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Determining Coefficients for the Sandia Array Performance Model

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Outline and Summary

- Sandia Array Performance Model
  - Predicts on-sun module performance with good accuracy
- Calibration using outdoor testing
  - Proven techniques, but,
  - Testing can take weeks
  - Documentation is lacking
- Calibration using indoor testing:
  - Proof of concept presented at 38th PVSC
  - Independently, D. King arrived at a similar approach
  - Cut turnaround time for module testing from weeks to hours
  - Predictions of on-sun module performance show similar accuracy
  - However, not all coefficients can be estimated using indoor testing

The Sandia Array Performance Model

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- Describes module output at SC, OC and MP points
- As a function of beam and diffuse irradiance (E_b and E_{diff}), cell temperature (T_C), air mass (AM_a) and angle of incidence (AOI)
- 14 empirical coefficients, 2 empirical functions (f_1 and f_2)
- With exception of f_2, coefficients determined for individual modules

$$V_{OC} = \boxed{V_{OC0}} + N_S \boxed{n} \delta(T_C)\ln(E_e) + \boxed{\beta_{OC}}(T_C - T_0)$$

$$V_{MP} = \boxed{V_{MP0}} + \boxed{C_2} N_S \boxed{n} \delta(T_C)\ln(E_e) + \boxed{C_3} N_S \left(\boxed{n}\delta(T_C)\ln(E_e)\right)^2 + \boxed{\beta_{MP}}(T_C - T_0)$$

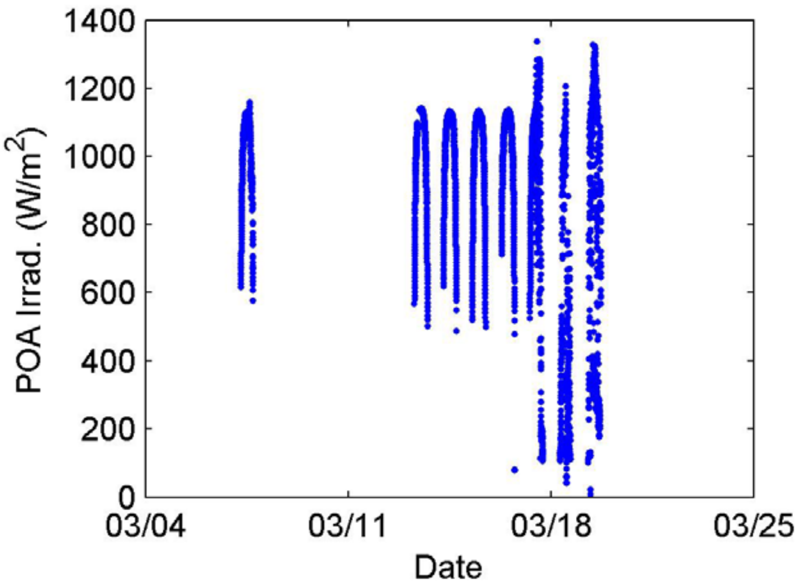
$$I_{SC} = \boxed{I_{SC0}}\,\boxed{f_1(AM_a)}\,E_e\left(1 + \boxed{\alpha_{SC}}(T_C - T_0)\right)$$

$$I_{MP} = \boxed{I_{MP0}}\left(\boxed{C_0}E_e + \boxed{C_1}E_e^2\right)\left(1 + \boxed{\alpha_{MP}}(T_C - T_0)\right)$$

$$E_e = E_b\,\boxed{f_2(AOI)} + E_{diff}\,\boxed{f_d}$$

SAPM calibrated by Outdoor Testing

- I-V curves measured on 2-axis tracker during three sequential tests:
  - Thermal performance
  - Electrical performance
  - Incident angle
- Can take several weeks to obtain I-V curves during all important conditions



Example of parameter estimation

- Estimate temperature coefficient for VOC from thermal performance test
  - Maintain $AOI = 0$
  - Clear-sky conditions

