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A Performance Model for AC Modules

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Module Level Power Electronics Are Growing

- For residential and small commercial systems, MLPE have a number of advantages
  - NEC Rapid Shutdown compliance (NEC 690.12)
  - Design flexibility and shade tolerance
  - Lower DC voltages
- The market for MLPE is growing
  - In 2013 microinverters and DC optimizers were used in *half* of all residential installations
  - The market share leader, Enphase, shipped 162 MW_{AC} of microinverters in Q1 2015

Evolution of the AC Module

- MLPE are becoming more highly integrated into PV modules
  - Smart modules such as Trinasmart
  - SunPower purchase of Solarbridge

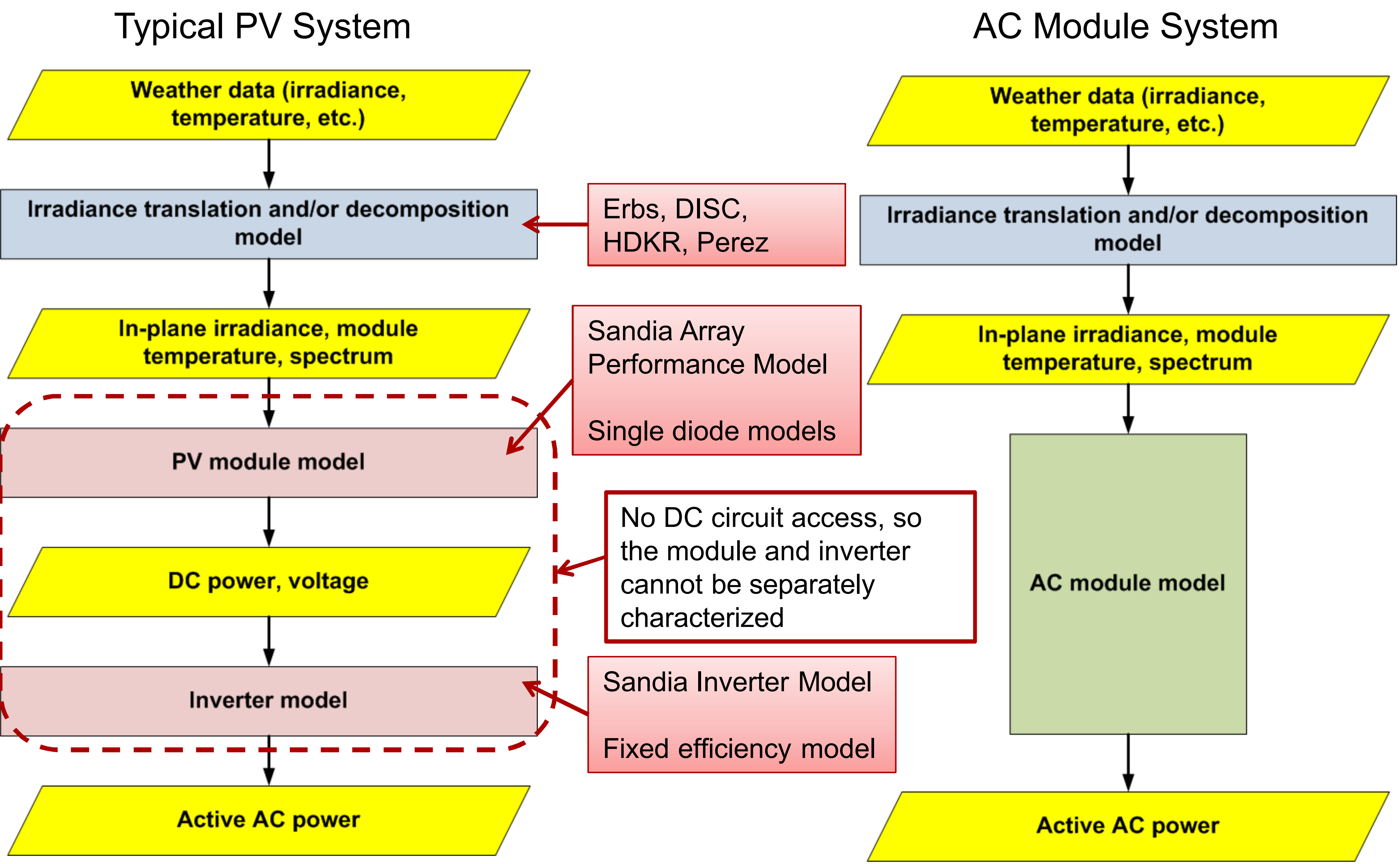
- PV module and microinverter are fully integrated
  - AC power is generated when exposed to sunlight (assuming normal grid conditions)
  - No access to the DC circuit

