SAND2013-4883C

Exceptional service in the national interest

Sandia National Laboratories

PVPerformance MODELING COLLABORATIVE

Joshua S. Stein, Ph.D.

Sandia National Laboratories, Albuquerque, NM

IEA PVPS Task 13 Workshop

June 16, 2013 Tampa, FL

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

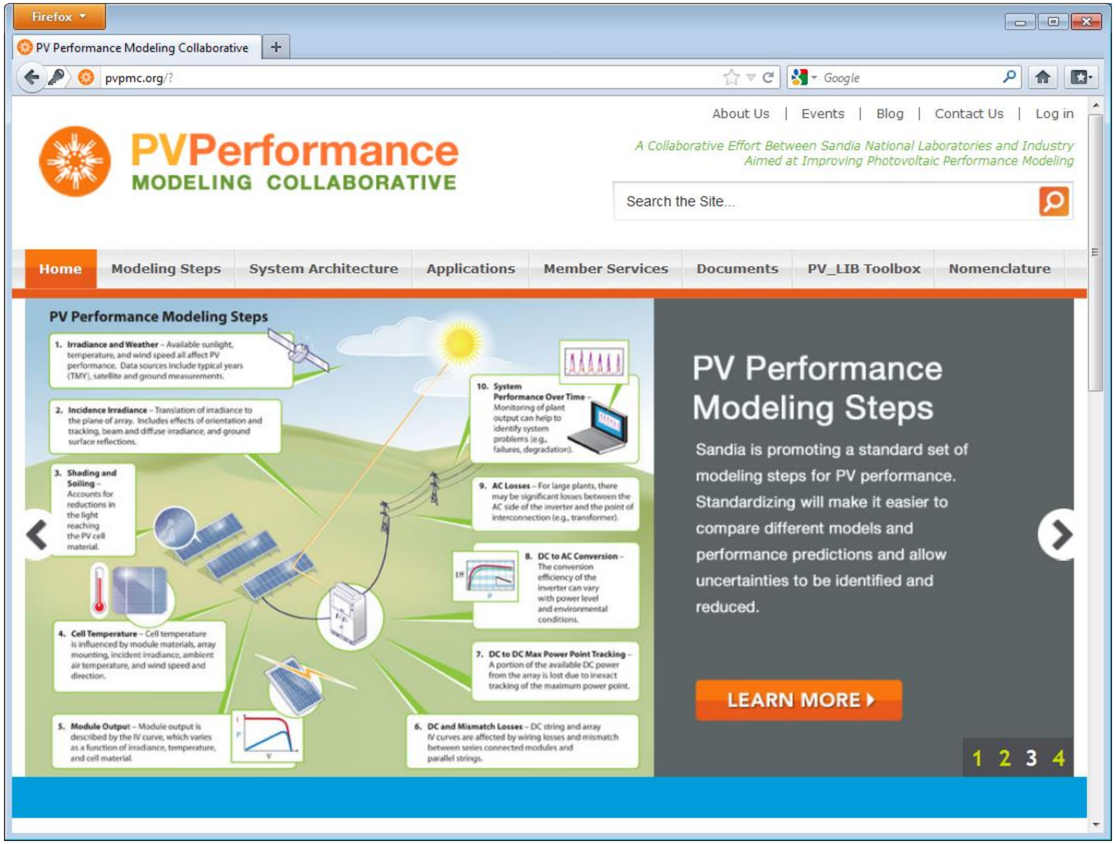
- Introduce the PV Performance Modeling Collaborative
  - History, website, tools, coming
- Review highlights of the 2nd PV Performance Modeling Workshop (May 2013 in Santa Clara, CA)
- Ideas for Next Steps

PV Performance Modeling Collaborative

- Started after 1st PV Performance Modeling Workshop (Albuquerque, NM, Sept. 2010)
- PV performance modeling lacked organization.
  - Accurate information about algorithms, validation data, best practices difficult to find and access.
- PVPMC.org started to provide an information hub on PV performance modeling
  - Model agnostic, focus on algorithms, methods, data, etc.
  - Detailed Modeling Steps (online textbook)
  - Modeling function library in Matlab (PV_LIB)
  - Member contact list, document library, bibliography, glossary, blog, events, …
- 2nd PV Performance Modeling Workshop (Santa Clara, CA, May 2013)
- PVPMC and IEA PVPS Task 13 share many goals and can work together.
  - "The overall objective of Task 13 is to collect and communicate data that will help to improve the operation, the reliability and, thus, the electrical and economic output of PV systems and subsystems."