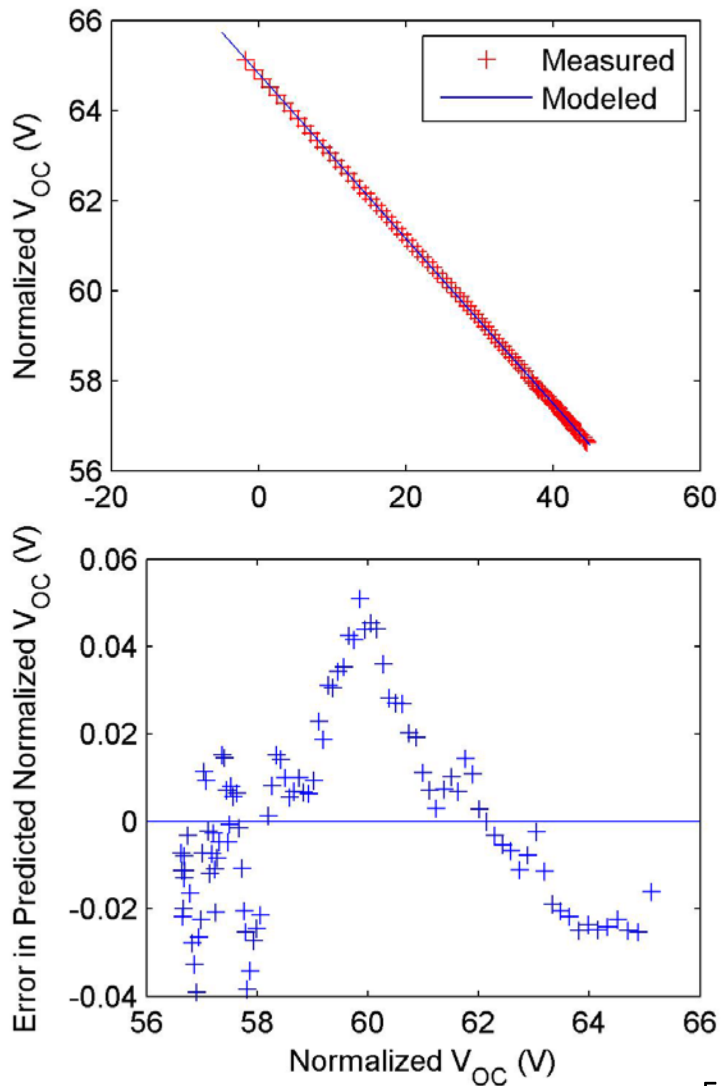
$$\left.\begin{array}{l}\text{Maintain } AOI = 0\\ \text{Clear-sky conditions}\end{array}\right\} E_e \approx 1$$

$$V_{OC} = V_{OC0} + N_S n\delta(T_C)\ln(E_e) + \beta_{OC}(T_C - T_0)$$

$\Downarrow$ simplifies to

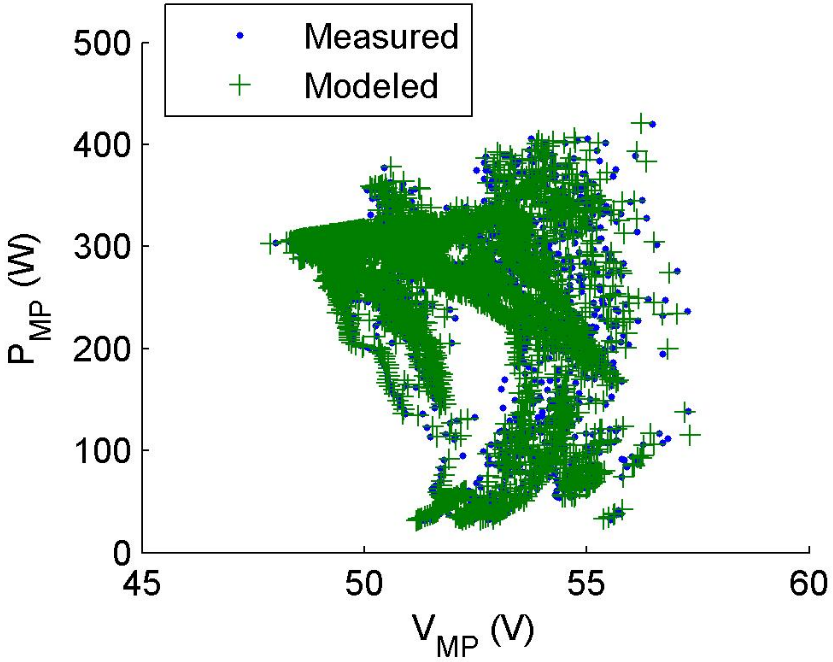
$$V_{OC} = V_{OC0} + \beta_{OC}(T_C - T_0)$$