AC Module Performance Descriptions

- Determining the expected performance of AC modules is difficult
  - No standard performance rating condition (such as STC for DC PV module)
  - Manufacturers do not have consistent performance metrics on specification sheets
  - Reported specification metrics are less than helpful
    - Why include I-V curves of the PV module?
    - Module nominal STC power exceeds maximum AC output
- How should I compare or describe the performance of AC modules?

We need some standard performance reporting metrics!

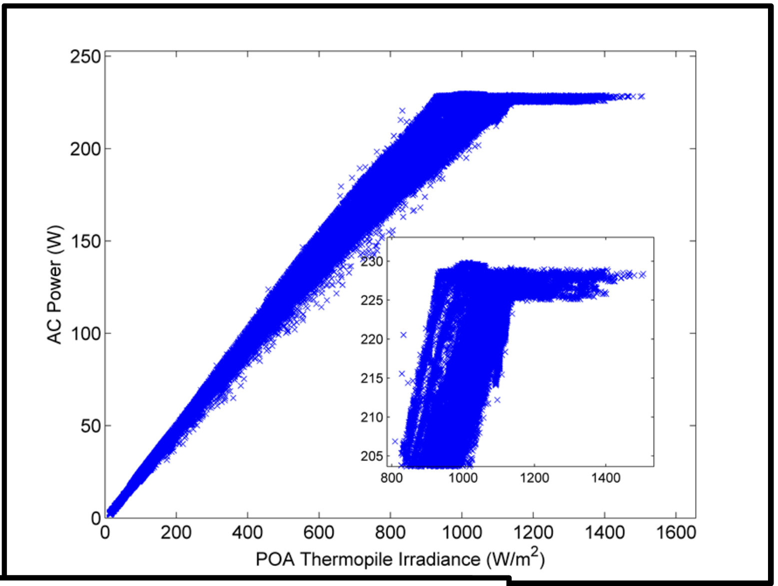
PV System Modeling Steps

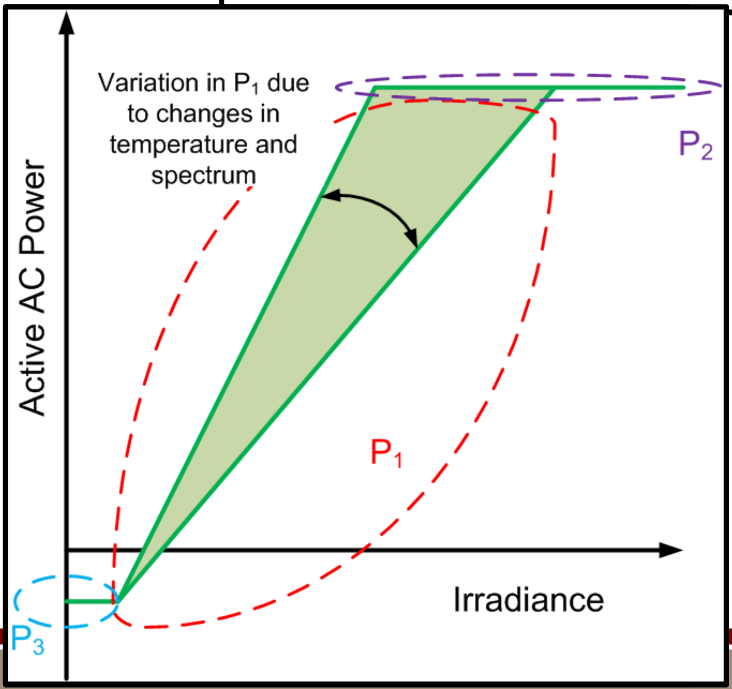


AC Module Performance Model

- Active AC power is controlled by the microinverter and has three principle operating states
  - P_3 – Low irradiance self-consumption
  - P_2 – Maximum power self-limiting
  - P_1 – Typical operating state
- The performance model is a piecewise function with three subdomains

