Characterizing and Modeling AC PV Modules

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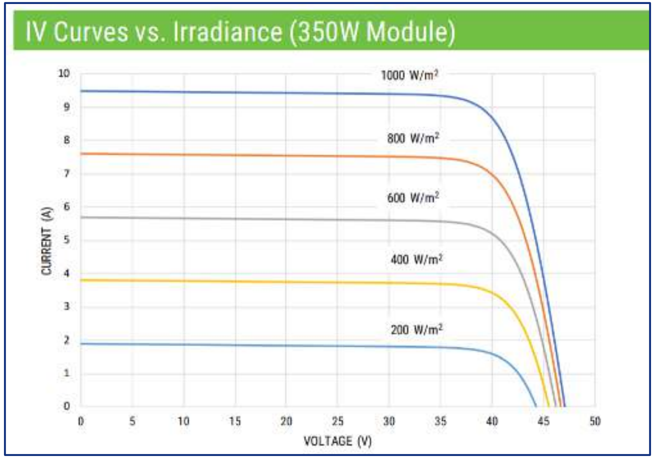
EUPVSEC 2020 Workshop

AC Module Definition

- An AC photovoltaic module is created when a PV module and a microinverter are fully integrated
  - AC power is generated when exposed to sunlight
  - No access to the DC circuit
- AC modules provide benefits
  - Reduced installation time
  - Design flexibility and shade tolerance
  - Lower DC voltages

AC Module Difficulties

- Describing AC module performance is difficult
  - No standard rating definition
  - Performance metrics on spec sheets are not consistent across manufacturer
  - Performance metrics on spec sheets unhelpful
    - How are I-V curves or I_{MP} and V_{MP} helpful when talking about an AC module?

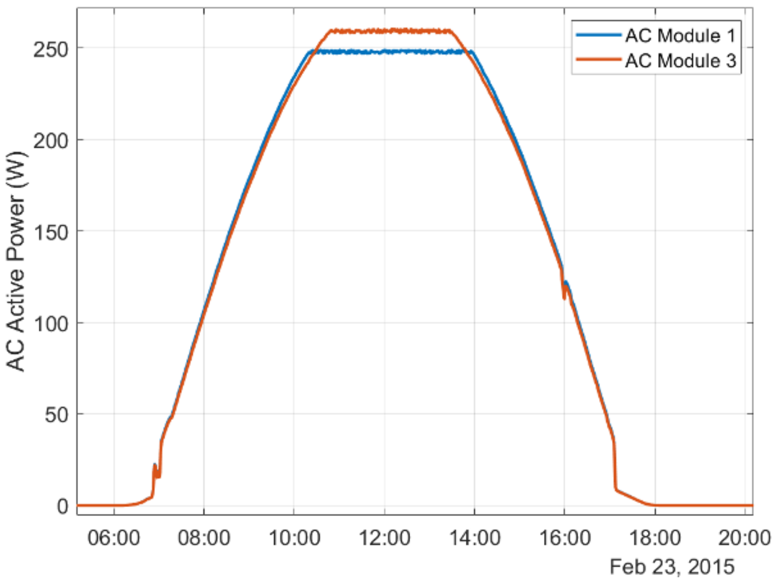


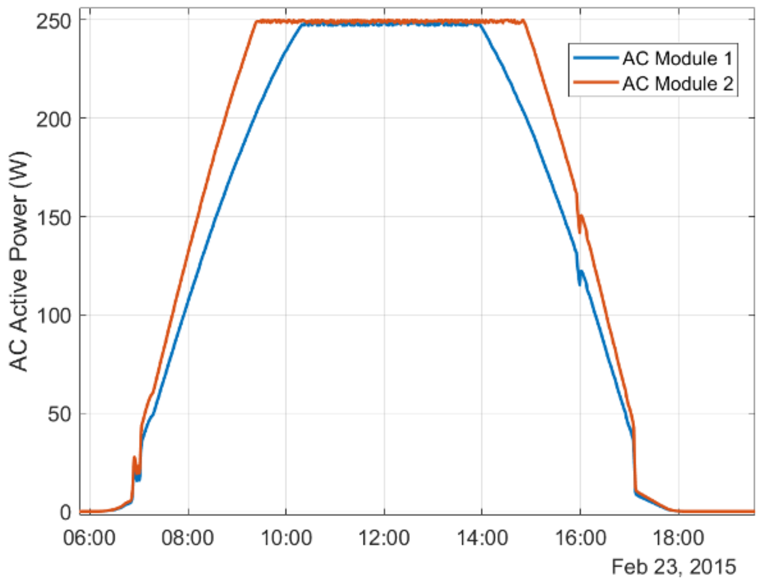
Temperature Coefficients(DC)	
NOCT	45 ± 2 °C
Pmpp	-0.41 %/°C
Voc	-0.29 %/°C
Isc	0.04 %/°C

Rated Voltage	Vmpp	40.5 V
Rated Current	Impp	5.93 A

The Question for AC Modules

- How do we compare or describe the performance of AC modules?





