - Modules may require 10’s of hours of operation at 1000 W/m^2 to reach steady-state performance conditions
  - May be sensitive to operating temperature
  - Performance stabilization may reverse after storage in the dark (or overnight?)
- Parameters reported to be sensitive to metastability include Voc, Vmp, fill factor and temperature coefficients
- Spectral response is not the same as c-Si – accurate performance models need air mass modifiers





Outdoor Module Characterization at Sandia

Sandia National Laboratories



Outdoor characterization is performed on a flexible, fully programmable two-axis solar tracker.

Range of Technologies; flat plate, CPV, etc.

Instrumentation
- Calibrated Silicon Reference Cell
- Calibrated Precision Spectral Pyranometer
- Custom IV sweep hardware and software

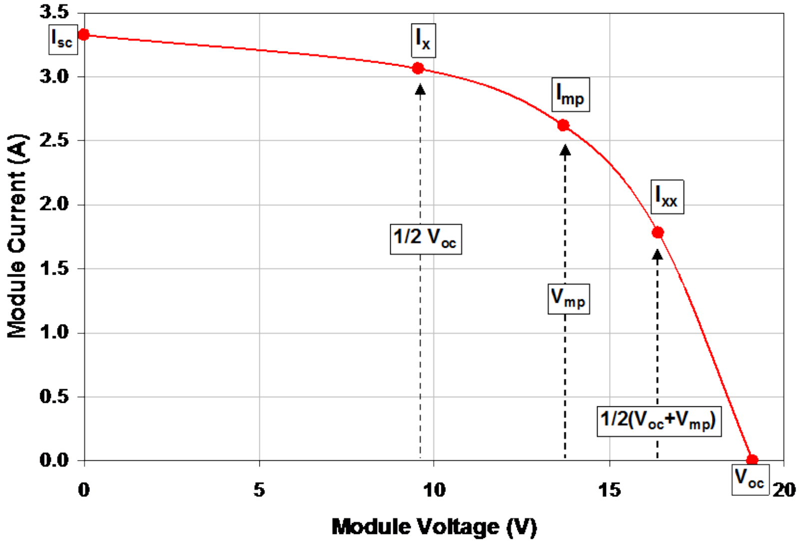
Electrical performance test (IV curves) measured at 2 minute intervals
- Sunrise to sunset, multiple days
- Clear and Cloudy conditions
- Approximately 1000 IV curves minimum

Thermal test to determine temperature coefficients for Isc, Imp, Voc and Vmp

Angle of incidence (AOI) response

Characterization takes approximately two weeks
- Exact length of testing depends on local weather conditions

Sandia Array Performance Model (SAPM)



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

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

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

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

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

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

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

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

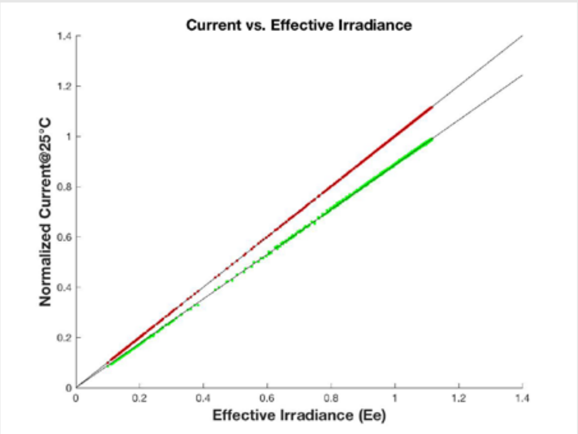
Semi-empirical model that defines five points on the IV curve

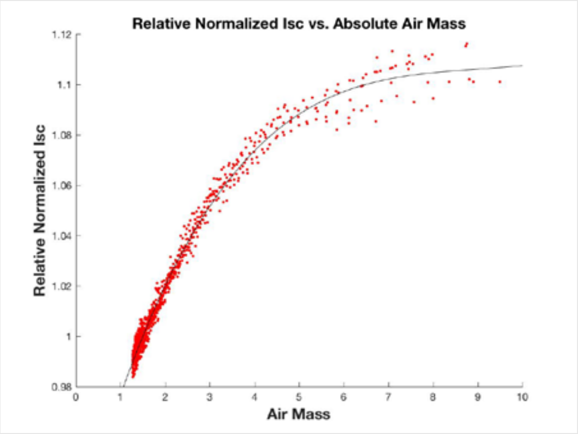
Inputs
- Measured I-V curves from outdoor testing
- Thermal performance of cell
- Angle of Incidence (AOI) response of module