Website: http://pvpmc.org

- 650 Members (and growing)
- Over 15,000 visits in May 2013, up 75% from April
- 213 web pages published



When you join you will set up a *username* and *password*

-Sign up for weekly email updates separately

PV Performance Modeling Steps

Sandia National Laboratories

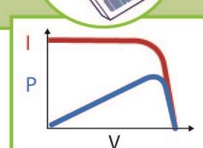
1. **Irradiance and Weather** – Available sunlight, temperature, and wind speed all affect PV performance. Data sources include typical years (TMY), satellite and ground measurements.

2. **Incidence Irradiance** – Translation of irradiance to the plane of array. Includes effects of orientation and tracking, beam and diffuse irradiance, and ground surface reflections.

3. **Shading and Soiling** – Accounts for reductions in the light reaching the PV cell material.

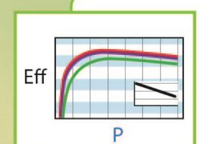
4. **Cell Temperature** – Cell temperature is influenced by module materials, array mounting, incident irradiance, ambient air temperature, and wind speed and direction.

5. **Module Output** – Module output is described by the IV curve, which varies as a function of irradiance, temperature, and cell material.



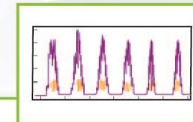
6. **DC and Mismatch Losses** – DC string and array IV curves are affected by wiring losses and mismatch between series connected modules and parallel strings.

7. **DC to DC Max Power Point Tracking** – A portion of the available DC power from the array is lost due to inexact tracking of the maximum power point.



8. **DC to AC Conversion** – The conversion efficiency of the inverter can vary with power level and environmental conditions.

9. **AC Losses** – For large plants, there may be significant losses between the AC side of the inverter and the point of interconnection (e.g., transformer).



10. **System Performance Over Time** – Monitoring of plant output can help to identify system problems (e.g., failures, degradation).