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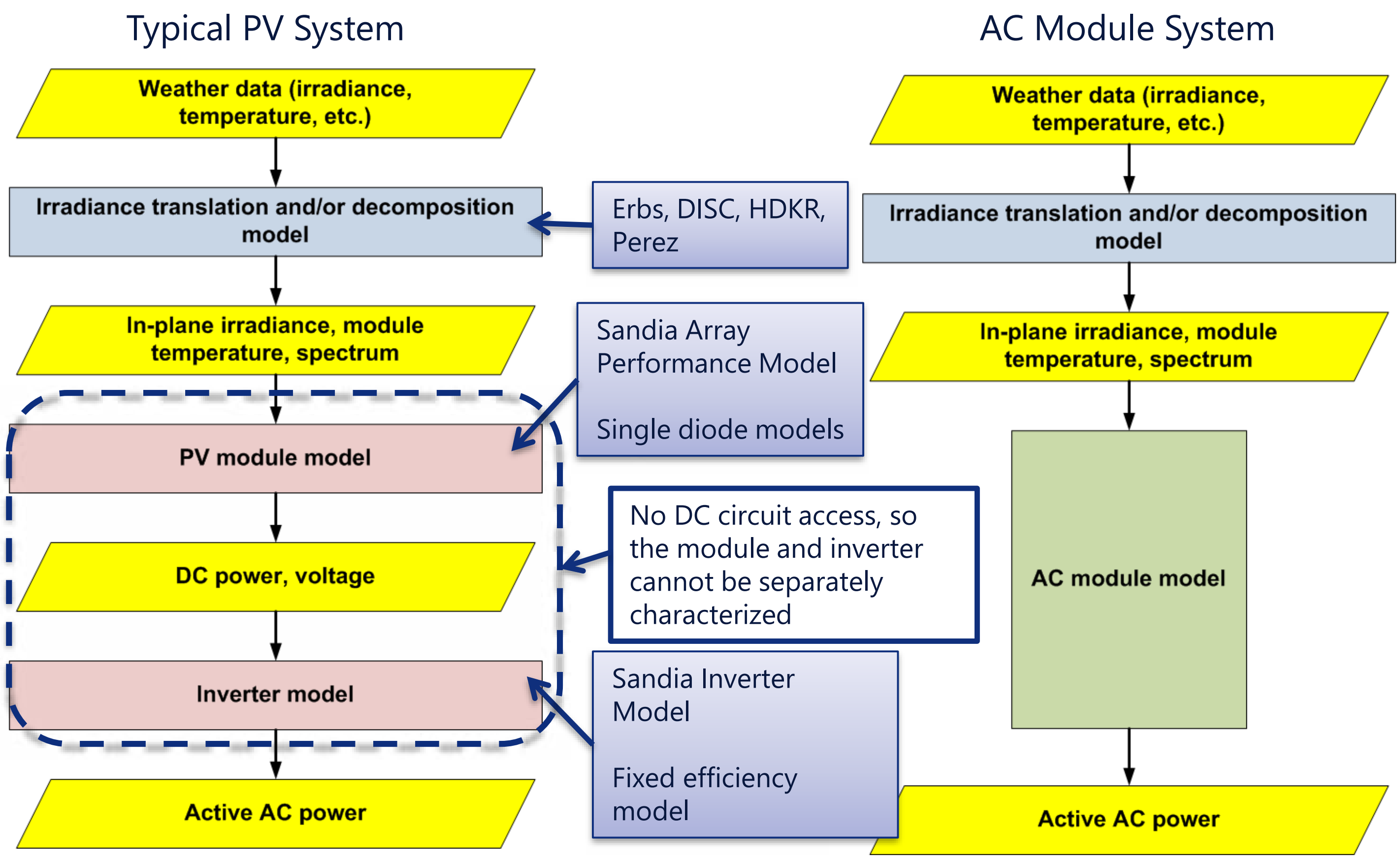
Sandia National Laboratories historical work

