SAND2014-19771PE

Exceptional service in the national interest

Sandia National Laboratories

Accuracy of Performance Predictions for PV Systems

IEA-PVPS Joint Tasks Workshop
China Hall of Science and Technology Beijing, China
November 30, 2014

Clifford Hansen
Sandia National Laboratories, New Mexico (USA)

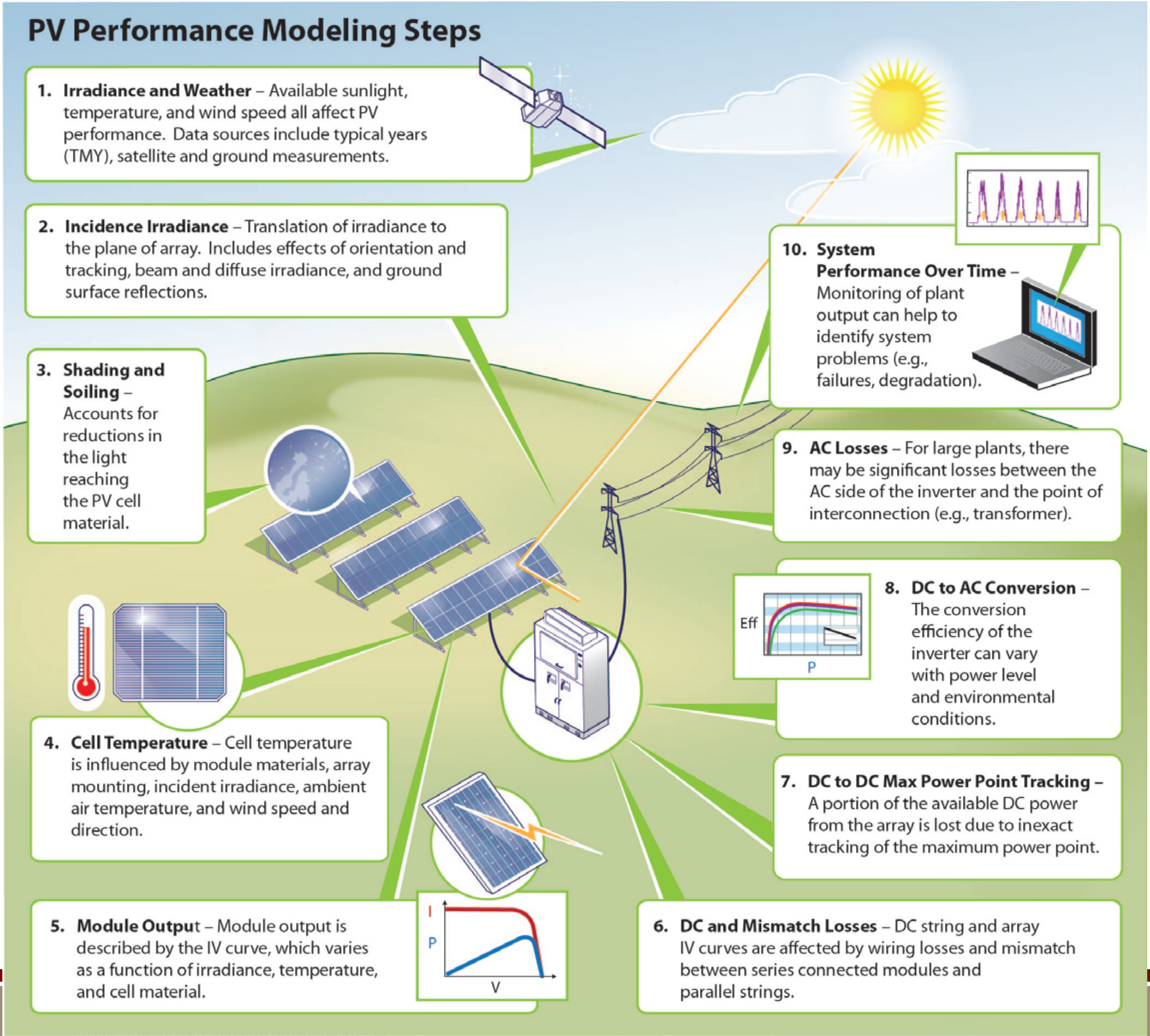
U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