Coefficients can be used with PV_Lib, SAM and other modeling packages to predict system performance

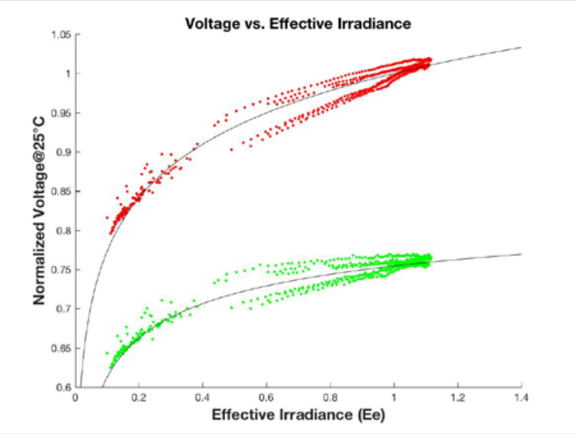
Standard method of determining coefficients utilizes stepwise filtering and regression analysis to progressively solve each equation

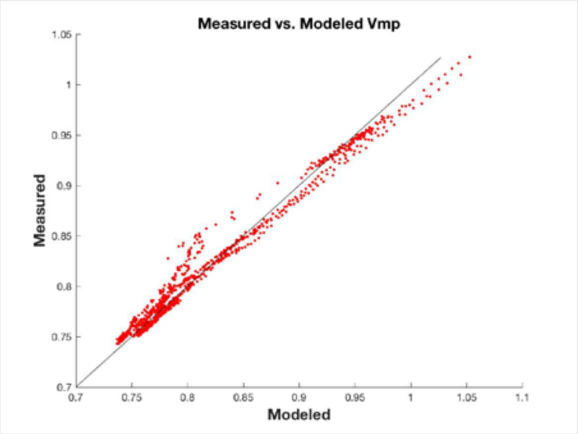
And the problem……





- Applied to a prototype CIGS module, the standard analysis method fails
- Calibrated model does not predict measured data used to calibrate the model
- Temperature corrected data appears to “split” between morning and afternoon
- Terms involving current look good, suggests the problem lies with module voltage





The Suspected Culprit - Temperature Coefficients: Sandia's Method (in use for nearly 2 decades)