- In 2014 Sandia National Laboratories
  - Developed AC Module characterization tests
  - Developed a performance model for AC Modules
  - Evaluated the characterization techniques and performance model on 4 AC Modules

- Funded by the United States Department of Energy, Solar Energy Technologies Office

PV Performance Modeling



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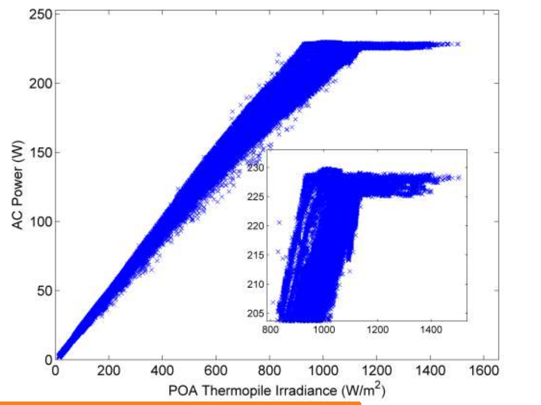
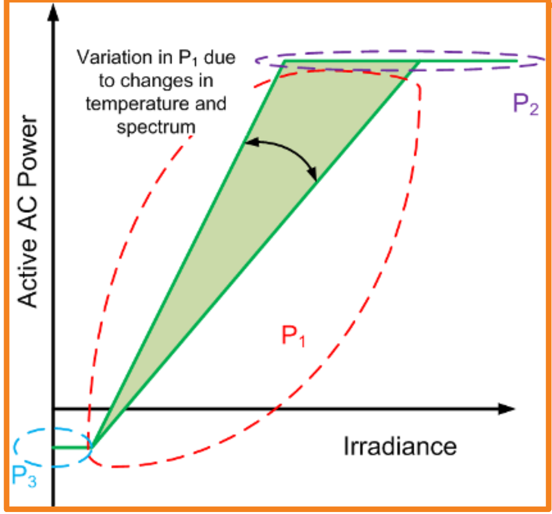
Basic AC Module Model Description

- 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



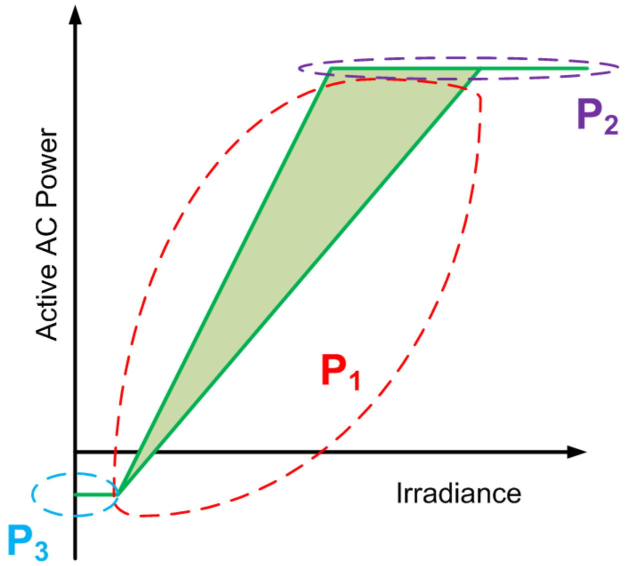
- The performance model is a piecewise function with three subdomains

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



Equation Subdomains

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



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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 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