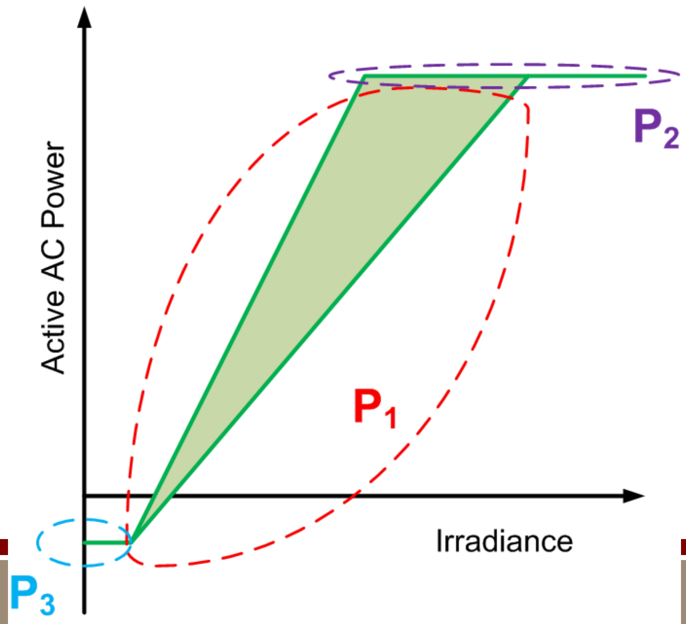
$$P_{AC} = \begin{cases} P_1 & P_3 \le P_1 \le P_2 \\ P_2 & P_1 > P_2 \\ P_3 & P_1 < P_3 \end{cases}$$





Equation Subdomains

- P_3 may be a function of input conditions, I use a constant
  - $P_3 = -1 \times P_{NT}$
  - P_{NT} is the night tare value, obtained by testing or via spec sheet
- P_2 may also be function of the conditions, I use a constant
  - $P_2 = P_{AC,max}$
  - $P_{AC,max}$ is the maximum active AC power output, obtained by testing or spec sheets
    - Spec sheets may be quite inaccurate, so I recommend testing



Equation Subdomains (continued)

- P_1 is a function of environmental conditions
  - $$P_1 = Pac_{ref} \times f_1(AMa - AMa_{ref}) \times \left[C_0 \times \frac{E_{POA}}{E_{ref}} + C_1 \times \ln\left(\frac{E_{POA}}{E_{ref}}\right)\right] \times [1 + \gamma_{ac}(T_c - T_0)]$$
  - Absolute airmass, as a proxy for spectrum
  - Absorbed plane of array (POA) irradiance
    - Accounts for surface reflections
  - PV cell temperature
- Model parameters must be obtained by outdoor testing
  - 6 parameters listed above
    - Pac_{ref} – Reference active AC power at reference conditions
    - C_0, C_1 – Adjust estimated power for irradiance
    - E_{ref} – Reference irradiance (may not be 1000 W/m^2)
    - γ_{ac} – Temperature coefficient for AC power
    - T_0 – Reference cell temperature
  - 3 parameters are embedded in f_1 for airmass adjustments – A_1, A_2, A_3
  - 1 used for to account for surface reflection losses (model by Martin & Ruiz) – a_r
    - If the module has flat glass without AR coating, a representative parameter may be used