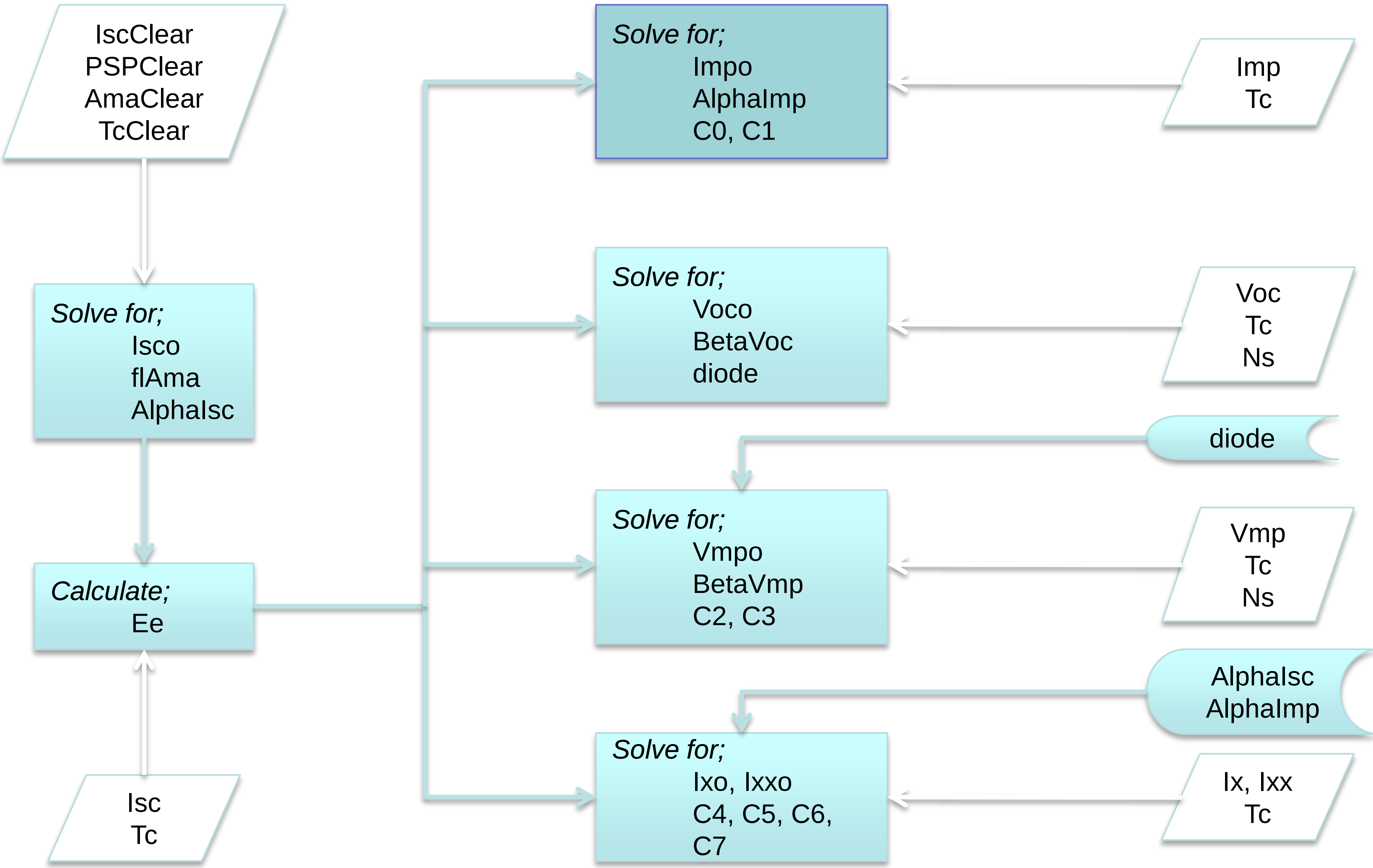
Sandia National Laboratories

- Module is instrumented with temperature sensors and the back of the module is thermally insulated to improve temperature uniformity.
- Module is then covered with an opaque sheet and allowed to cool to ambient temperature.
- Once at ambient, the cover is removed and IV curves and module temperatures are measured rapidly (~ 2 samples per minute) while the module heats up to an equilibrium temperature.
- Temperature coefficients are determined from linear regression analysis
- A typical test requires approximately 30 minutes once the cover has been removed.
- Consistent with international standards (IEC 60891, 61853)
- Inherently transient

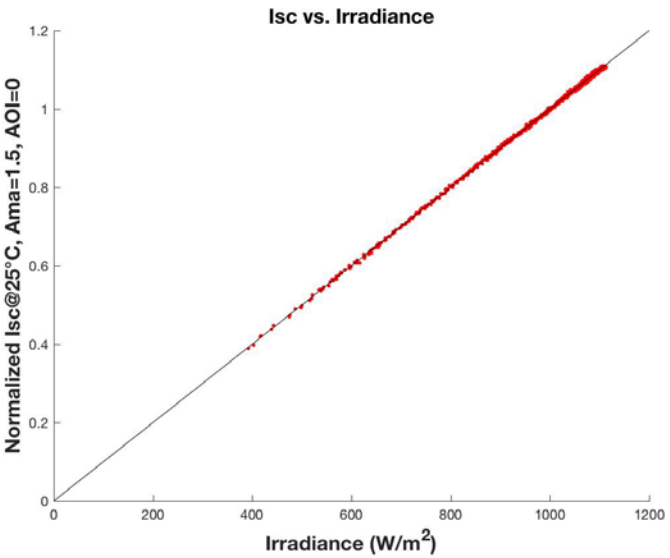
The Solution - Alternate Method to Determine Model Coefficients

