SAND2020-9250C

Characterizing and Modeling AC PV Modules

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Technology Collaboration Programme
by iea

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

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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?
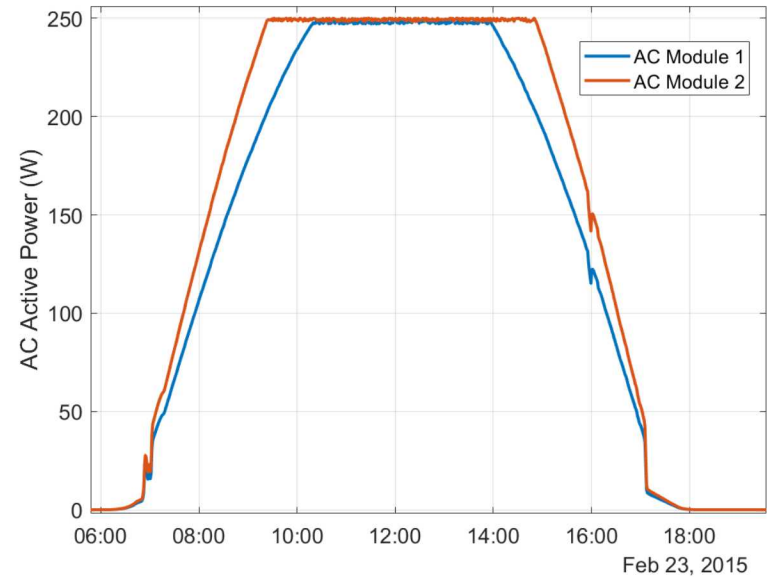

IV Curves vs. Irradiance (350W Module)

1000 W/m²
800 W/m²
600 W/m²
400 W/m²
200 W/m²
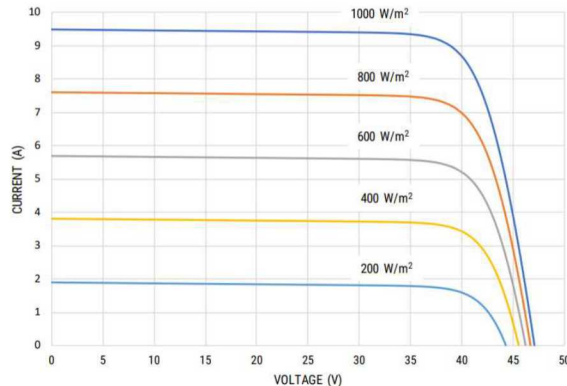
Temperature Coefficients(DC)	
NOCT	45 ± 2 °C
Pmpp	-0.41 %/°C
Voc	-0.29 %/°C
Isc	0.04 %/°C