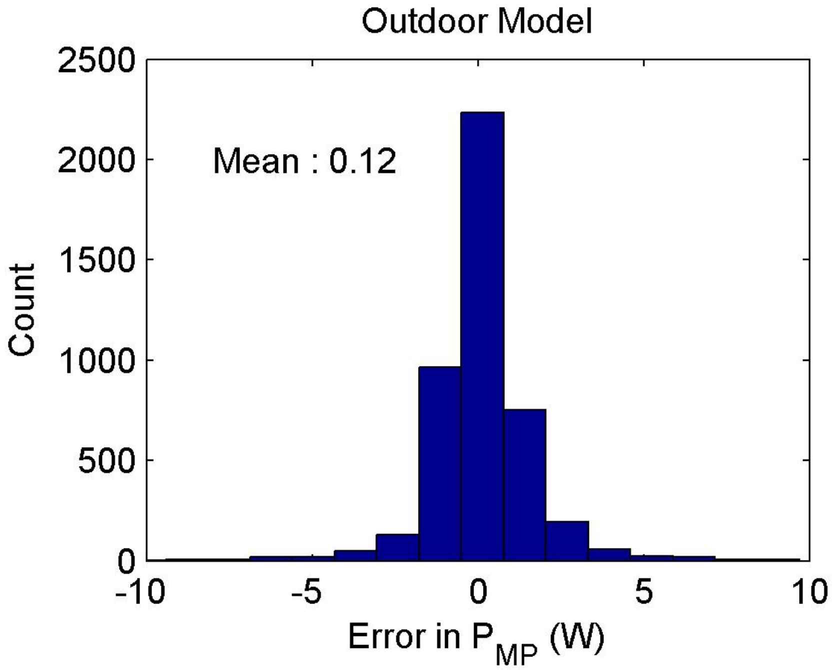
- Cover module and cool to ambient
- Uncover and measure I-V curves while module heats to operating temperature
- Normalize measured V_{OC} to 1000 W/m²
- β_{OC} estimated from (T_C , V_{OC}) by linear regression



Performance of “outdoor” model

- One SunPower 305W cSi module
- Albuquerque, NM, in March 2012
- “In sample” model verification

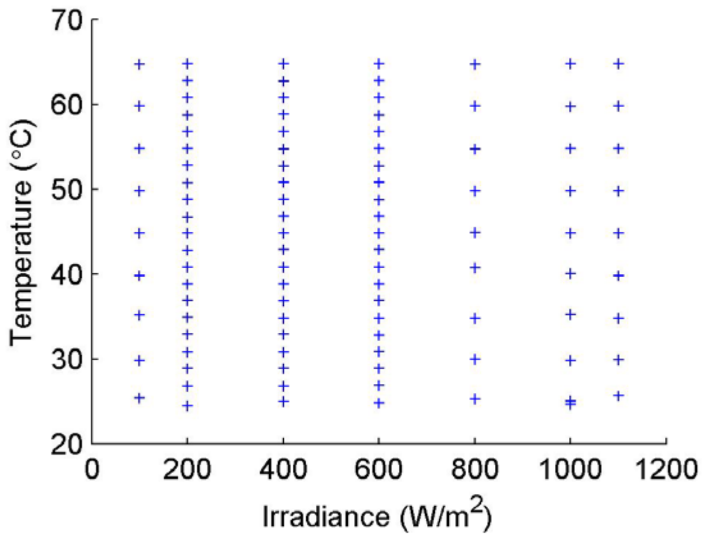




Indoor testing (reported at 38th PVSC)