Standard Modeling Steps

- Irradiance and Weather
  - Definitions and Overview
  - Sun Position
    - Solar Position Algorithm (SPA)
    - Simple models
    - Sandia's code
  - Irradiance and Insolation
    - Extraterrestrial radiation
    - Air Mass
    - Direct Normal Irradiance
      - DISC Model
      - DIRINT Model
    - Global Horizontal Irradiance
    - Diffuse Horizontal Irradiance
    - Spectral Content
      - AM 1.5 Standard Spectrum
    - Satellite derived data
  - Weather Observations
    - Air Temperature
    - Wind Speed and Direction
    - Precipitation
    - Air Pressure
  - Irradiance Data Sources for Performance Modeling
    - National Solar Radiation Database
    - Typical Meteorological Years
    - Site-Specific Data
    - Measure Correlate Predict
    - Irradiance Modeling
  - Uncertainty and Variability
    - Characterization of Irradiance Variability
      - Interannual variability
      - Short-term variability
      - Spatial variability
    - Clear Sky Irradiance models
- Incident Irradiance
  - Definitions and Overview
  - Array Orientation
    - Fixed tilt
    - Single Axis Tracking
      - 1-Axis Horizontal Roll
      - 1-Axis Tilted Roll
      - 1-Axis Equatorial
    - Two-Axis Tracking
      - 2-Axis Azimuth-Elevation
      - 2-Axis Polar
      - 2-Axis Tilt-Roll
    - Array Orientation Errors
      - Effect of Array Tilt Errors
      - Effect of Array Azimuth Errors
  - Plane of Array (POA) Irradiance
    - Measuring POA Irradiance
    - Calculating POA Irradiance
      - POA Beam
      - Angle of Incidence
      - POA Ground Reflected
        - Albedo
      - POA Sky Diffuse
        - Isotropic Sky Diffuse Model
        - Simple Sandia Sky Diffuse Model
        - Hay Sky Diffuse Model
        - Reindl Sky Diffuse Model
        - Perez Sky Diffuse Model
    - Concentrators
    - POA Irradiance Uncertainty and Validation
- Shading, Soiling, and Reflection Losses
  - Definitions and Overview
  - Shading
    - Far Shading
    - Near Shading
  - Soiling and Snow
    - Soil Monitoring Studies
    - Snow Effects
  - Incident Angle Reflection Losses
    - Physical Model of IAM
    - ASHRAE Model
    - Martin and Ruiz IAM Model
      - Soiling effects on Incident Angle Losses
    - Sandia Model
- Cell Temperature
  - Definitions and Overview
  - Module Temperature
    - Thermocouple
    - Voc method
    - Sandia Module Temperature Model
    - Faiman Module Temperature Model
  - Cell temperature
    - Sandia Cell Temperature Model
    - PVsyst Cell Temperature Model
    - Transient Cell Temperature Models
- Module IV Curve
  - Definitions and Overview
  - Effective Irradiance
    - Spectral Mismatch
  - Single Diode Equivalent Circuit Models
    - De Soto "Five-Parameter" Module Model
    - PVsyst Module Model
  - Point-value models
    - Sandia PV Array Performance Model
    - Loss Factor Model
    - PVWatts
      - Improvements to PVWatts
- DC and Mismatch Losses
  - Definitions and Overview
  - Module IV Curves
  - String IV Curves
    - String Mismatch Losses
  - Array IV Curves
    - Array Mismatch Losses
  - DC Wiring Losses
  - Uncertainty and Validation Studies
- Maximum Power Point Tracking
  - Definitions and Overview
  - Array Utilization
  - MPPT Voltage
  - MPPT Efficiency
  - MPPT Algorithms
  - Uncertainty and Validation
- DC to AC Conversion
  - Definitions and Overview
  - Inverter Efficiency
    - CEC Inverter Test Protocol
    - Operating Temperature
    - Sandia Inverter Model
    - Driesse Inverter Model
  - Inverter Saturation
  - Loss of Grid
  - Advanced Inverter Features
    - Power Factor Control
  - Uncertainty and Validation
- AC Losses
  - Definitions and Overview
  - AC Wiring Losses
  - Transformer Losses
- PV System Output
  - Definitions and Overview
  - PV System Monitoring
    - Monitoring Equipment
    - Data Filtering
    - Data Filling
  - PV Performance Metrics
    - Performance Ratio
    - Performance Index
    - Annual Yield
  - PV Systems Operations and Maintenance
    - Definitions and Overview
    - Availability
    - Failure Mode and Rates
- References

Example Model Description

Sandia National Laboratories

- Brief description
- Equation support
- Hyperlinking
- Link to PV_LIB functions
- References
- Contributor info

- We are looking for additional models and process descriptions

About Us | Events | PVPMC Blog | Contact Us | Log in

PVPerformance MODELING COLLABORATIVE

A Collaborative Effort Between Sandia National Laboratories and Industry Aimed at Improving Photovoltaic Performance Modeling

Search the Site...

Home | Modeling Steps | System Architecture | Applications | Member Services | Documents | PV_LIB Toolbox | Nomenclature

Modeling Steps

- Incident Irradiance
- Plane of Array (POA) Irradiance
- Calculating POA Irradiance
- POA Sky Diffuse
  - Isotropic Sky Diffuse Model
  - Simple Sandia Sky Diffuse Model
  - Hay Sky Diffuse Model
  - Reindl Sky Diffuse Model
  - Perez Sky Diffuse Model

« Hay Sky Diffuse Model Perez Sky Diffuse Model »

Reindl Sky Diffuse Model

The Reindl sky diffuse irradiance model (Reindl et al., 1990;Reindl et al., 1990b; Loutzenhiser et al., 2007) represents three components of diffuse radiation on the POA, including isotropic, circumsolar brightening, and horizon brightening. This model extends the Hay model by adding an additional factor to the "brightening" term to account for horizon brightening.