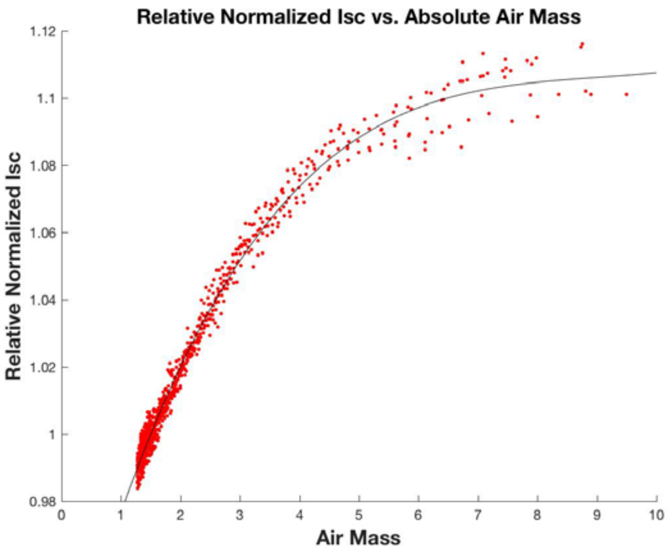
- Simultaneously solve each SAPM constitutive equation for fundamental parameters, e.g. STC electrical parameters, airmass function, temperature coefficients, etc.
- Does not use temperature coefficients from a discrete test
- Uses all IV data collected over a test interval
- Eliminates “piece-wise” model coefficient generation that has been the standard

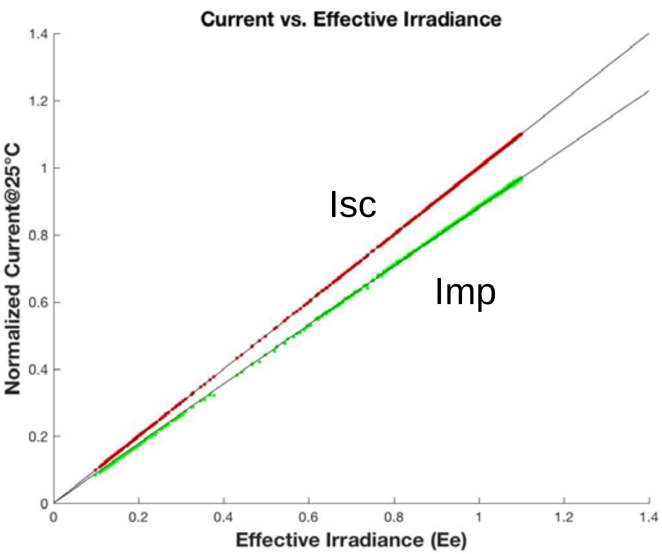
Alternate Method – Simultaneous Solution



