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# A Standardized Approach to PV System Performance Model Validation

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**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.

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# 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 loses, 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

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# Inverter and DAS Configuration

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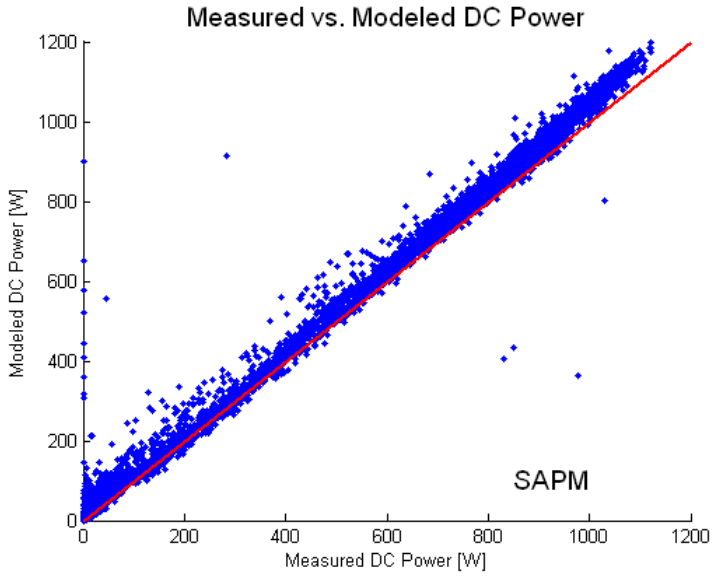
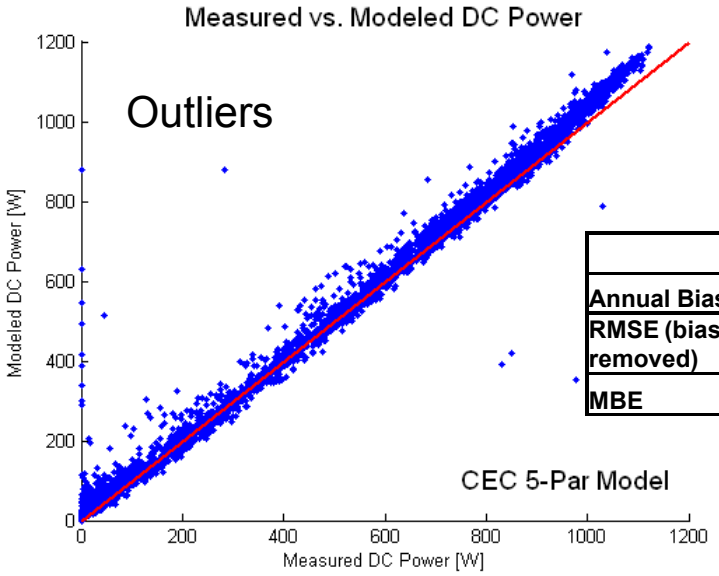
# Comparison of DC Power

- **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???**




| | SAPM | CEC 5 Par |
|---|---|---|
| **Annual Bias** | 5.6% | 3.3% |
| **RMSE (bias removed)** | 26 W | 23 W |
| **MBE** | 27 W | 16 W |

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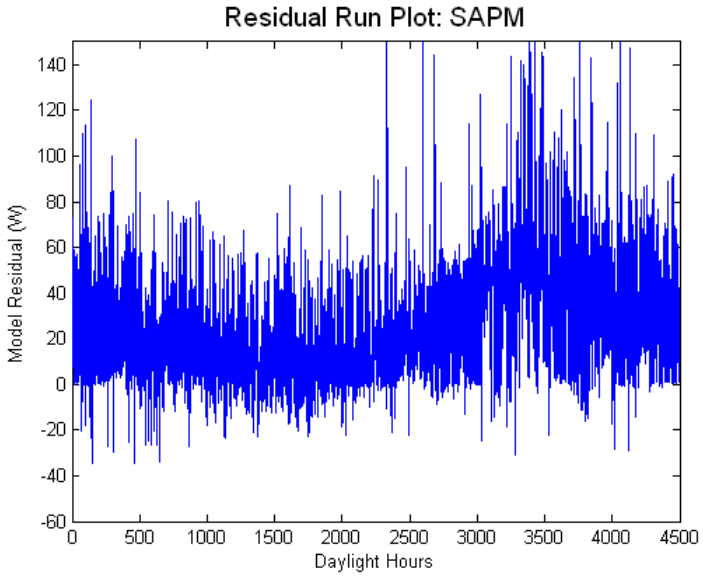
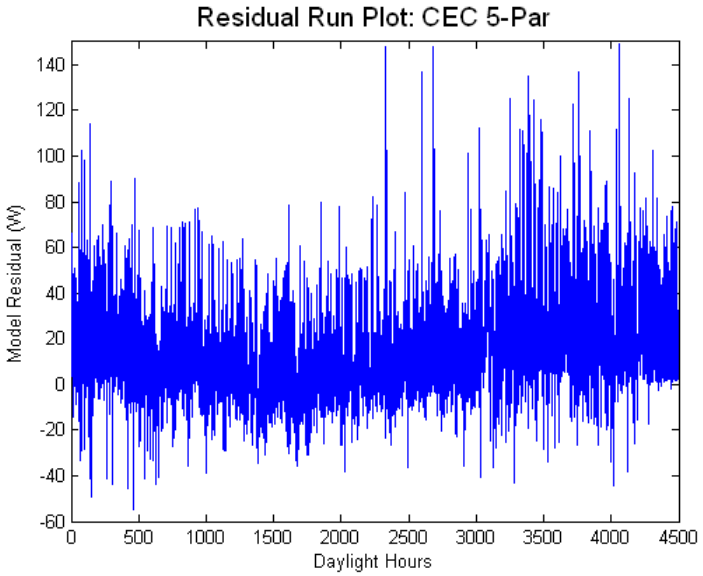
# Residual vs. Time