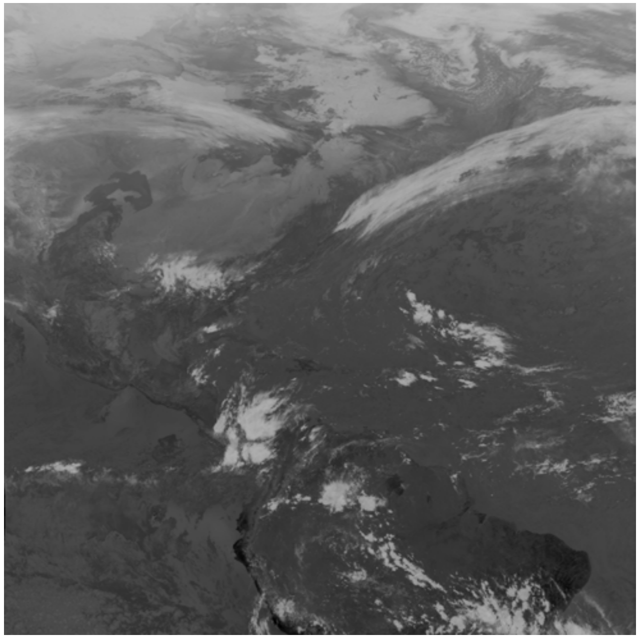
- Here, PV system performance refers to <u>power and energy output</u>
  - I am not addressing other aspects which may require modeling, e.g., electrical design and safety, longevity
- Modeling process
  - Data and models
  - Uncertainty in predictions and sources of uncertainty
- IEA Task 13 research

Overview of PV Modeling



Meteorological information

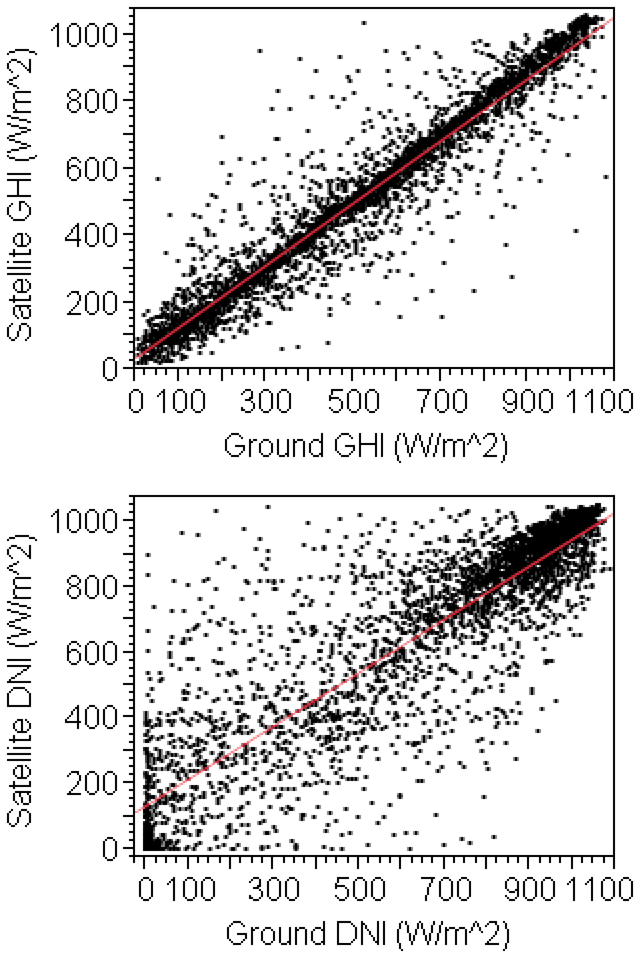
- **<u>Irradiance (GHI, DNI)</u>**
  - Satellite modeled ‘data’ : wide coverage, spatially and temporally coarse : ~1km^2 and 30 minutes
  - Ground measurements : short time intervals, spatially limited
  - Typical years (irradiance is mostly modeled from other measurements)
- Air temperature, ground wind speed
  - Ground measurements (nearby)
  - Weather models (often with satellite irradiance data)
- Snow/ice accumulation