As with the Hay model, an anisotropy index, A_i, is defined as:

$$A_i = \frac{DNI}{E_a},$$

where DNI is the direct normal irradiance and E_a is the extraterrestrial radiation.

The Reindl model formulation for sky diffuse radiation is then:

$$E_d = DHI \times \left[A_i \cos(AOI) + (1 - A_i) \frac{1 + \cos(T_a)}{2} \left(1 + \sqrt{\frac{DNI \times \cos(Z)}{GHI}} \sin^3\left(\frac{T_a}{2}\right) \right) \right]$$

.

DHI is the diffuse horizontal irradiance, AOI is the angle of incidence, DNI is the direct normal irradiance, GHI is the global horizontal irradiance, T_a is the tilt angle of the array, and Z is the solar zenith angle.

This model is implemented in the PV_LIB Toolbox and the function: pvl_reindl1990.

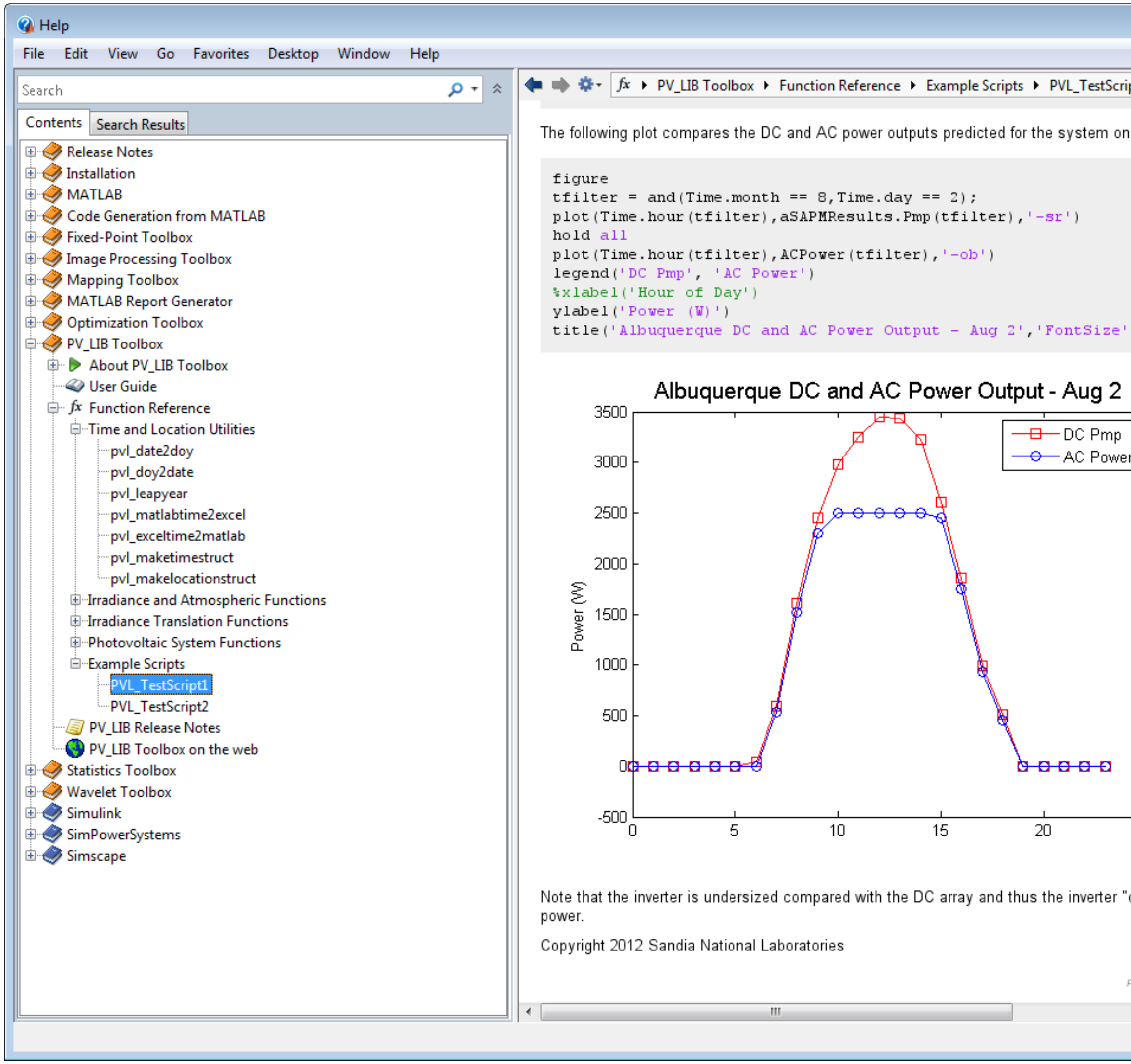
Content contributed by Sandia National Laboratories

