



Presented at the 35<sup>th</sup> Photovoltaic Specialist Conference  
Honolulu, HI

# A Standardized Approach to PV System Performance Model Validation

Joshua S Stein<sup>1</sup>, Christopher Cameron<sup>1</sup>, Ben Bourne<sup>2</sup>, Adrienne Kimber<sup>3</sup>, Jean Posbic<sup>4</sup>, and Terry Jester<sup>5</sup>

<sup>1</sup> Sandia National Laboratories

<sup>2</sup> SunPower Corporation

<sup>3</sup> First Solar

<sup>4</sup> *BP Solar*

<sup>5</sup> *Hudson Clean Energy Partners*

**PV Performance Modeling Workshop**  
**Sandia National Laboratories, Albuquerque, NM**  
**September 22 & 23, 2010**

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,  
for the United States Department of Energy's National Nuclear Security Administration  
under contract DE-AC04-94AL85000.





# Introduction

---

- **PV performance models are used for prediction of expected energy production for project proposals**
  - Evaluation of different designs (e.g., tracking vs. fixed, module technology, inverter, BOS) and locations.
- **Many performance models available**
  - Klise and Stein (2009) surveys available models
- **Models are based on different conceptual approaches and implementations are not consistent.**
- **Results vary between models run for same system and weather.**



# Goals

---

- **Develop a standard method for validating PV performance models in order to:**
  - Increase confidence and understanding in model results
  - Identify areas for model improvements, gaps in existing data, and sources of modeling error
  - Support consistent, well informed business decisions that will ultimately allow solar technology solutions to prosper.



# PV Modeling Steps

---

- **Read inputs:**
  - Array design (module, string, inverter, mounting, tracking, ground cover, etc.)
  - Weather (irradiance, temperature, wind speed, etc.)
- **Translate irradiance to plane-of-array (POA)**
  - Sun position calculation, irradiance model
- **Evaluate 'effective' irradiance**
  - Angle on incidence effects
  - Spectral effects (air mass correlations or physics models)
- **Determine cell temperature**
- **Calculate  $I_{mp}$ ,  $V_{mp}$ , and  $P_{mp}$**
- **Estimate and apply derates (soiling, DC losses, mismatch, array utilization, etc)**
- **Model inverter performance ( $P_{ac}$ )**



# Model Validation Process

---

- **Develop data sets including system description, weather data and performance data for multiple technologies, applications, and climates.**
  - Understand and document data uncertainty
- **Provide the system description and weather data to modelers, who will model the system and provide results.**
  - Fully document model parameters and assumptions
- **Apply a unified mathematical/statistical approach for comparing measured and modeled quantities and document comparisons in a standardized reporting format.**
  - Propagate uncertainties, if possible
- **Identify opportunities for model improvement**



# Mathematical/Statistical Approach

---

- **Identify quantities for validation**
  - DC + AC power, POA irradiance, module temperature, etc.
- **Calculate model residuals (Residual = modeled values – measured value)**
  - Calculate summary statistics ( $R^2$ , RMSE, MBE, annual bias, etc.)
  - Plot residuals vs. time
  - Plot distribution of residuals
  - Test correlation between residuals and other variables
- **Residuals from a valid model will be as small as possible and randomly distributed**



# Example Application of Validation Approach

---

- **1 kW DC, m-SI, fixed latitude tilt, photovoltaic system in Albuquerque, NM**
  - 1 year of hourly-averaged weather and performance data collected at site.
    - GHI, DNI, DHI, air temperature, wind speed (multiple instruments)
    - DC (and AC) current and voltage, module temperature
- **Run two performance models in Solar Advisor Model (SAM)**
  - Sandia PV Array Performance Model (SAPM)
  - CEC 5-Parameter Model (Univ. of Wisconsin)
- **Set derate factors to zero**

