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Performance Model Assessment for Multi-Junction Concentrating Photovoltaic Systems

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Relevance of Annual Energy Calculations

- PV Systems Increasingly Valued for Annual Energy Output
  - Power Purchase Agreements Common
  - Flat-Plate PV System Power Ratings Do Not Accurately Indicate Performance
  - Comparison with CPV System Ratings is Difficult
- System Performance Models are an Alternative to System Ratings
  - Provide Ability to Predict Annual Energy Production for Various Locations
- DOE/NREL Has Developed the Solar Advisor Model (SAM)
  - Key DOE Metrics are Annual Yield and Levelized Cost of Energy
  - Performance Models in SAM Include the Sandia PV Array Performance Model, the Sandia Inverter Model, and a Simpler CPV Model
  - Available Free at www.nrel/gov/analysis/sam

Model Validation Approach

- Through laboratory or field testing, develop performance coefficients for components or system
- Concurrently collect irradiance, weather, and system performance data over a period of time, preferably one year
- Model system performance using performance coefficients and measured irradiance and weather data
- Apply system derate parameters
  - Sometimes calculated, but usually estimated from experience
- Compare modeled to measured performance
  - As a function of environmental parameters
    - Irradiance, air temperature, wind speed, air mass
  - Also examine internal parameters, when available
    - For example, V_{dc}, module temperature…

Models Evaluated

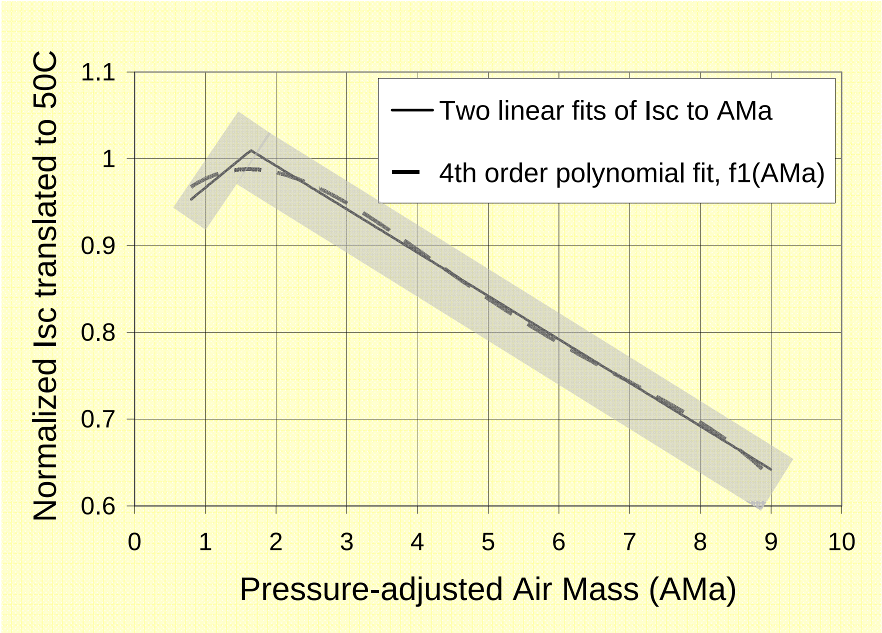
- Solar Advisor Model
  - Sandia Array Performance Model
    - Empirical Model – Inputs Include Irradiance, Air Temperature, Wind Speed, and Air Mass
  - Simple CPV Model
    - Applies Maximum Power Temperature Coefficient to Efficiency
    - Uses Sandia Model to Calculate Cell Temperature
  - Simple CPV Model Without Temperature Corrections
    - Sun-Hour Model (Eff ● DNI)
  - Sandia Inverter Model
  - AC and DC Derate Factors
- ASTM E 2527 – 06 Translation Equation
  - $P = E \cdot (a_1 + a_2 \cdot E + a_3 \cdot T_a + a_4 \cdot \nu)$

Generation of Performance Coefficients

Sandia Array Performance Model – DC

- Data is Collected During All-Day Testing and a Temperature Test
- Regression Analysis Generates
  - V_{oc}, I_{sc}, V_{mp}, I_{mp} and Temperature Coefficients for Each
  - Additional Coefficients that Determine V_{oc}, I_{sc}, I_{mp} and V_{mp} as a Function of Cell Temperature and Effective Irradiance
  - a, b, and ΔT Coefficients Relating Cell Temperature to Ambient Temperature, Wind Speed, and Irradiance

$$T_c = T_a + E \cdot \{e^{a + b \cdot WS}\} + E/E_o \cdot \Delta T$$



  - An Air Mass Function That Determines Effective Irradiance: $DNI \cdot f(AM_a)$

Generation of Performance Coefficients

SAM Simple CPV Model – DC

- Applies Maximum Power Temperature Coefficient
  - $P = P_o \cdot E/E_o \cdot (1\text{-}\gamma) \cdot (T_a\text{-}T_c)$
- Uses Sandia Model Cell Temperature Calculation with Typical Values of Coefficients
  - a = -3.2, b = -0.09, ΔT = 17