Uncertainty in irradiance

- Greatest source of uncertainty in PV performance modeling
- Point in time (correlates with power)
  - Ground measurements :
    - +/– 2% (best case instruments)
    - +/– 5% (typical inexpensive instruments)
    - Data quality control and redundant sensors
    - Extend spatially for large plants?
  - Satellite sources :
    - +/–6% for GHI ??, worse for DNI (location dependent)
    - Spatial resolution more appropriate for large areas
- Time-averaged values (correlates with energy)
  - Bias is generally <1% for satellite, greater for ground instruments (instrument calibration)

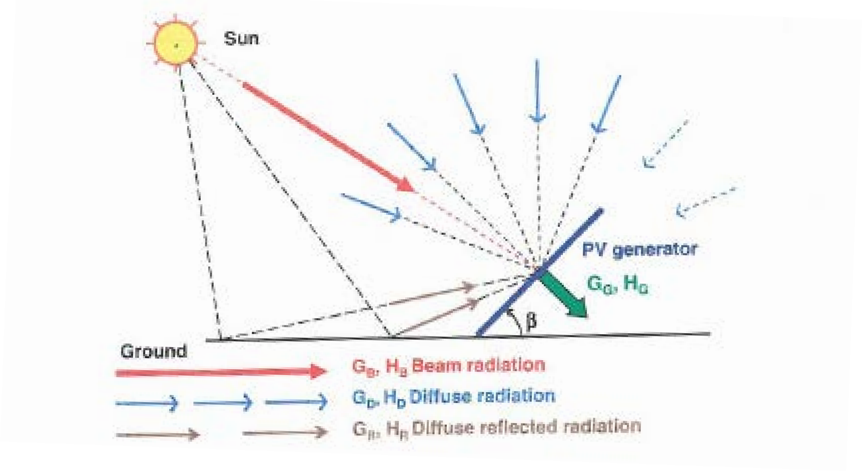
Satellite vs. ground irradiance values



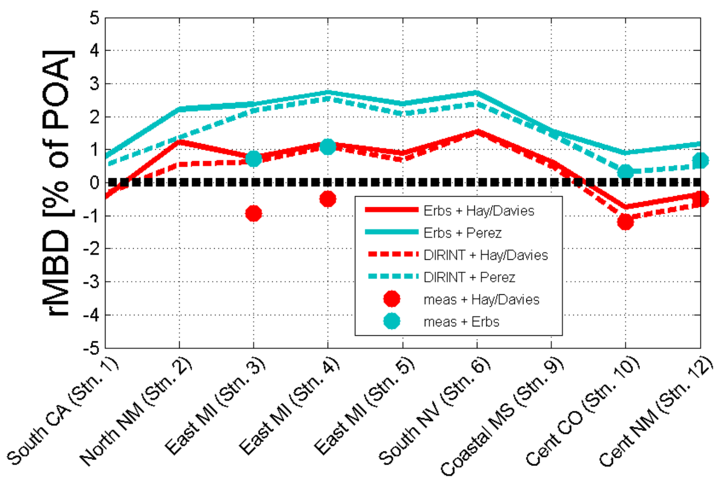
Source: Stein, 2010

Plane-of-array (POA) Irradiance

- Comprises Beam, Sky diffuse (circumsolar, horizon, rest of sky), and Ground reflections
- Translated from DNI and diffuse horizontal irradiance (DHI) by a transposition model
- If you only have GHI, decompose GHI to DNI and DHI with a decomposition model
  - From GHI, use Erbs + Hay/Davies
  - From measured DNI/DHI use Perez
- Uncertainty +/–2% for annual averages