# Sandia's Outdoor Test Facility

---



# Inverter and DAS Configuration

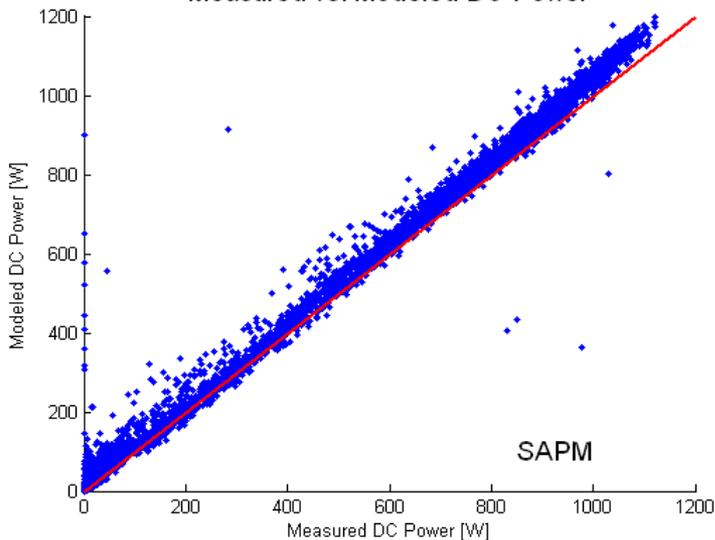
---



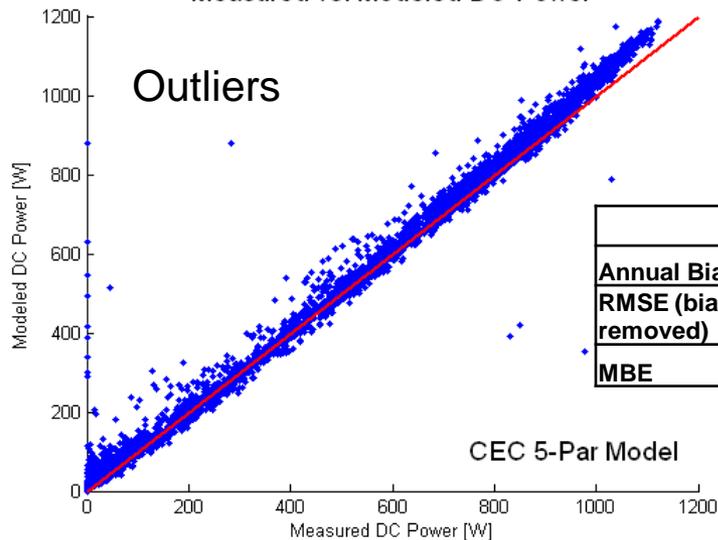
# Comparison of DC Power

- **Measured vs. Modeled looks nearly identical**
- **Slight difference in bias error**
  - Annual bias is same magnitude as typical derate factor
- **Is there a fundamental difference between the models???**

Measured vs. Modeled DC Power



Measured vs. Modeled DC Power

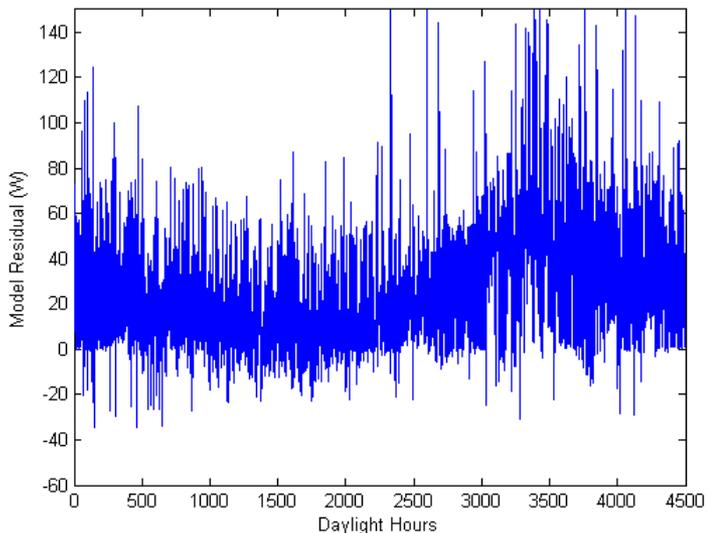


	SAPM	CEC 5 Par
<b>Annual Bias</b>	5.6%	3.3%
<b>RMSE (bias removed)</b>	26 W	23 W
<b>MBE</b>	27 W	16 W