- **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.**

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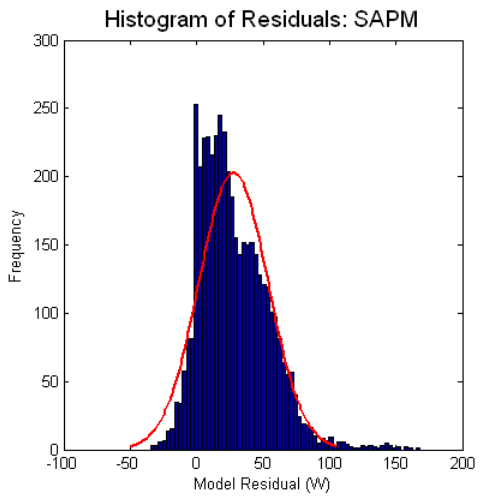
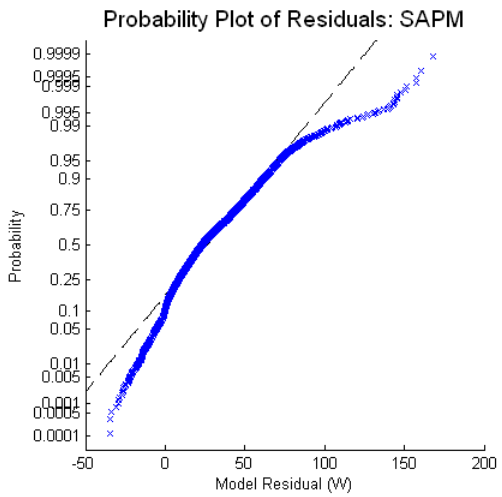
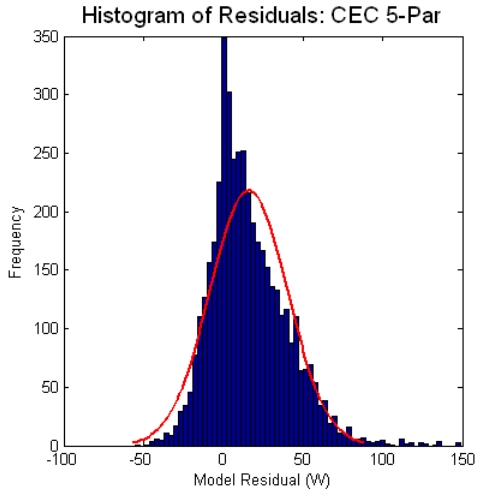
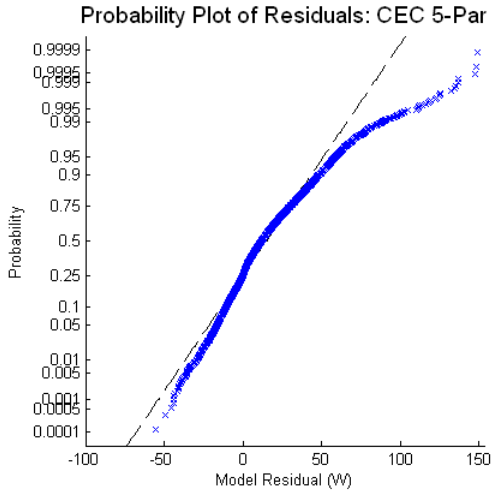
# Residual Distributions