Rated Voltage	Vmpp	40.5 V
Rated Current	Impp	5.93 A

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The Question for AC Modules

- How do we compare or describe the performance of AC modules?
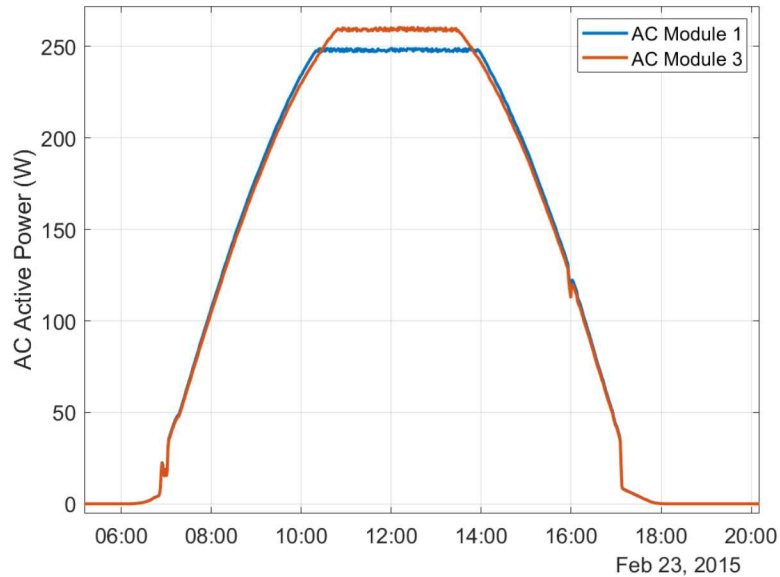
Sandia National Laboratories historical work
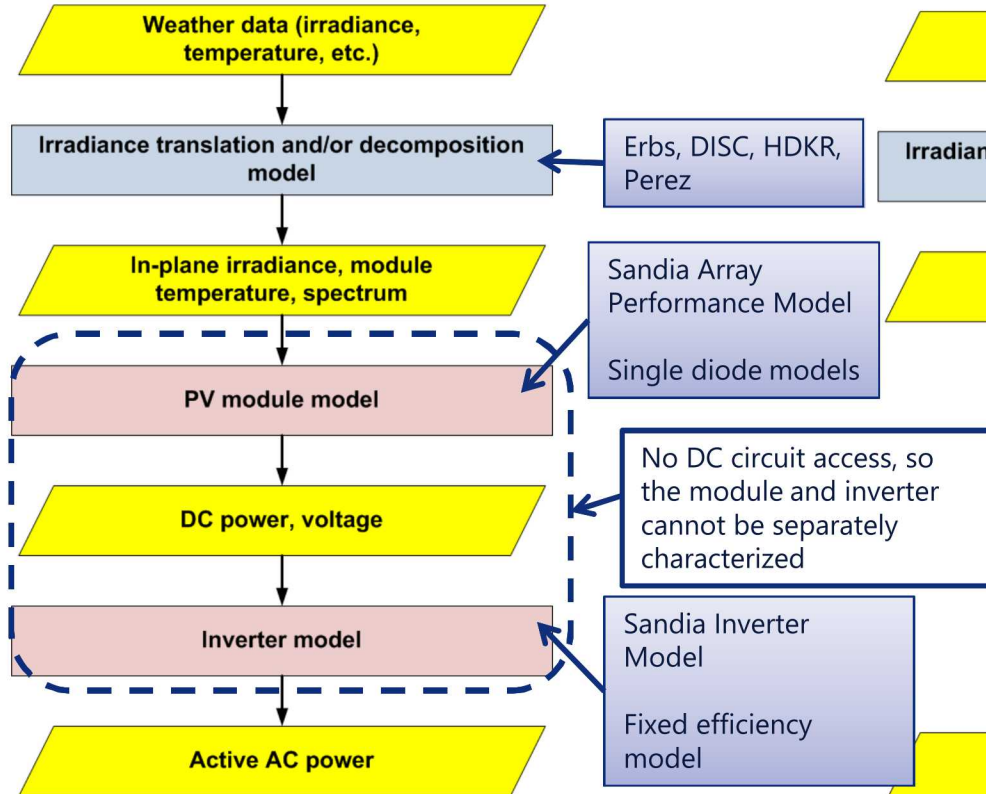
- In 2014 Sandia National Laboratories

  - 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
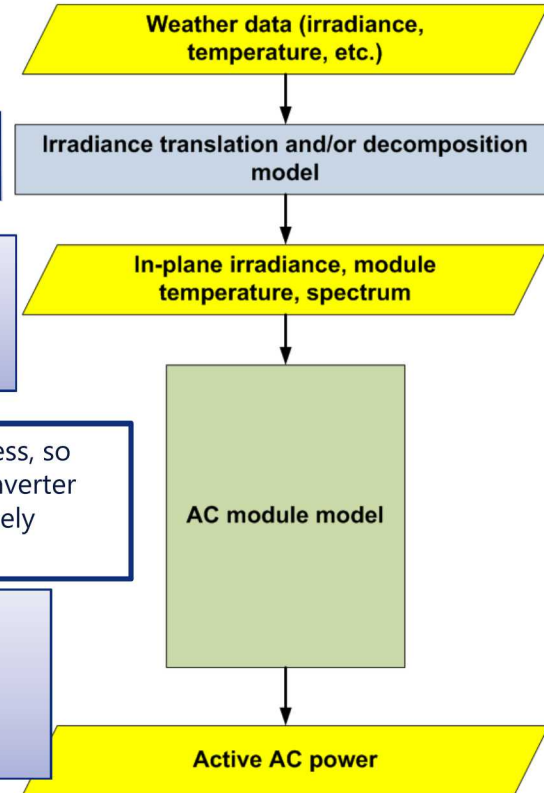
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PV Performance Modeling

Typical PV System

Weather data (irradiance, temperature, etc.)

↓

Irradiance translation and/or decomposition model ← Erbs, DISC, HDKR, Perez

↓

In-plane irradiance, module temperature, spectrum

↓

PV module model ← Sandia Array Performance Model / Single diode models

↓

DC power, voltage ← No DC circuit access, so the module and inverter cannot be separately characterized

↓

Inverter model ← Sandia Inverter Model / Fixed efficiency model

↓

Active AC power

AC Module System

Weather data (irradiance, temperature, etc.)