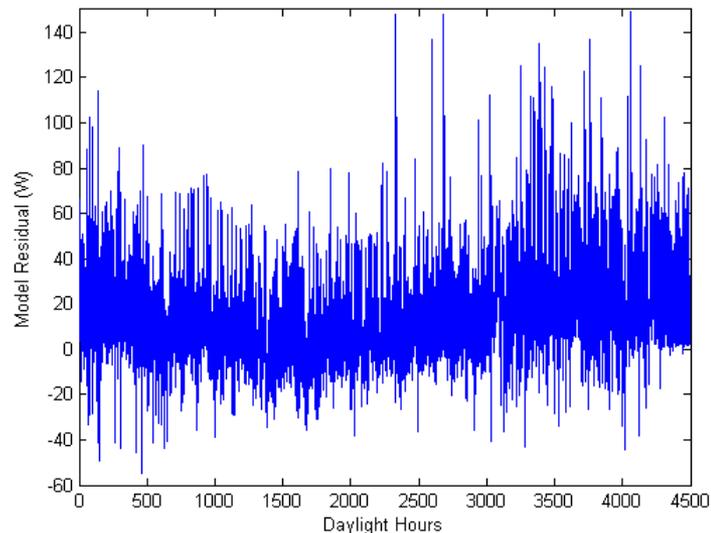
# Residual vs. Time

- **Period is from April 2007 to March 2008**
- **Outlier ( $-150 < R < 150$  W) and night time data are removed**
  - Outliers due to snow on sensor and array
- **Sustained jumps in residuals may indicate soiling/cleaning cycles**
- **Differences between the model begin to appear.**

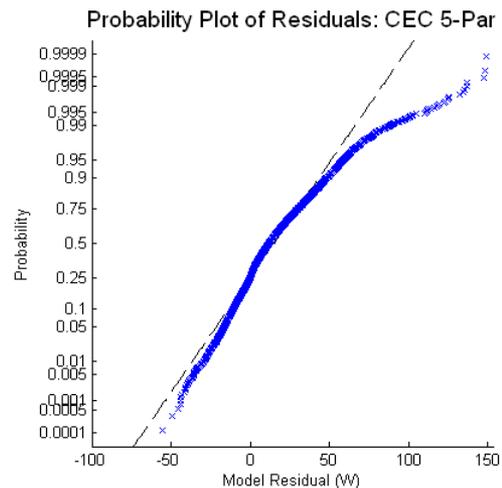
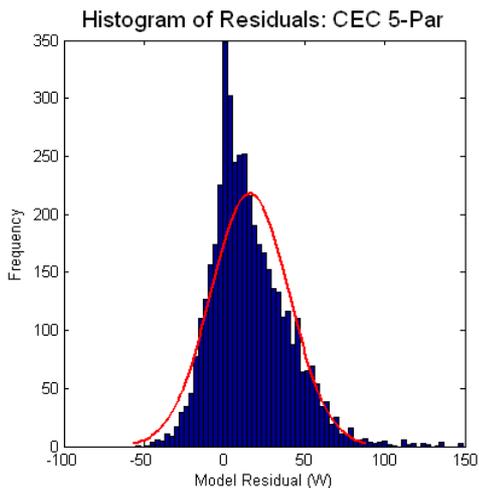
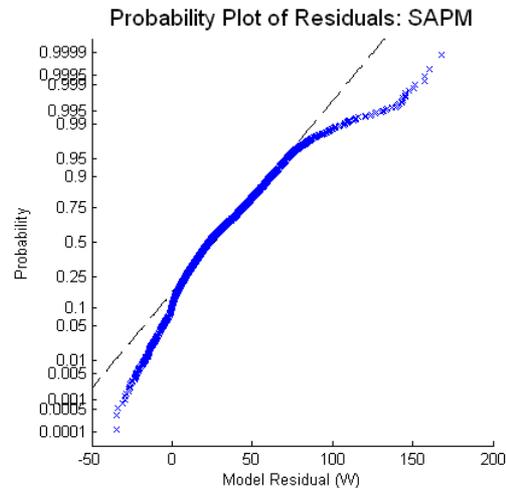
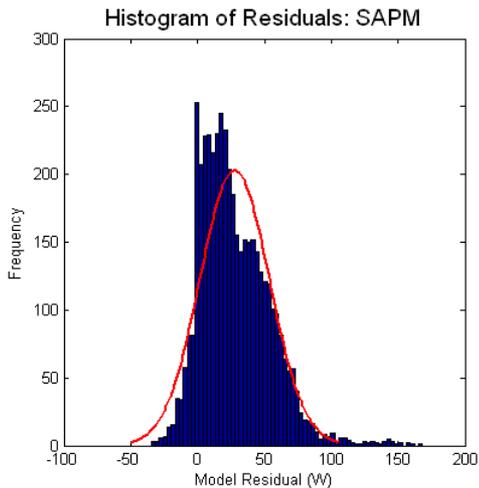
Residual Run Plot: SAPM