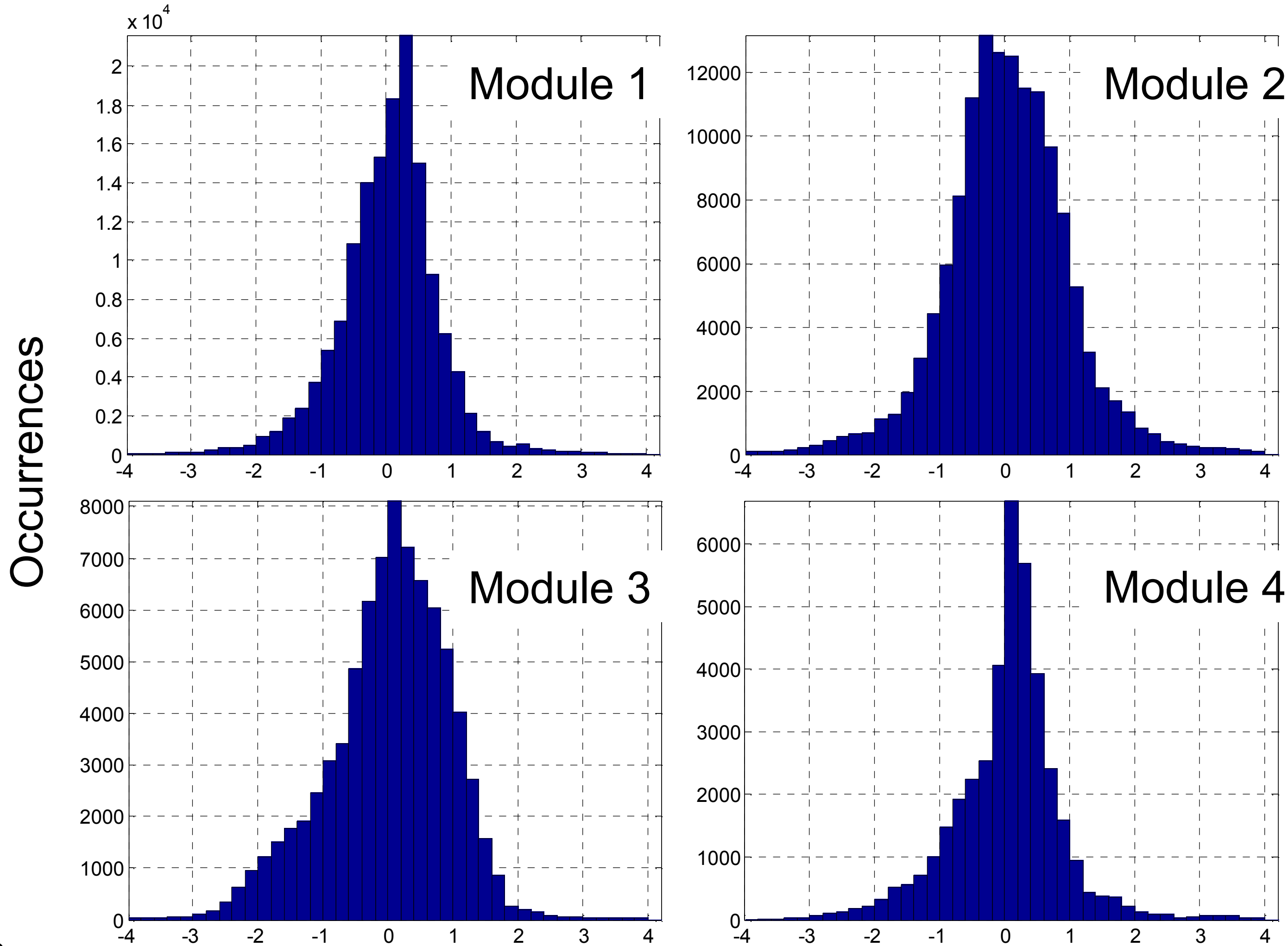
Validating the model

- Tested 4 different AC modules on a two axis tracker and developed model parameters for each module
- Evaluated the ability of the model to represent the parameter generation data set.

- Placed modules 3 and 4 in a fixed-tilt orientation for several days.
- Evaluated the ability of the model to represent data from this "typical use" case

Model Errors in the Parameter Generation Data Set

- Errors less than 2% of Pac_{ref}
- Approximately 0 mean
  - As expected
- Shows that the model form is capable of modeling an AC module