↓

Irradiance translation and/or decomposition model

↓

In-plane irradiance, module temperature, spectrum
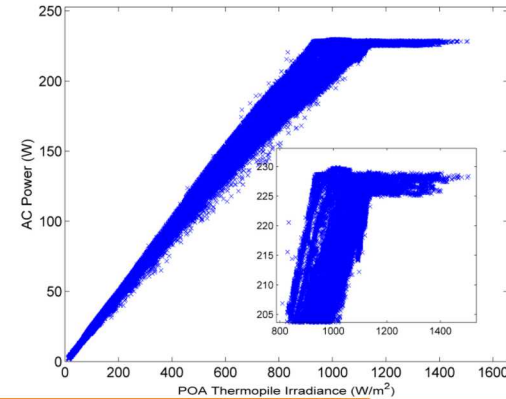
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AC module model

↓

Active AC power

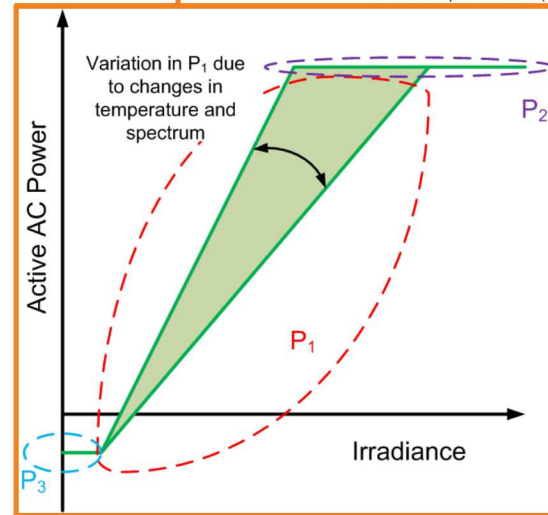PVPS

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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

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

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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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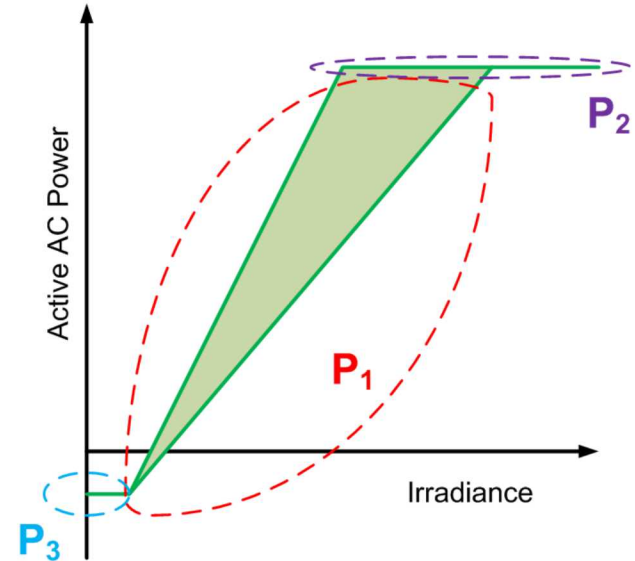
Equation Subdomains (continued)

- P_1 is a function of environmental conditions

$$P_1 = Pac_{ref} \times f_1\left(AMa - AMa_{ref}\right) \times \left[C_0 \times \frac{E_{POA}}{E_{ref}} + C_1 \times \ln\left(\frac{E_{POA}}{E_{ref}}\right)\right] \times \left[1 + \gamma_{ac}\left(T_c - T_0\right)\right]$$

  - 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/m²)
    - 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