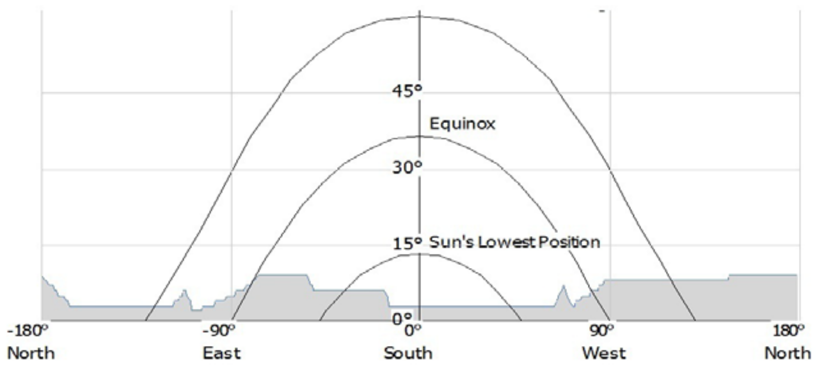
Source: Häberlin, 2012



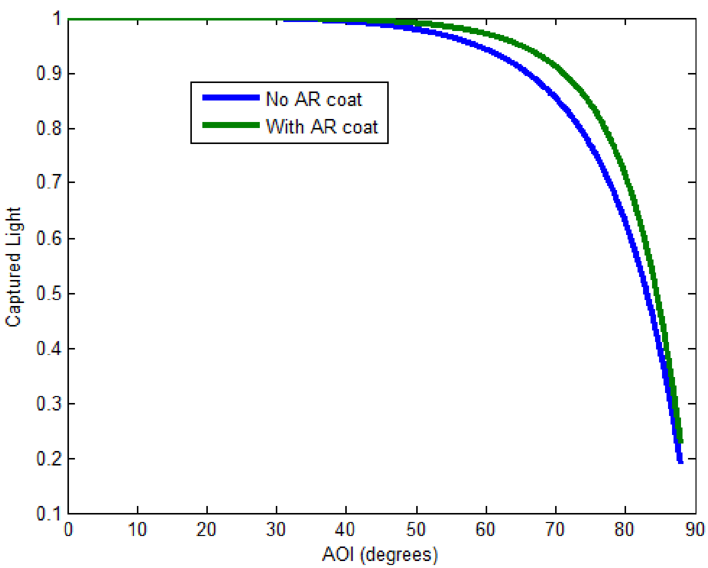
Source: Lave, 2014

Shading, Soiling, and Reflections

- Shading causes variation in array illumination
  - Small arrays (e.g., residential) shading may affect max. power point tracking
  - Large arrays are effective integrators – use average POA irradiance over the footprint
  - Effects are very site dependent; no general predictive models
- Soiling
  - Annual derate value
  - Very location dependent
  - No reliable predictive models
- Reflections
  - Generic reflection loss curve is usually acceptable