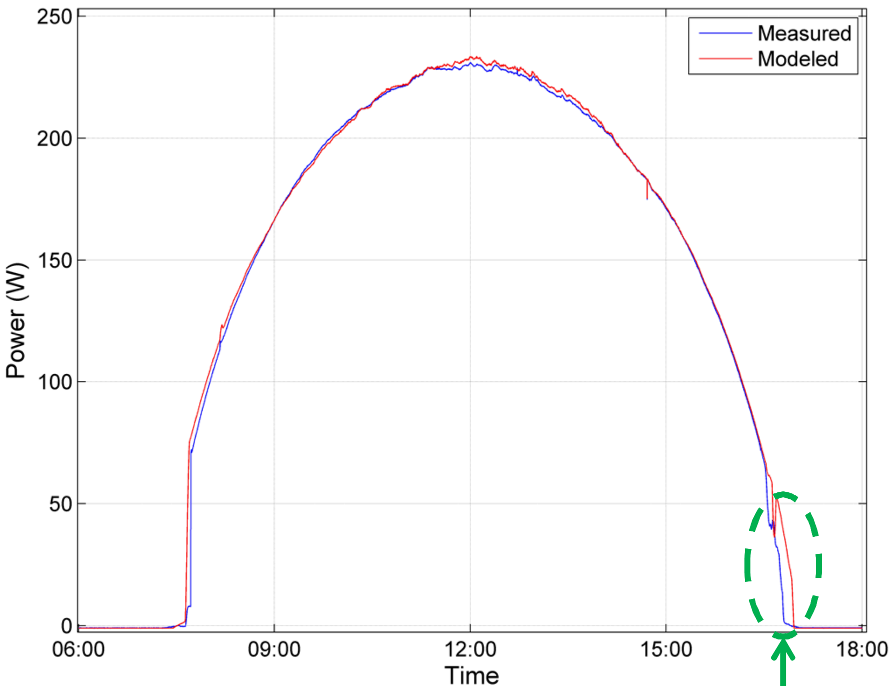
$$\frac{Pac_{model} - Pac_{measure}}{Pac_{ref}} \times 100$$