Residual Run Plot: CEC 5-Par



# Residual Distributions



Both models have residuals that appear quite normal

Slight left skewness due to concentration of near zero residuals and a positive mean residual (no derate)



# Residual Correlations

---

- **Residuals are differences (model – measured)**
- **Residuals from a ‘Perfect’ model will be randomly distributed and uncorrelated with input variables.**
- **Residual analysis identifies any correlations if they exist.**
  - These represent potential ‘flaws’ in the model and/or parameters.
- **Stepwise regression allows variables which affect residuals to be indentified and ranked.**

$$Y = b_0 + \sum_{j=1}^P b_j X_j$$

$Y$  = dependent variables

$X = P$  vectors of independent variables

$b$  = linear regression coefficients

# Stepwise Results

- Stepwise regression was run for each model
  - Variables examined include incident beam, diffuse, and total radiation, air temperature, wind speed, sun zenith and azimuth angles, angle of incidence, and air mass
- Incremental  $R^2$  value is the fraction of the residual variance explained by the correlation with the variable identified (in order of influence)

SAPM residuals most correlated with air temperature (18% of variance)

CEC 5-Par residuals most correlated with incident beam radiation (12% of variance)

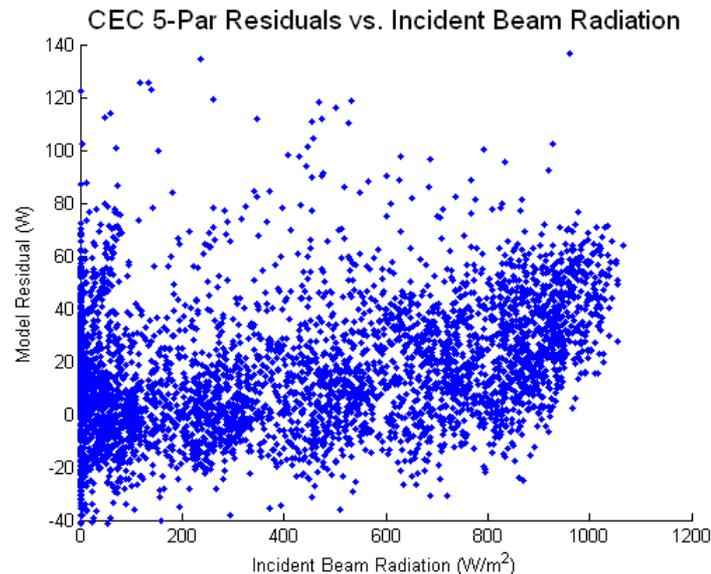
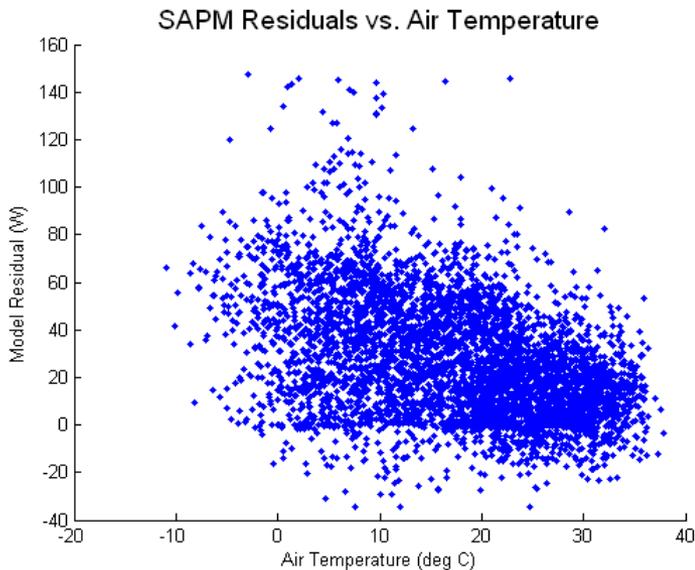
SAPM			
Order	Variable	R <sup>2</sup>	Incremental R <sup>2</sup>
1	Temp	0.18	0.18
2	Incident Tot	0.35	0.17
3	Azimuth	0.37	0.02
4	Zenith	0.39	0.02
CEC 5-Par			
Order	Variable	R <sup>2</sup>	Incremental R <sup>2</sup>
1	Incident beam	0.12	0.12
2	Temp	0.22	0.10
3	WS	0.27	0.05
4	Azimuth	0.28	0.01