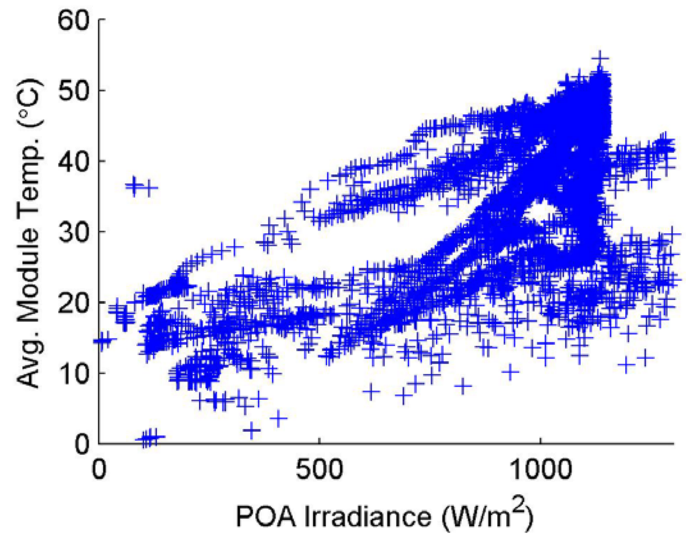
- Conducted by CFV Solar Test Laboratory, Inc (Albuquerque, NM)
- HALM solar simlulator integrated with a thermal chamber
  - Varies irradiance between 0.1 and 1.1 suns
  - Temperature between 25C and 75C via laminar air flow heater
- We measured I-V curves for irradiance and temperature combinations following IEC 61853-1

Indoor IV curves



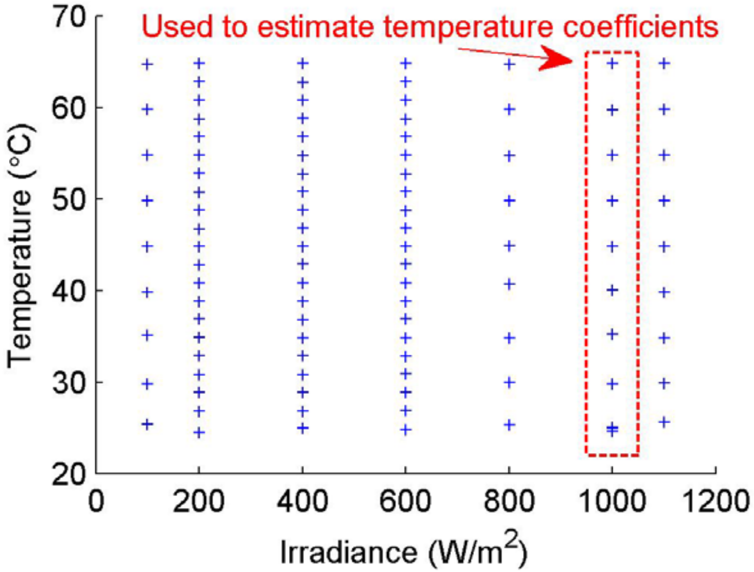
Much less data than for outdoor testing

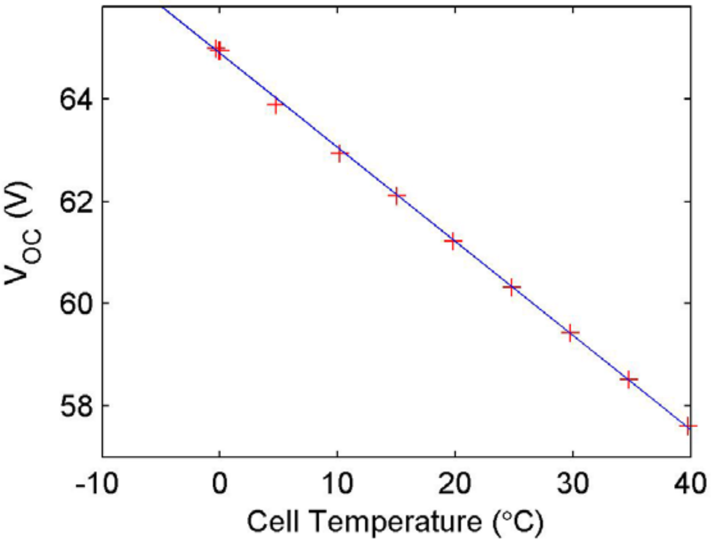
Outdoor IV curves



Parameters from indoor testing

- IEC 61853 test matrix
- Two-stage process analogous to outdoor test methods
  - Estimate thermal coefficients, then
  - Use thermal coefficients in estimation of other parameters
- Other methods (e.g., full simultaneous) performed worse
- D. King independently arrived at similar approach