Model Residuals as a percentage of the reference power

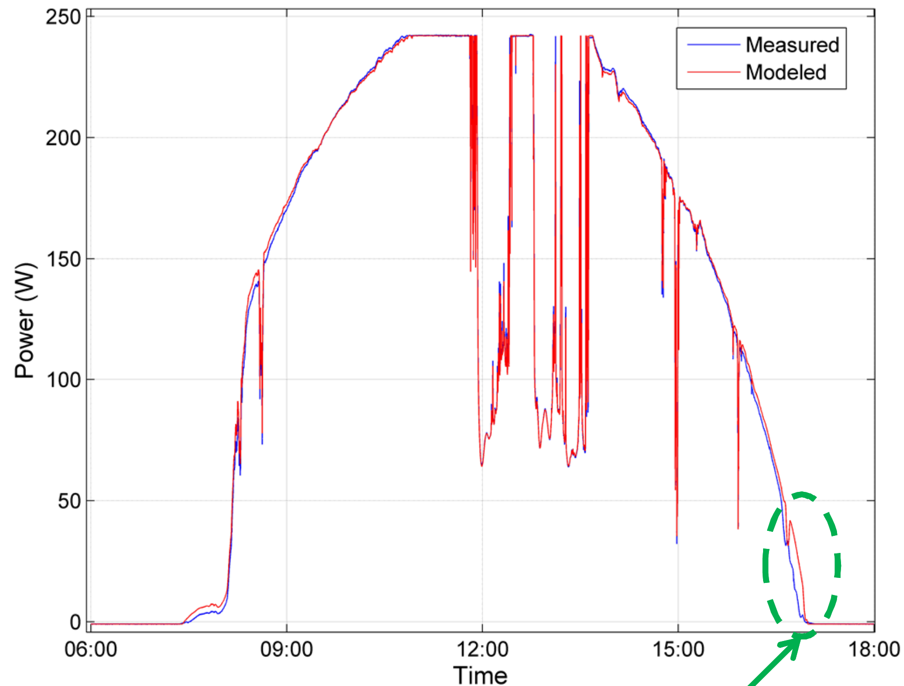
Results from Module 3, Fixed Tilt

Two of nine test days shown here with measured power and modeled power

- A warm, calm, sunny day



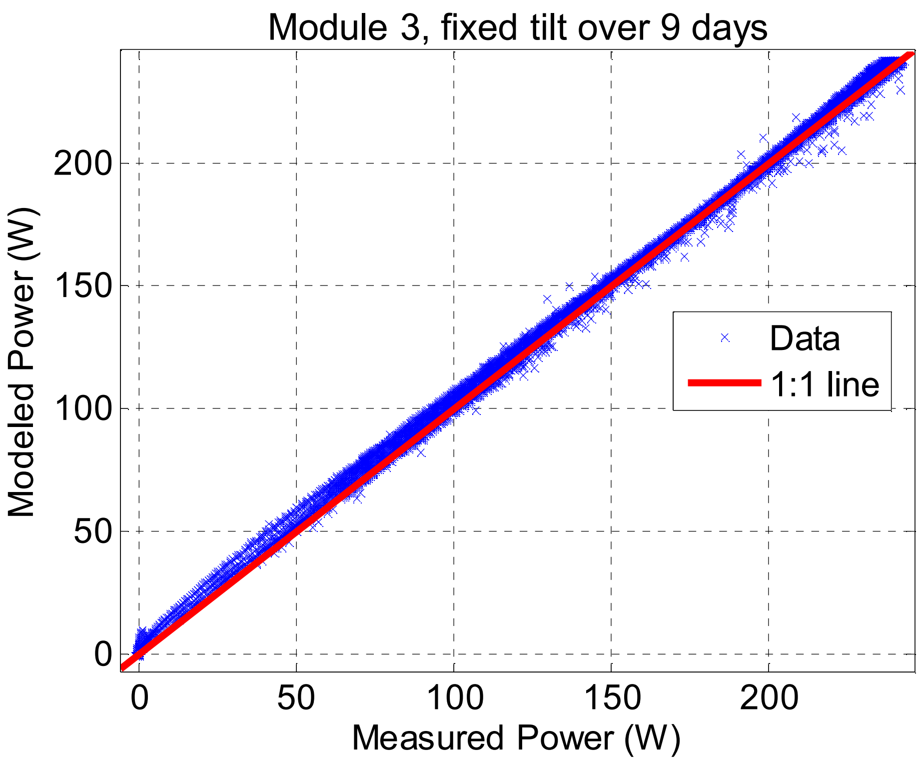
- A cool, breezy, partly cloudy day
- Good transition to power limiting

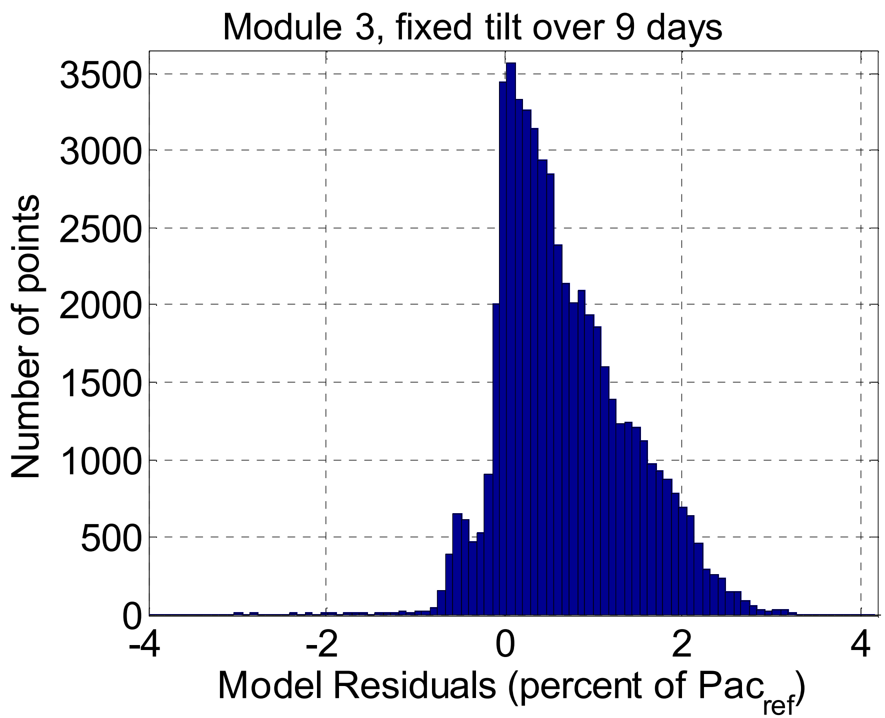


Shading of the module but not the irradiance sensor. Data omitted from subsequent analyses.