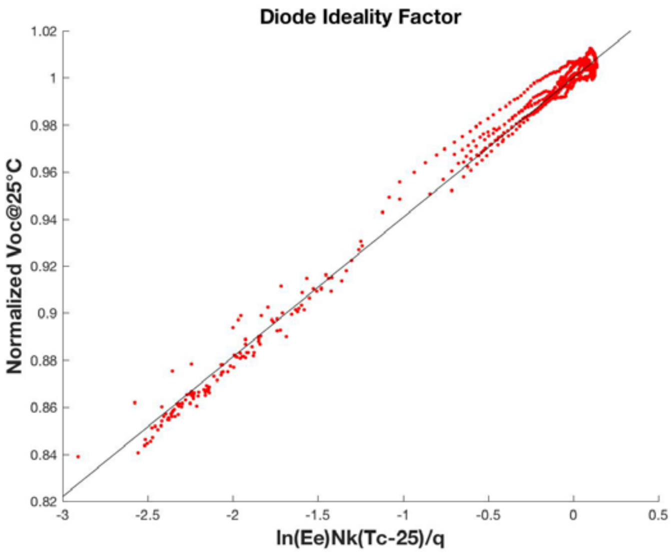
Output – Currents

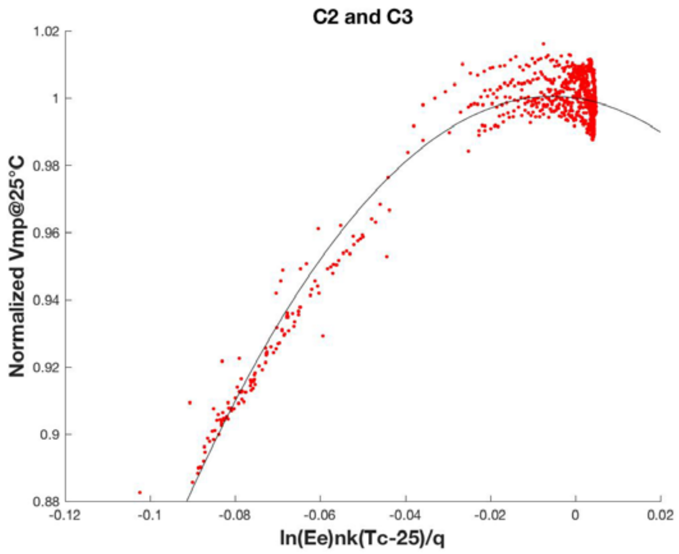


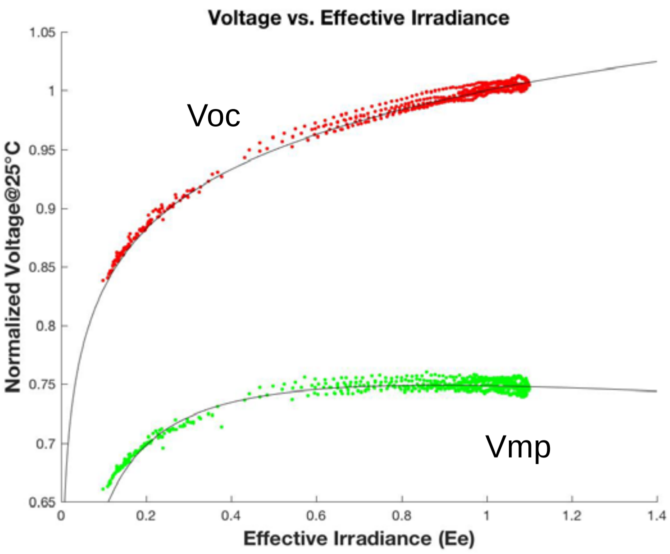




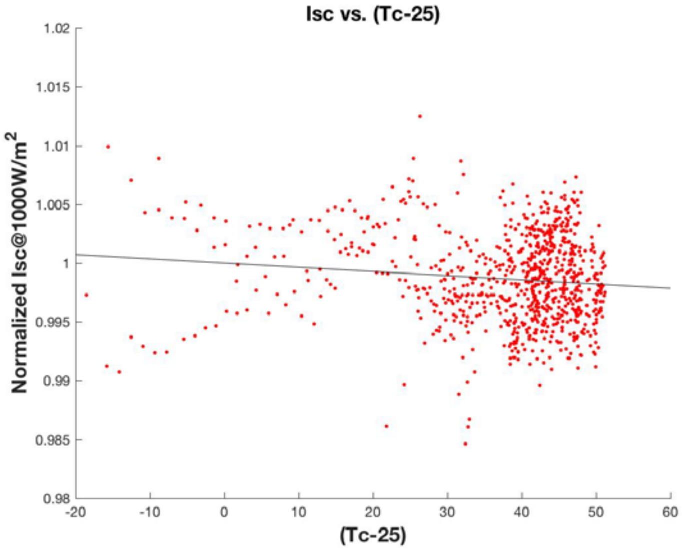
Output - Voltages