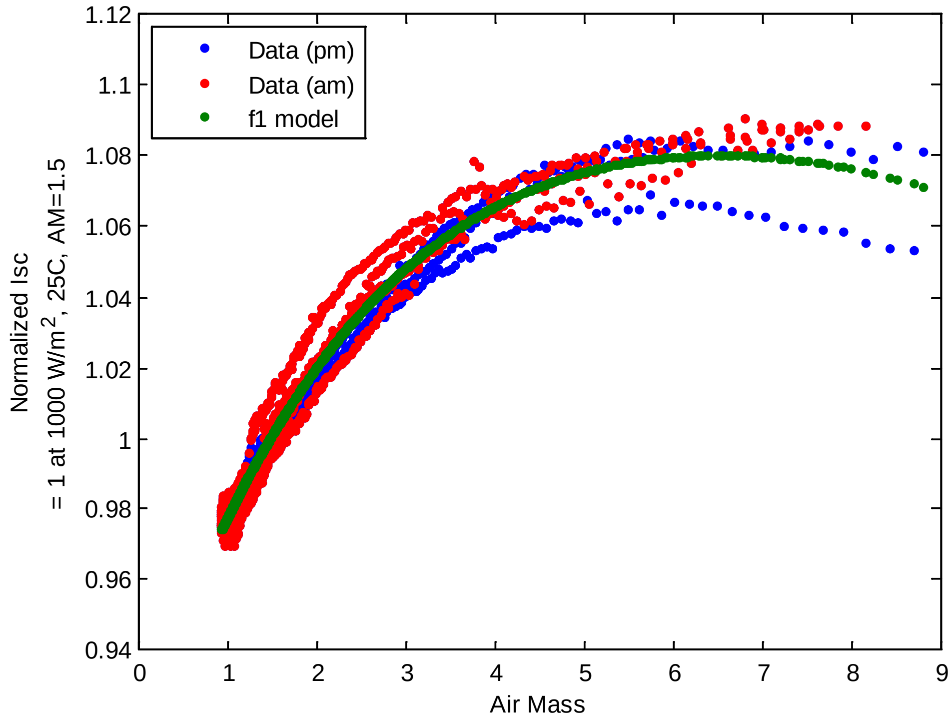
A 2D sunpath diagram in PV*SOL, with horizon data imported.



Source: King, 2004

Solar spectrum mismatch

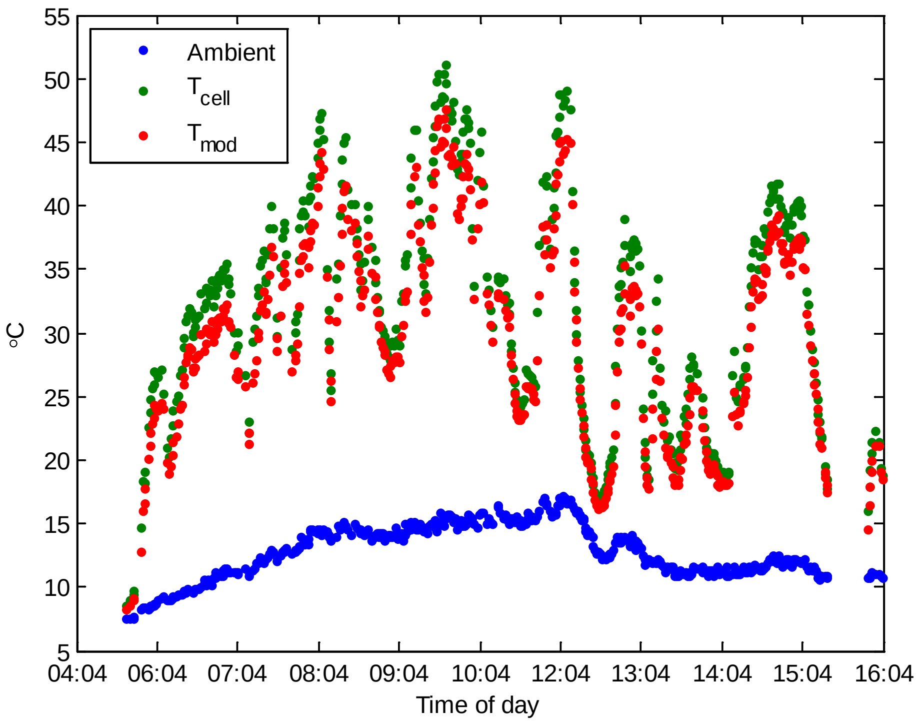
- Accounts for changing spectral content of light and quantum efficiency of cells
- Implemented in different ways
  - Most common, mismatch factor/function
  - E.g., polynomial in air mass
  - Less commonly, convolution of spectrum and quantum efficiency
- Variation in current up to 10%
- Point in time uncertainty typically +/–2%
- Time averaged values similar