Model Errors for a Typical Use Case – Fixed Tilt Orientation

- Slight positive bias in model residuals (indicates model over-prediction of power)
- Errors still mostly less than 2% of Pac_{ref}

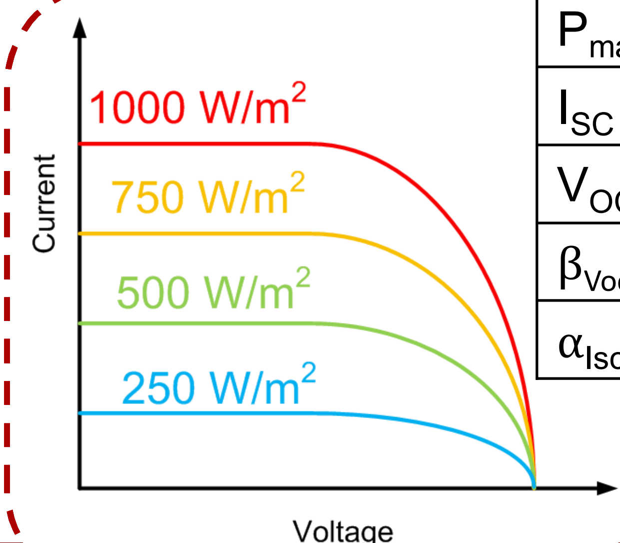




	MBE (watts)	MBE (% of Pac_{ref})	RMSE (watts)	RMSE (% of Pac_{ref})
Daytime data only	1.700	0.6776	2.484	0.9903

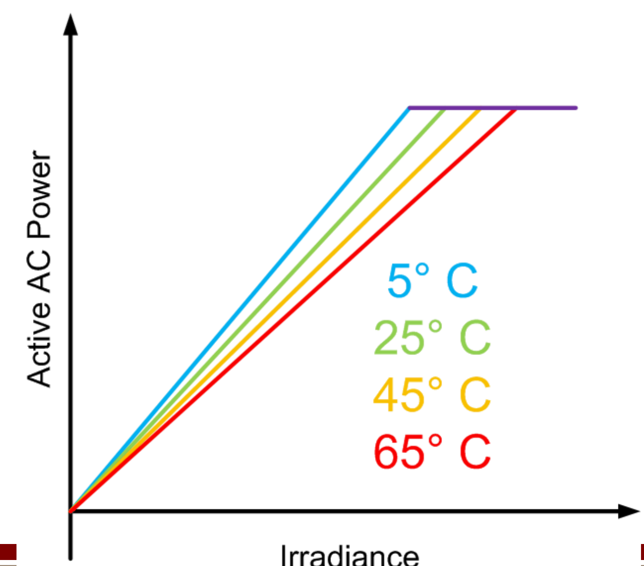
How can the model be used to help the AC module industry?

- The same way that performance models have helped the PV industry in general
  - Performance evaluation of potential (unbuilt) systems
    - Expected energy
    - Selecting between two types of AC modules
  - Measured vs. Modeled comparison of existing systems for health evaluation
- As a basis for a standard performance rating condition
- As a basis for standard performance reporting metrics for specification sheets



P_{max}	250 W_{DC}
I_{SC}	9 A_{DC}
V_{OC}	36 V_{DC}
β_{Voc}	-0.45 %/°C
α_{Isc}	0.05 %/°C

Is this useful for an AC module?



Conclusions

- As PV modules and power inverting electronics become more highly integrated, current methods for characterizing and modeling performance become obsolete.
- Sandia has developed an AC module performance model to characterize and model AC modules
  - Test processes
  - Analysis techniques
  - RMSE approximately 1% in a typical installation case
  - MBE 0.68% in a typical installation

For More Information

- A complete white paper (SAND2015-0179) with test processes, analysis techniques, more discussion, and model validation is available at

  http://1.usa.gov/1B3sxum

  - Or just search for SAND2015-0179