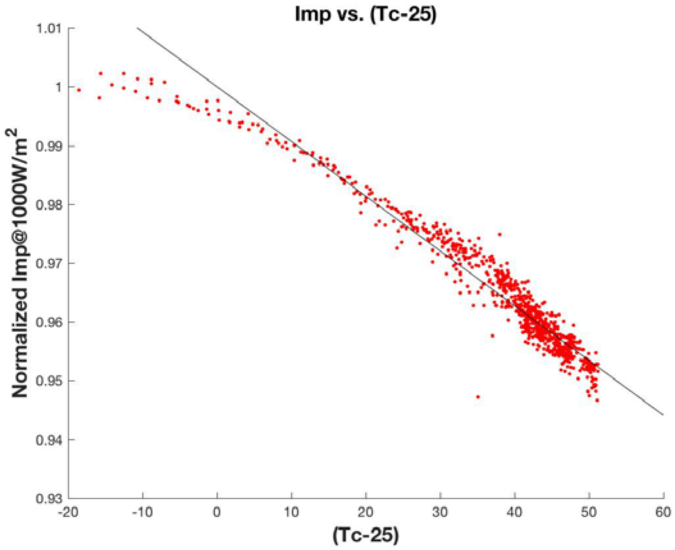


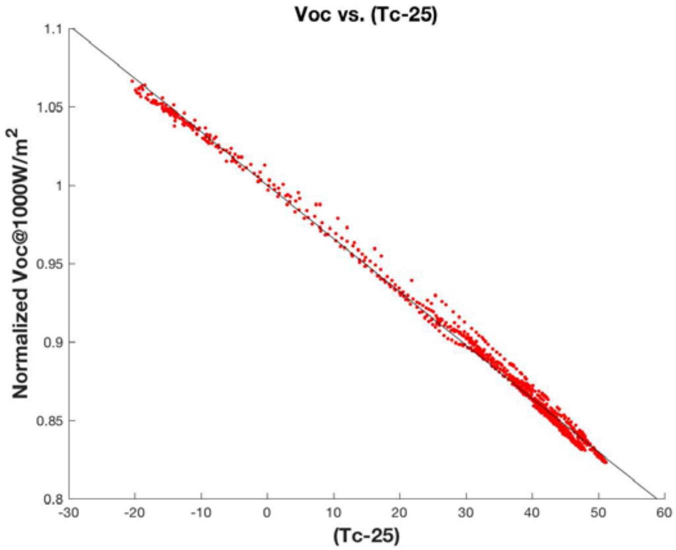


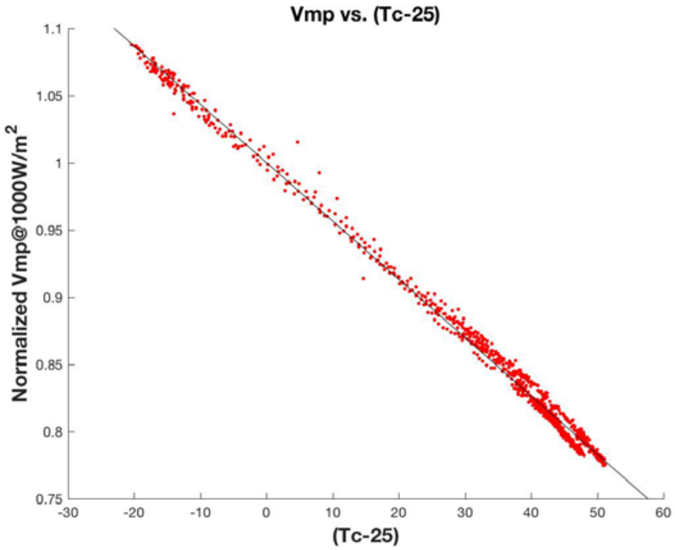


Temperature Coefficients

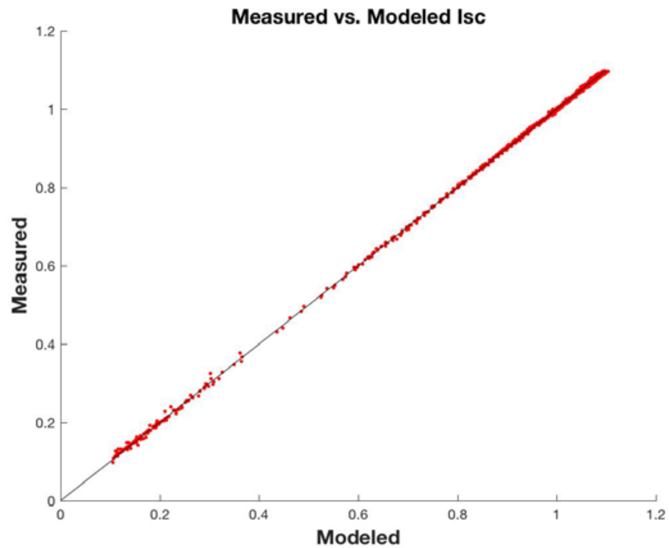


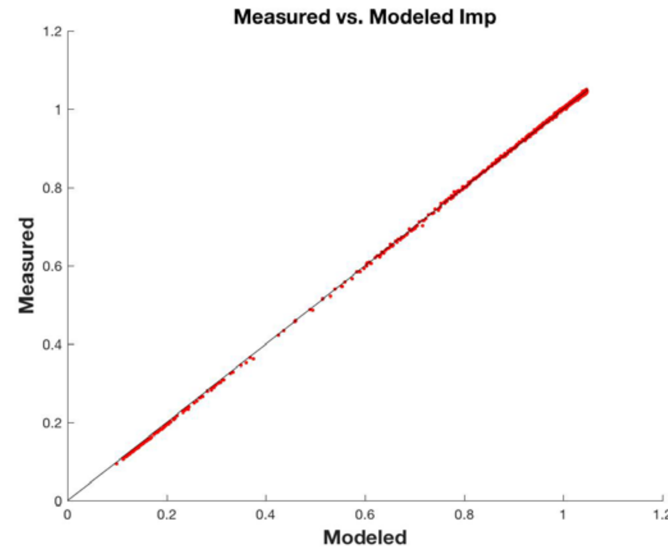