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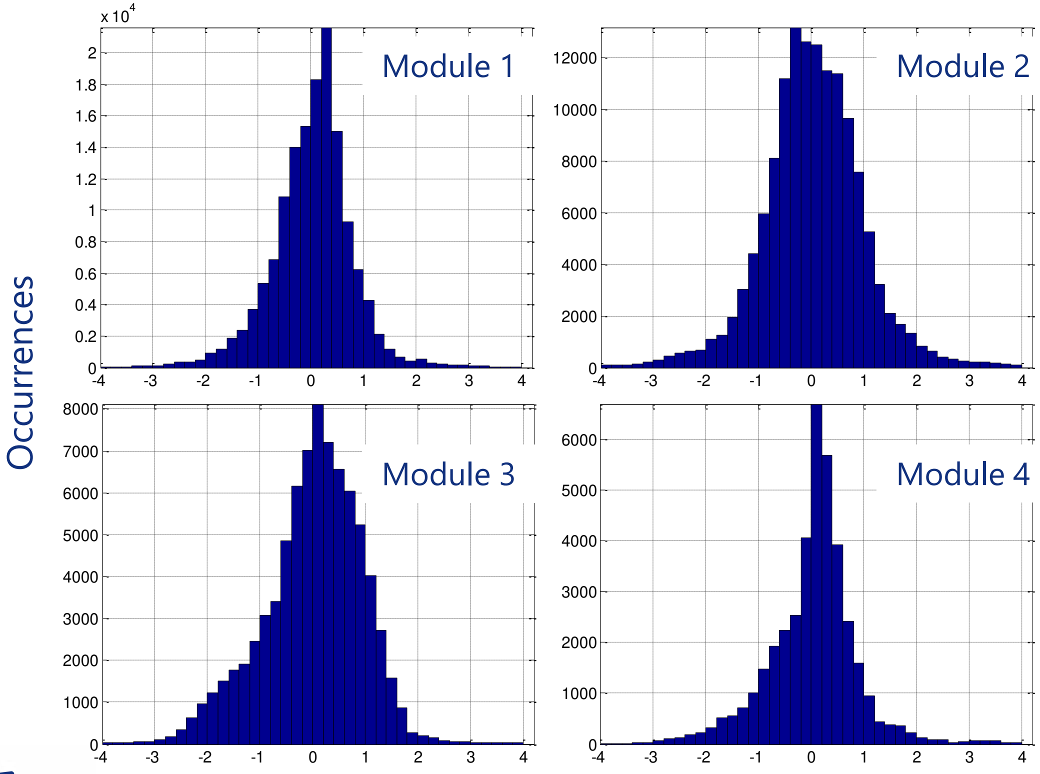
Validating the AC Module Model

- Tested 4 different AC modules on a two axis tracker and developed model parameters for each module
- Placed modules 3 and 4 in a fixed-tilt orientation for several days.
- Compared the active AC power predicted by the model to the measured AC power from the module

Model Errors in the Parameter Generation Data

- 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

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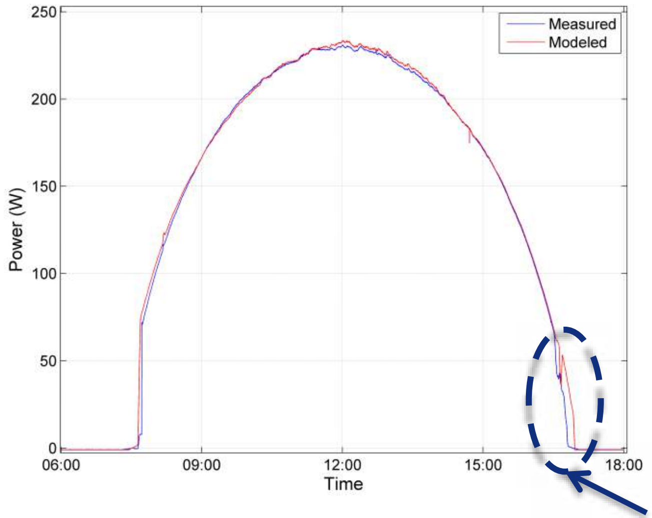
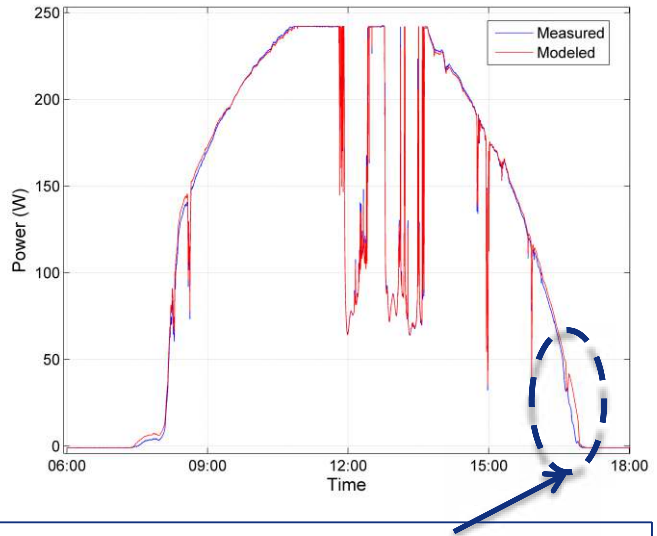
Results from Module 3, Fixed Tilt