Sandia Inverter Model

- Coefficients are Derived from California Energy Commission Test Data that Relate Efficiency to DC Input Power and Voltage

AC and DC Derate Factors

- Set to Match Measured and Modeled Power Over Total Measurement Period, ~30 days in fall 2009

ASTM E 2527 – 06 Translation Equation – AC

- Coefficients Generated by Regression Analysis over Few Clear Days

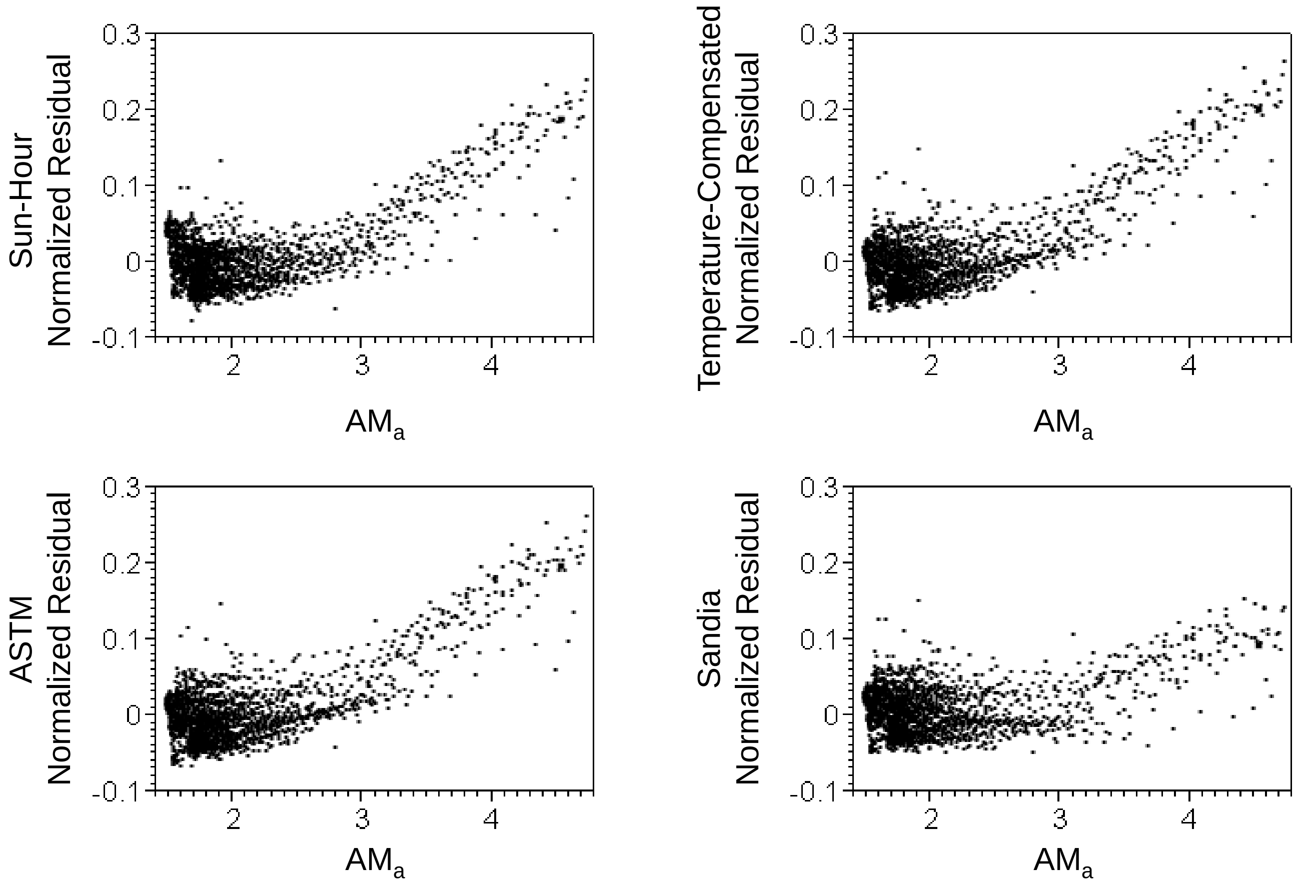
Residual Analysis

- Normalized residuals are the difference between modeled (bias removed) and measured results
  - $(P_{mod}-P_{meas})/P_{rating}$ (W/W_p)
  - Since the systems are different sizes, we normalized to the nominal rating
- Model results were "derated" to remove bias error
- Standardized deviation of normalized residuals show all models work well over the short duration of the test