Modeling Steps: Areas Needed for Contributions

- Tracking, backtracking models
- Shading models and effect on performance
- Soiling (and cleaning) models
- Module IV parameter estimation methods
- Degradation models / processes
- MPPT algorithms
- Monitoring standards
- System Architecture (component and design descriptions)
- Applications (model reviews, features, case studies, validation)
- Much more…………………………

PV_LIB Toolbox for Matlab

- Over 30 functions
  - Example scripts
  - Time and Location Utilities
  - Irradiance and atmospheric functions
  - Irradiance translation functions
  - Photovoltaic system functions
- Education, model validation, transparency



New Features Coming Soon!

- http://wiki.pvpmc.org/ (coming in Fall 2013)
  - This was a request at the 2^{nd} PV Performance Modeling Workshop
  - Platform to collaboratively develop content for the main site.
  - Provides a collaboration area for working groups to develop standards
  - Account requests will be made online.
  - Equations, files, flowchart navigation
- PV_LIB in Python! (Fall-Winter 2013)
  - Python is free, large user base, similar features to Matlab
  - Provide easy way to submit library functions and deliver updates (using GitHub).

2013 PV Performance Modeling Workshop

http://pvpmc.org/home/2013-pv-performance-modeling-workshop/

Topical Sessions:

- PV Module Models (Coefficient generation)
- PV System Performance Models (updates on new features)
- Solar Resource Data (focus on uncertainty vs. variability)
- Systems Losses and Derates (standard definitions are needed)
- Performance Degradation (field data and modeling studies)
- Modeling for the Real World (Existing models still have significant limitations, but this represents opportunities! Data sets are being collected that can help).