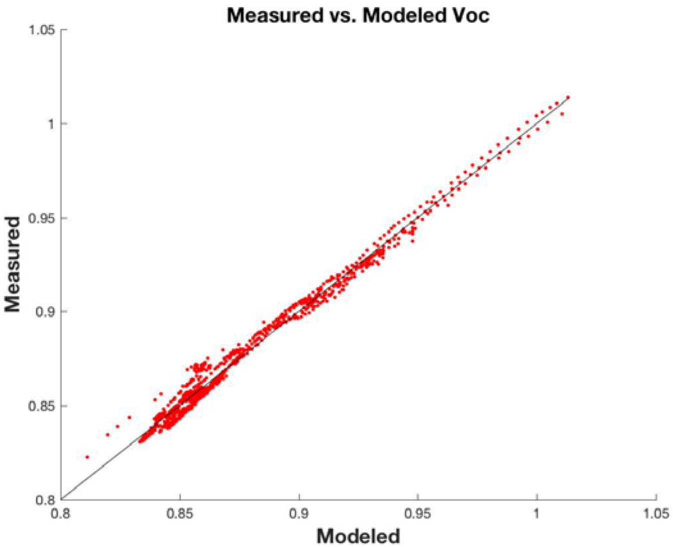


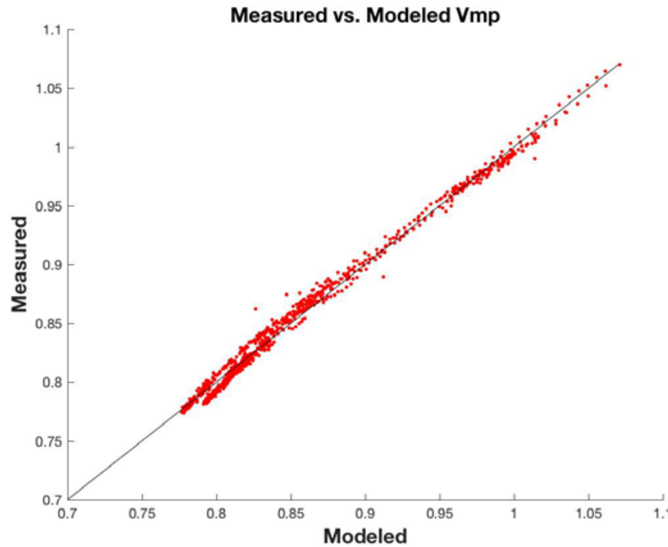


Measured vs Modeled







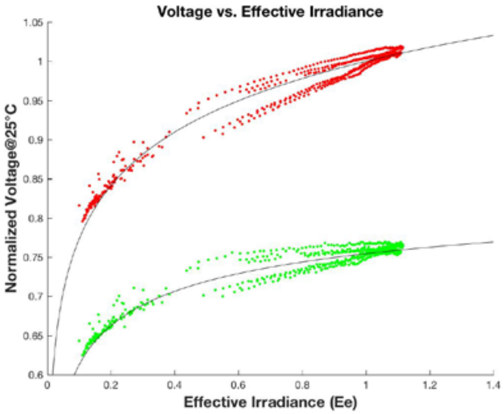


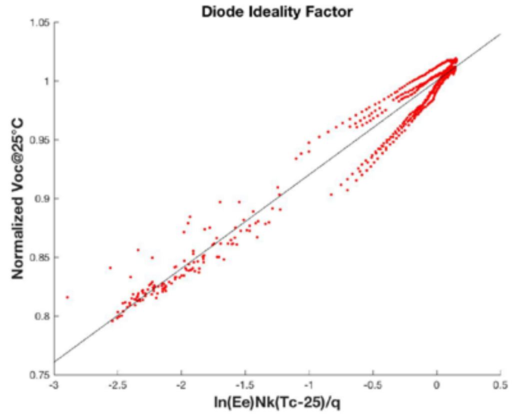
Select Parameters (Normalized)