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)

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# 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

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# 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** | **$R^2$** | **Incremental $R^2$** |
| 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** | **$R^2$** | **Incremental $R^2$** |
| 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

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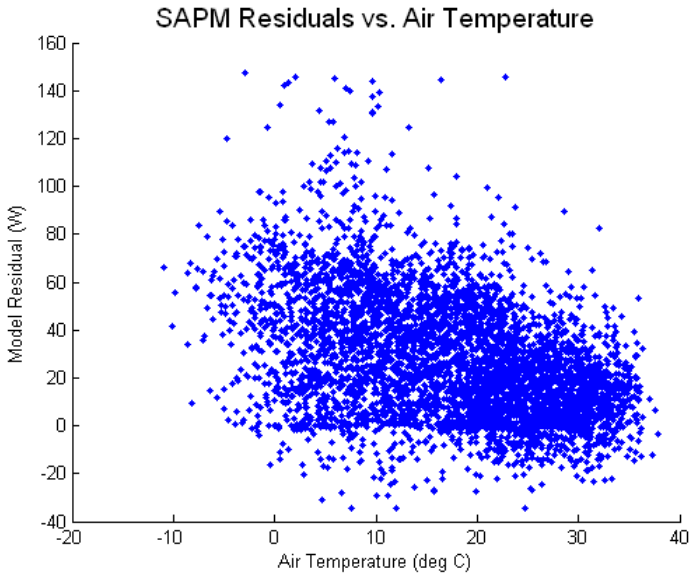
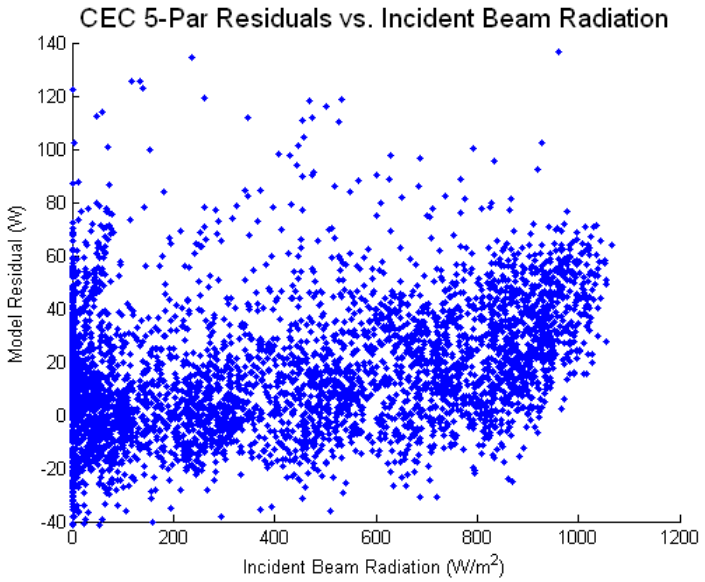
# Primary Variable Correlations

- **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

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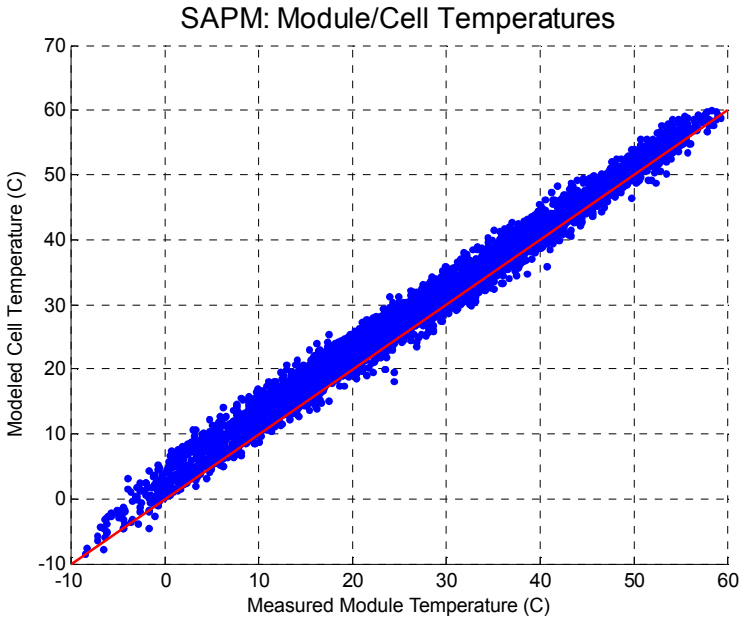
# Module Temperature Model

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

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# 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

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# 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.**

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