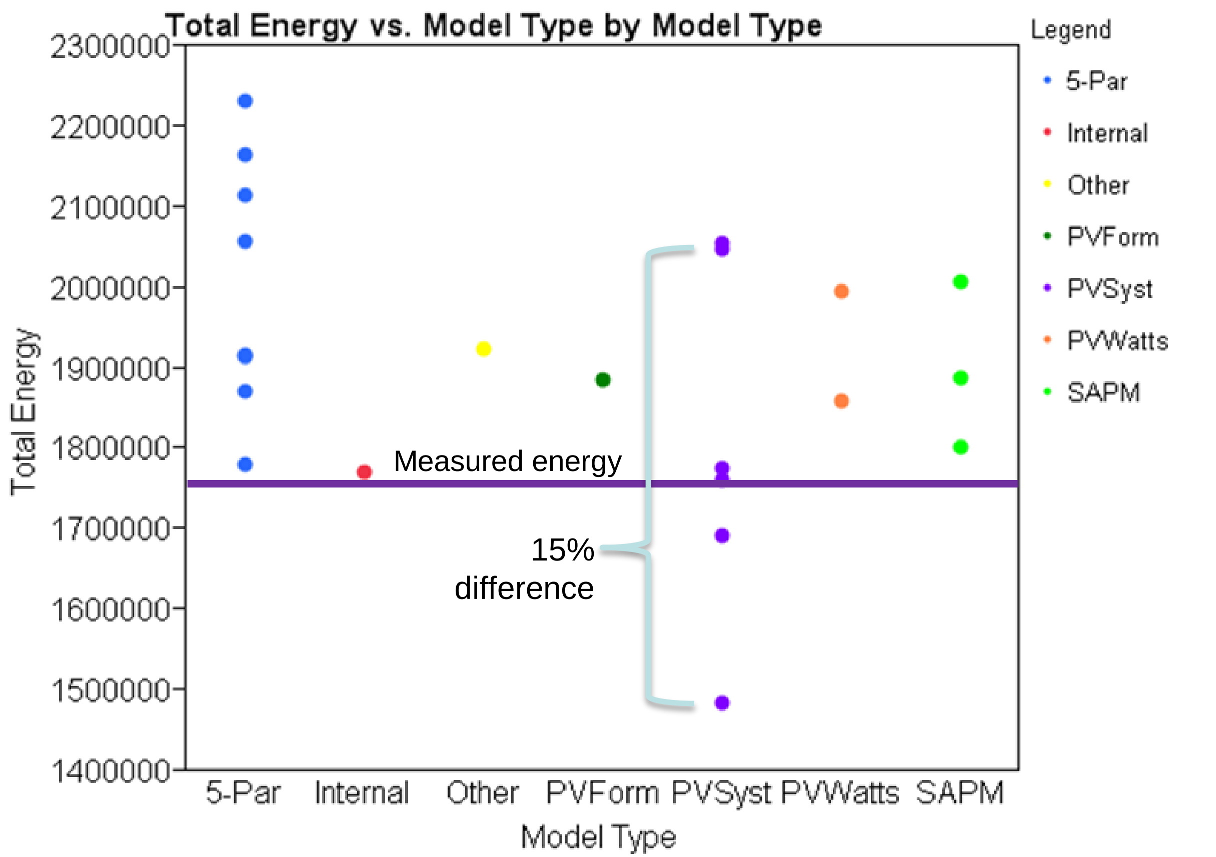
Feedback from Participants (survey results):

- Topics for next workshop:
  - Most votes: Solar resource, Inverters, dynamic performance (subhourly)
- Best practices guides are needed (system monitoring, modeling guides)
- Development of test data and case studies for illustrating analysis methods

2010 “Blind” Modeling Study Example

Blind Study Facts

- ~20 participants
- Each given measured weather and irradiance
- Each given 3 PV system designs
- Asked to predict annual energy from systems
- Results compared with measured annual energy
- Most results over-predicted annual energy
- Differences were significant even when same model was used.



Lesson Learned: Greater consistency and transparency in modeling is needed.

2013 "Blind" IV-Coefficient Estimation

- Exercise led by Cliff Hansen (Sandia National Laboratories)
- IV curves from two modules (A&B) were provided (range of irradiance and temperatures)
- 7 Participants estimated module coefficients for CEC and PVsyst models.
- Module A included IV curves measured at Sandia's outdoor test facility
- Module B was made up by using the single diode model to forward calculate IV points.

Module A (STC)

Parameter	PVsyst #1	PVsyst #2	PVsyst #3	Pvsyst #4	CEC #1	CEC #2	CEC #3
IL (A)	5.96	5.96	5.97	5.96	5.964	5.965	5.97
Rsh (Ω)	960	800	700	500	438	419	688
Rs (Ω)	0.43	0.48	0.52	0.42	0.31	0.34	0.53
Io (nA)	0.017	0.006	0.046	0.006	0.03	0.017	0.035
n	0.98	0.94	1.03	0.94	1.00	0.981	1.02