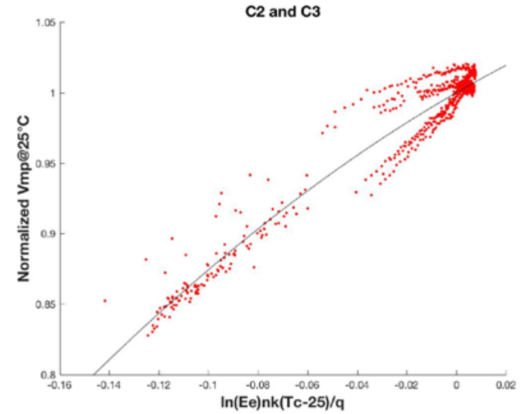
	Alternate Method	Standard Method	Lab Estimates
Pmpo	1.02	1.05	1
Isco	1.02	1.01	1
Voco	1.01	1.05	1
Alpha-Isc (%/°C)	-0.0036	-0.0036	-0.0034
Alpha-Imp (%/°C)	-0.100	-0.107	-0.066
Beta-Voc (V/°C)	-0.097	-0.123	-0.095
Beta-Vmp V/°C)	-0.093	-0.117	-0.086
Gamma-Pmp (%/°C)	-0.534	-0.636	-(0.45 - 0.50)
Diode factor	1.69	2.35	-

Example Improvement

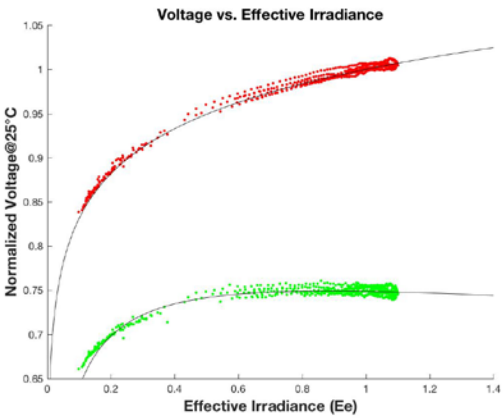
Standard Method

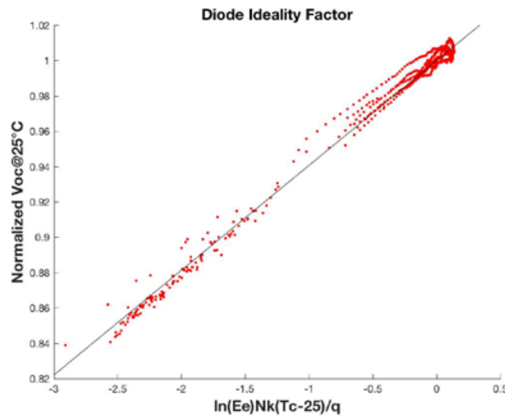


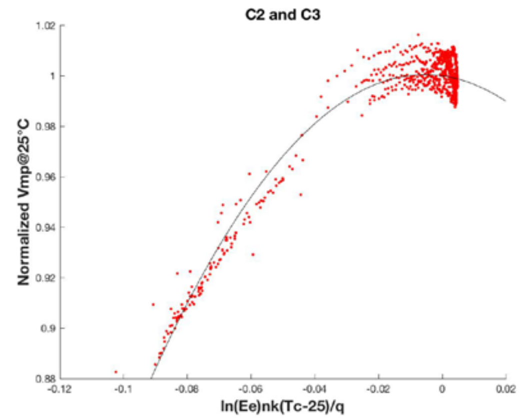




Alternate Method







Summary

- CIGS Modules present challenges to measurement and modeling due to metastable behavior
- Standard outdoor methods for measuring temperature coefficients may produce values that are not representative of a CIGS module's behavior during normal, steady state operation
- An alternate analysis method was developed to determine temperature coefficients simultaneously with the solution of all other model parameters
- The alternate method resulted in a more accurate model for the test case
- Validation against historical data sets indicates the method is applicable to other technologies and possibly produces a more accurate model in general
- This method may eliminate the need to perform separate thermal tests