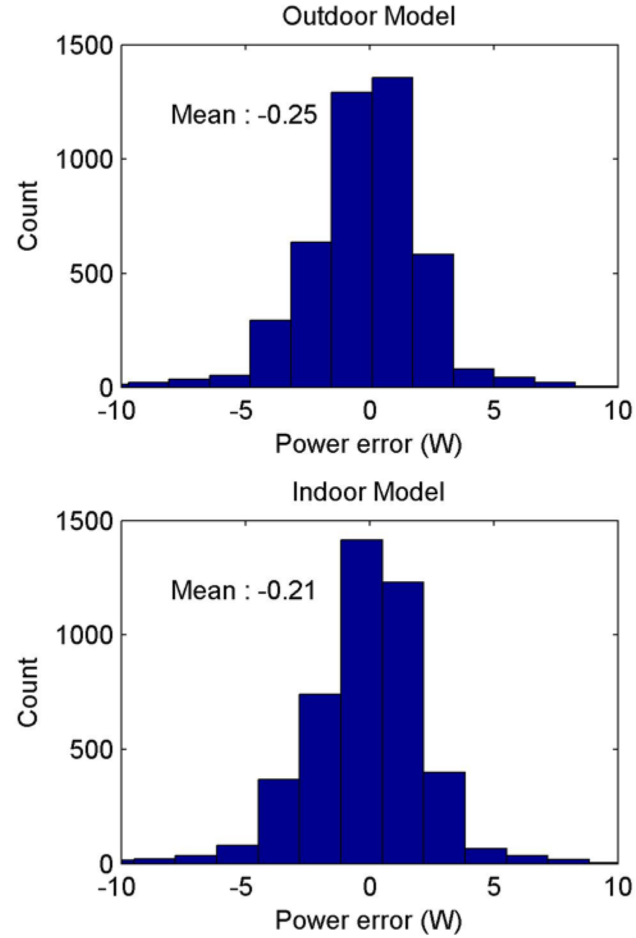


Performance of “indoor” model

- Parameter values obtained are similar for outdoor and indoor models

Parameter	Outdoor Model	Indoor Model
β_{OC} (V/°C)	–0.195	–0.197
V_{OC0} (V)	65.044	64.882
β_{MP} (V/°C)	–0.183	–0.184
V_{MP0} (V)	54.193	54.15
α_{MP} (1/°C)	–0.00017	–0.000169
I_{MP0} (A)	5.623	5.631
α_{SC} (1/°C)	0.000425	0.000378
I_{SC0} (A)	5.976	5.969
n (unitless)	1.12	1.074
$C_0;C_1$ (unitless)	1.0121; –0.0121	1.0069; –0.0069
$C_2;C_3$ (unitless)	0.3114; –5.0257	0.3379; –4.7201
N_S (cells in series)	96	96

- Similar accuracy predicting outdoor performance



Conclusions, and Future Work

- For outdoor testing:
  - Testing and parameter estimation methods have proven reliable but should be better documented
- For indoor testing:
  - Most (but not all) parameters for SAPM can be determined from indoor testing if irradiance and module temperature can be varied separately
  - Currently, we cannot determine f1 or f2 from indoor measurements
  - Using surrogate f2 function from analog modules has been acceptable
  - Methods need better documentation

Available references

Sandia Array Performance Model

- King et al. 2004, *Photovoltaic Array Performance Model*, Sandia Report 2004-3535

Generating coefficients for SAPM

- Hansen et al. 2011 PVSC Paper, *Parameter Uncertainty in the Sandia Array Performance Model for Flat-Plate Crystaline Silicon Modules*
- Hansen et al. 2012 PVSC Paper, *Calibration of the Sandia Array Performance Model Using Indoor Measurements*

Copies available at pv.sandia.gov, PV Publications page