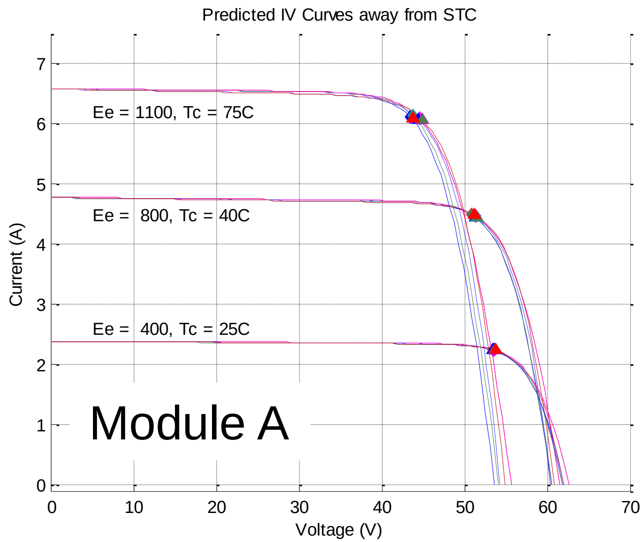
Module B (STC)

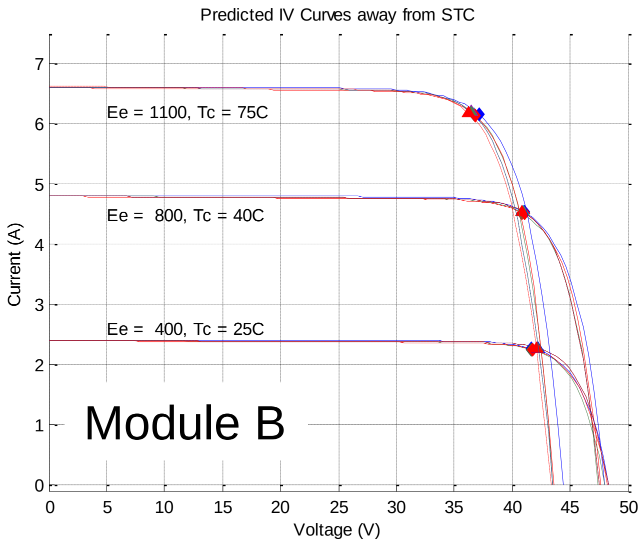
Parameter	Exact Value	PVSyst #1	PVSyst #2	PV Syst #3	CEC #1	CEC #2	CEC #3
IL (A)	6	6.00	6.00	5.99	5.992	5.992	6.002
Rsh (Ω)	2000	2065	700	700	675	675	594
Rs (Ω)	0.02	0.03	0.037	0.02	0.175	0.175	0.183
Io (nA)	1	0.82	0.11	0.186	0.0034	0.0034	0.0053
n	1.2	1.13	1.09	1.12	0.957	0.957	0.974

Parameter results vary but are the differences significant?

2013 “Blind” IV-Coefficient Estimation

- P_{mp} over a range of irradiance and temperature conditions shows differences between 1%-2%.
- These differences are due to both the method used of estimate parameters and the choice of model (PVsyst or CEC).
- These differences demonstrate that there is still room for improvement and standardization of analysis methods to estimate performance coefficients.
  - 1-2% variation is enough to influence the choice of module for a large project.





Summary

- Performance modeling is a key part of PV project bankability.
- Currently many models and analysis methods are still opaque.
- Uncertainty with data and methods remains significant.
- PV Performance Modeling Collaborative provides a venue to
  - Document PV performance modeling methods and practice.
  - Build an international PV performance modeling community
  - Share methods and tools needed for model validation
  - Establish PV performance modeling as a "discipline" and train future practitioners.
- "*Task 13 aims at being a platform for collecting, providing and exchanging international information on the reliability [and performance] of PV systems*."
  - The PV Performance Modeling Collaborative can contribute to this mission.

Thank You!

jsstein@sandia.gov

http://solar.sandia.gov

http://PV.sandia.gov

http://pvpmc.org