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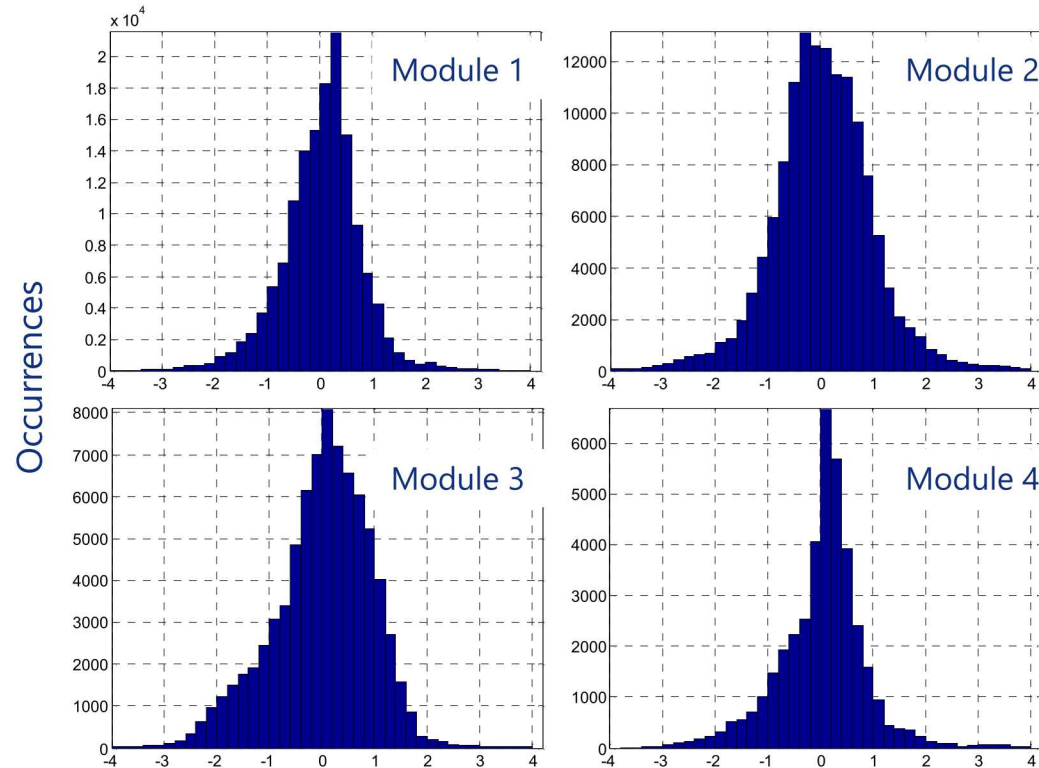
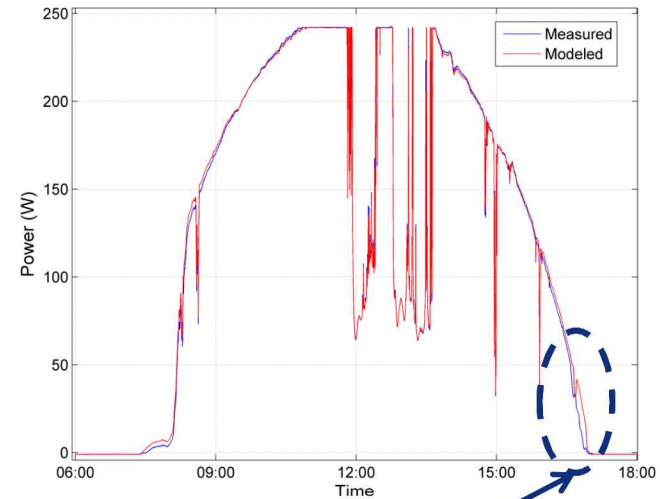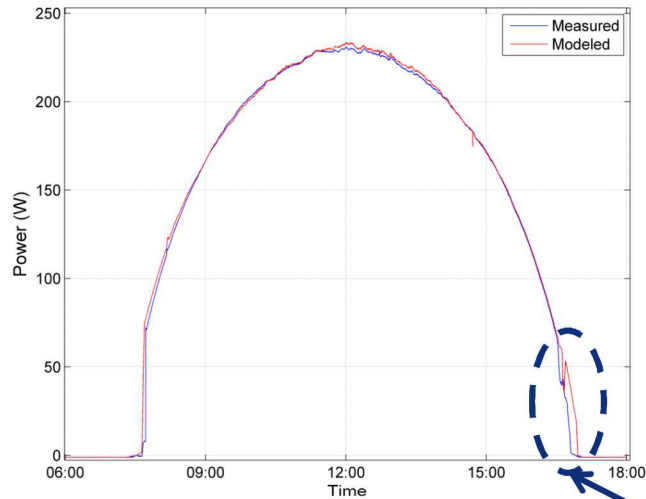$$\frac{Pac_{model} - Pac_{measure}}{Pac_{ref}} \times 100$$