39% of SAPM variance explained

28% of CEC 5-Par variance explained

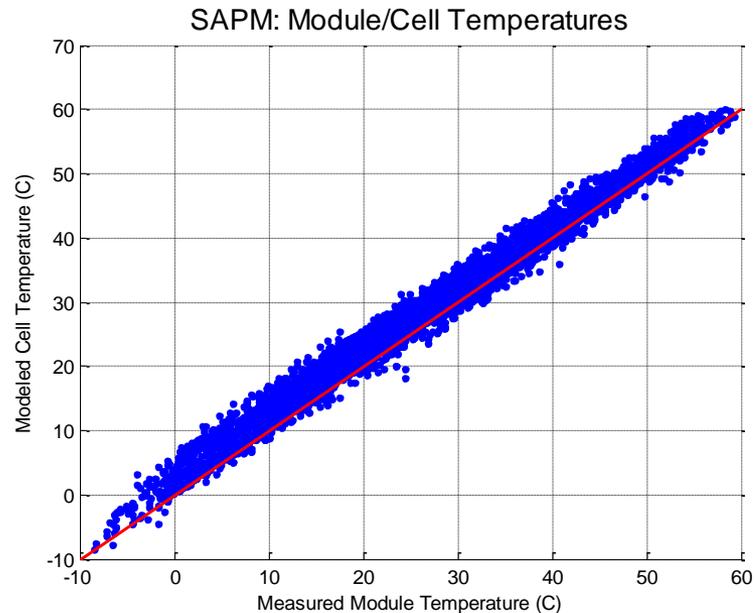
# Primary Variable Correlations

- **SAPM residual correlation with air temperature suggests:**
  - Module temperature coefficients need to be adjusted or cell temperature model needs to be improved.
- **CEC 5-Par residual correlation with incident beam radiation**
  - Still investigating this correlation



# Module Temperature Model

- **Module temperature model appears to work well for this rack-mounted system.**
- **Module temperature coefficients likely need to be adjusted.**





# Ongoing Work

---

- **Collection of performance and weather data from more systems is needed.**
  - **Selection of different technologies**
  - **Diverse locations**
  - **Multiple configurations**
- **Side-by-side comparisons are important because weather data is similar and measurement accuracy is consistent across systems.**
- **Sandia National Laboratories will publish reference data sets for validation.**
- **Sponsor workshop this fall/winter on PV performance modeling**
  - **Participants simulate a reference system**
  - **Comparison of results from various models**



# Summary

---

- **A standardized model validation approach has been developed with input from industry partners.**
  - Based on residual analysis
  - Provides valuable information for model developers
- **Provided an example application of the approach**
- **Next steps include:**
  - collection of data from a representative range of technologies, climates, and designs
  - Model validation report (template?)
- **PV modeling workshop being planned for end of 2010.**



**THANK YOU**