Standardized deviation of normalized residuals

	Sun-hour	Temp Comp	ASTM	SNL
System 1	0.0458	0.0508	0.0499	0.0343
System 2	0.0516	0.0538	0.0502	0.0476

Normalized Residuals vs. Air Mass



For a valid model, residuals should be randomly distributed

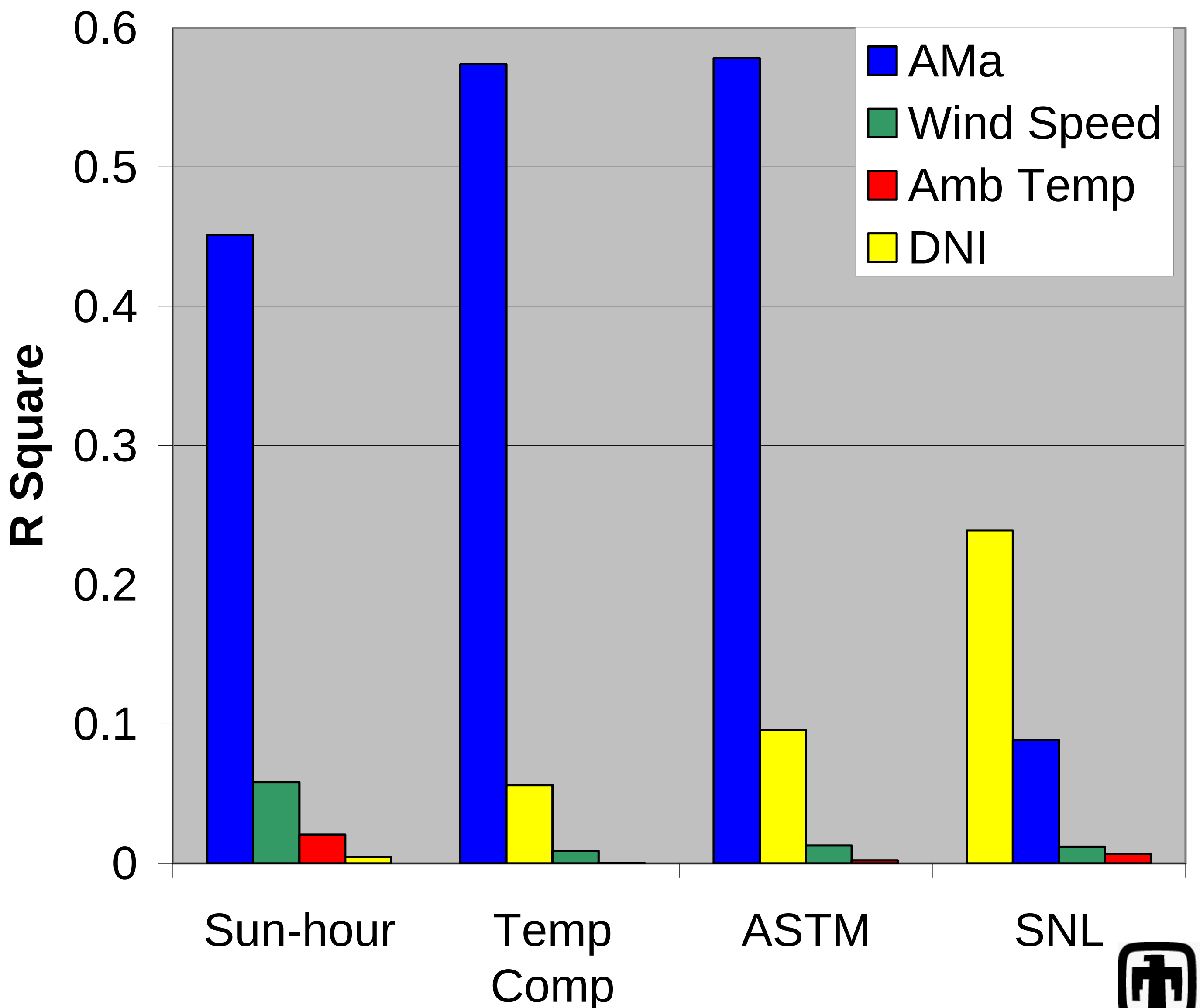
Residual Analysis

- Our objective – to see how models can be improved
  - Correlation between residuals and model inputs indicates opportunities for improvement
- Stepwise regression uses a stepped series of linear regressions:

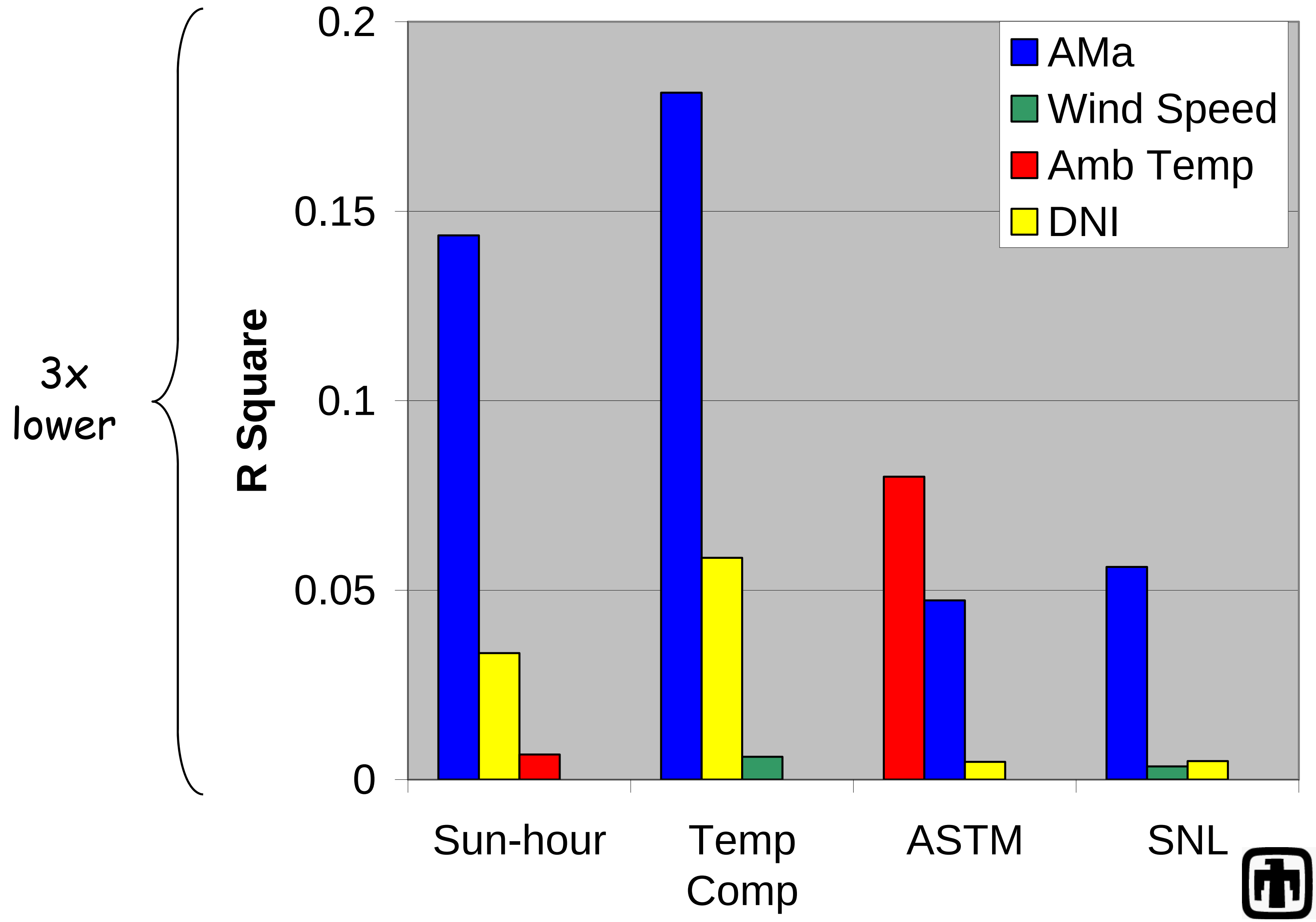
$$Y = b_o + \sum_{j=1}^{P} b_j X_j ,$$

  - Y is the model residuals
  - X includes DNI, Air Mass, Ambient Temperature, Wind Speed

Results – System 1



Results – System 2



Conclusions

- All models, even the simplest, worked well
  - A longer test (greater variations in input parameters) and multiple locations might produce different results
  - Only the Sandia model corrects for air mass
    - Step-wise analysis of the residuals of the other models showed the most sensitivity to air mass
    - The sun-hour model, having no temperature correction, was also sensitive to wind speed and temperature
- Future work
  - Analyze data for a longer test period (1 year)
  - Expand the number of systems and locations
  - Evaluate derate factors
  - Evaluate modeling of self-shading