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

- A warm, calm, sunny day



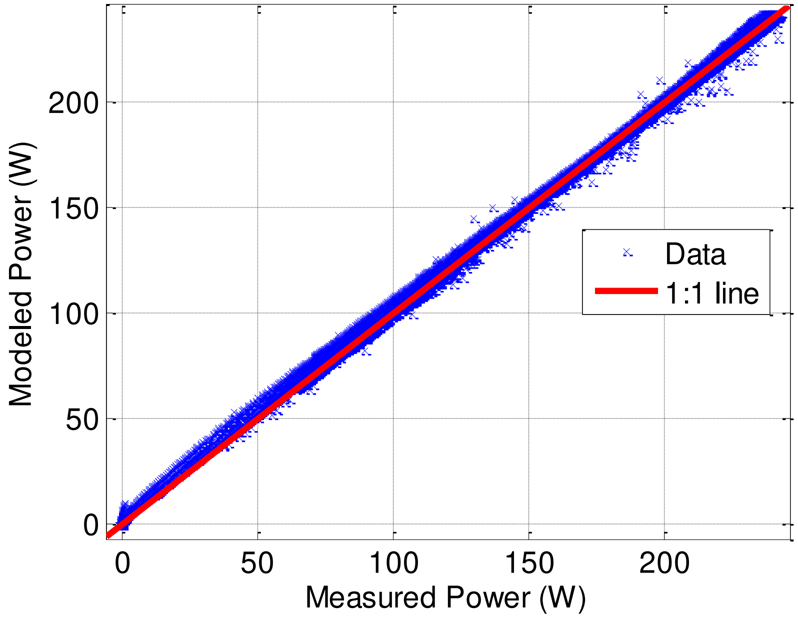
- A cool, breeze, partly-cloudy day
- Good transition to power limiting

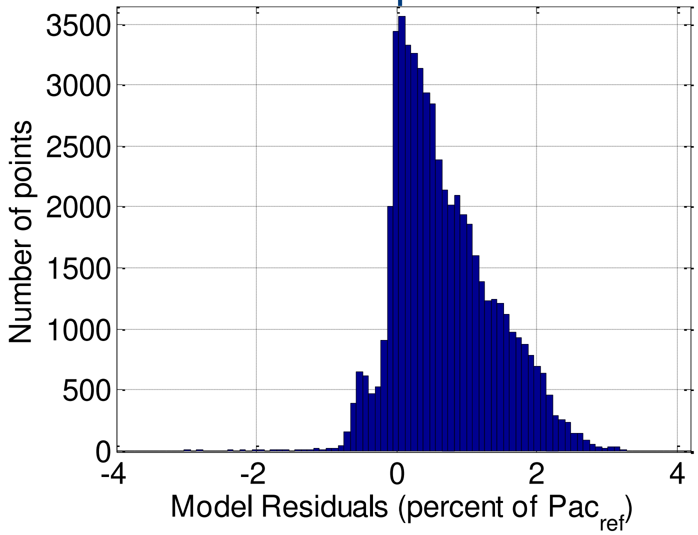


Shading of the module but not the irradiance sensor. Data omitted from subsequent analyses.

Model Errors for Typical Use – Fixed Tilt

- 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

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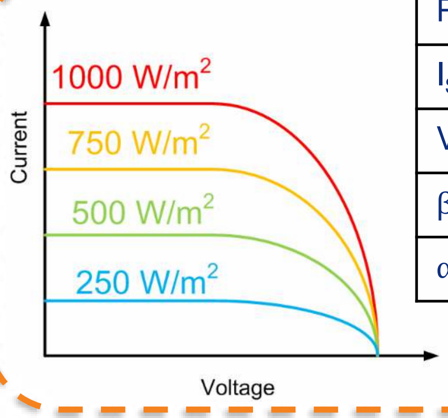
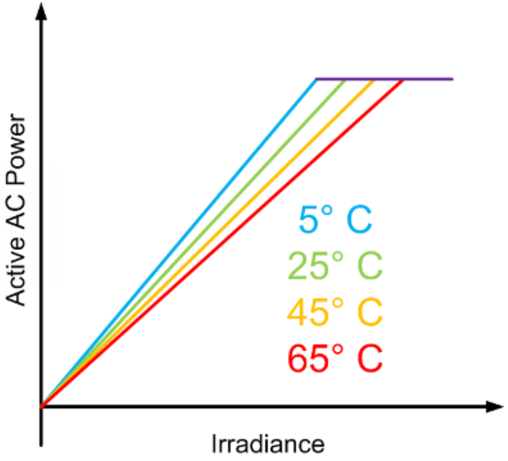
How can the model help industry?

- 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 conditions and metrics



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?



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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% of the reference power
  - MBE 0.68% of the reference power

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 in your favorite search engine

Thank you

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