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
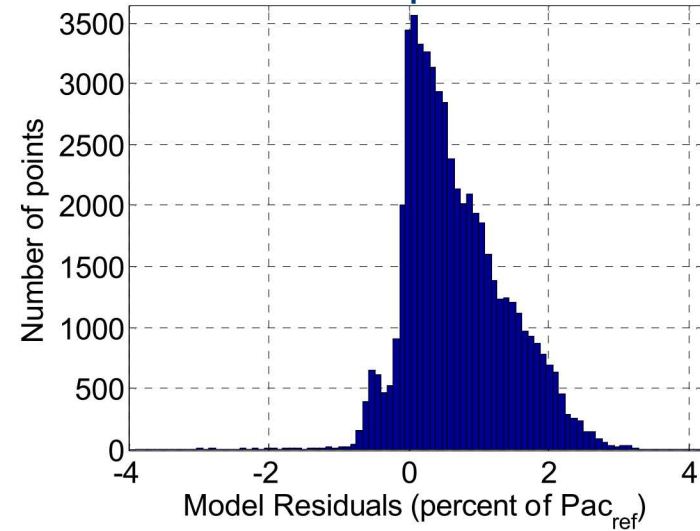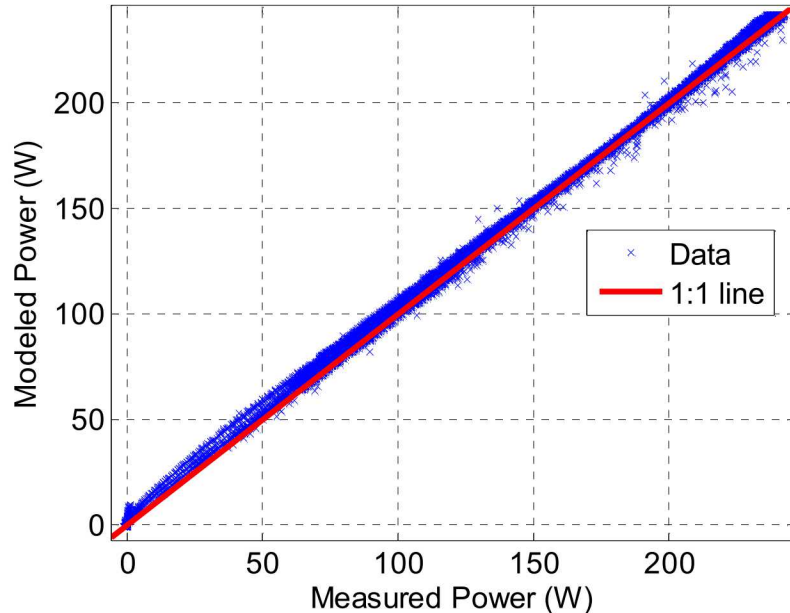
- Good transition to power limiting

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

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Model Errors for Typical Use – Fixed Tilt

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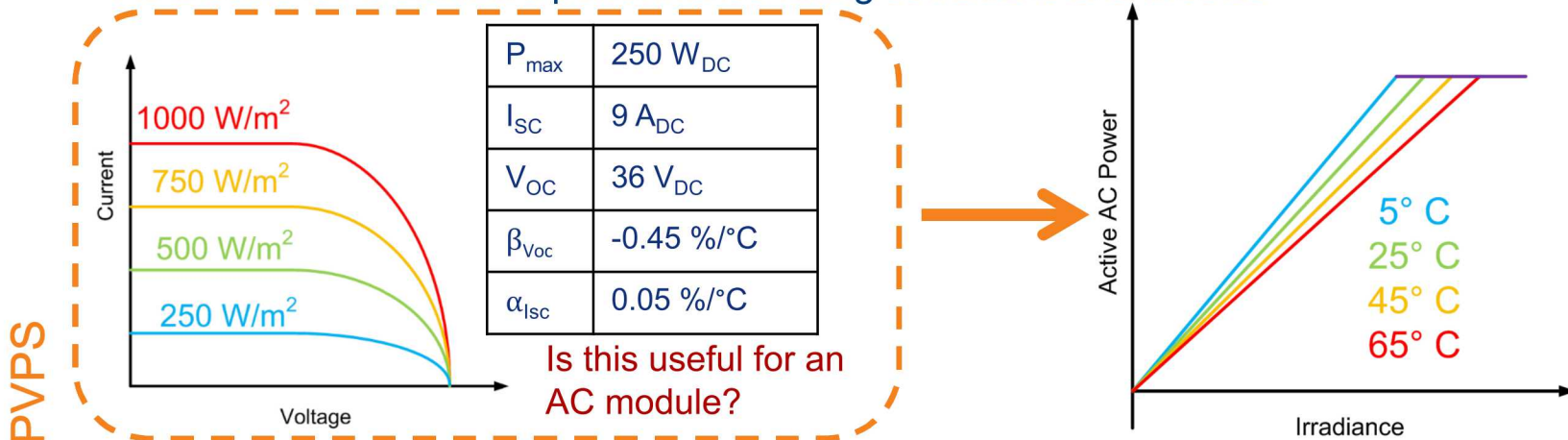
- Errors still mostly less than 2% of Pac_{ref}

	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?

5° C
25° C
45° C
65° C

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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

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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

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Thank you

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