Cell Temperature

- Power decreases with increasing cell temperature
  - –0.3 to -0.5 %/C (depends on cell tech., module materials)
- Cell temperature difficult to measure directly in situ
  - Cell temperature > ambient (~30C difference)
  - Cell temperature > back-of-module temperature (~1 – 4 C)
- Models tend to be simple

- Effect of <u>random</u> uncertainty in cell temperature is small, but
- Effect of <u>systematic</u> uncertainty can be significant in predicted energy



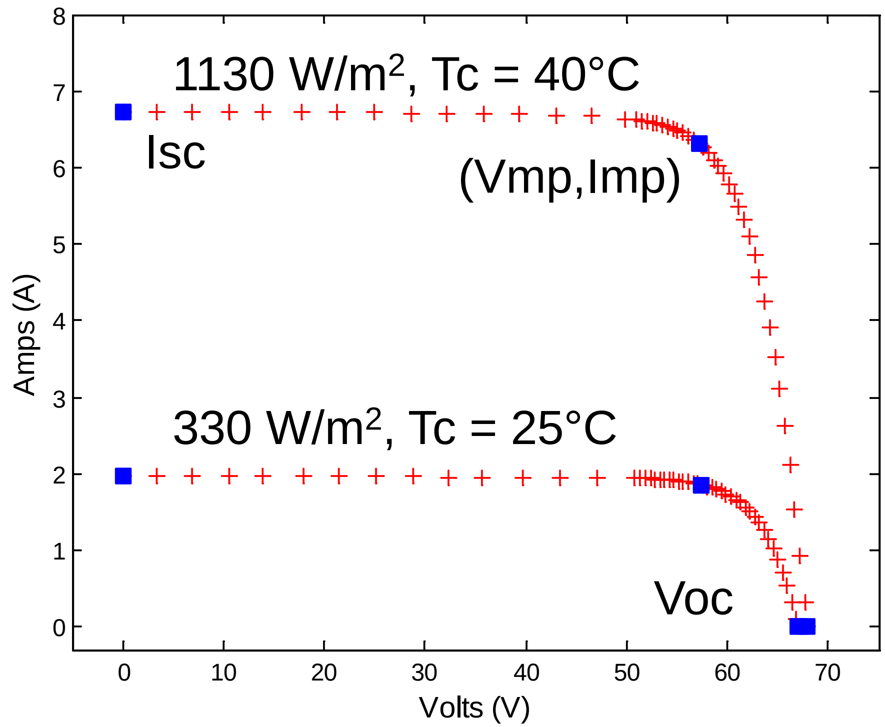
$$T_C = T_M + \frac{E}{E_0}\Delta T$$

$$= T_{amb} + \frac{E}{E_0}\exp\left(a + bWS\right) + \frac{E}{E_0}\Delta T$$

Source: King, 2004

Module Output

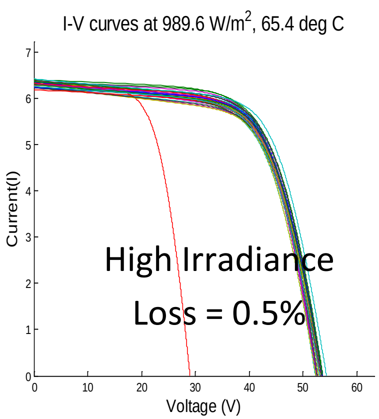
- Predict DC voltage and current over the range of POA irradiance and cell temperature
  - IV curve models (aka 'diode' models)
    - E.g., '5 parameter model', 'PVsyst', 'PV*SOL'
  - Point models
    - E.g., Sandia model
- Point in time accuracy +/–2%
- Time average uncertainty drops rapidly to zero for properly calibrated models
- There are less accurate models, e.g., PVWatts



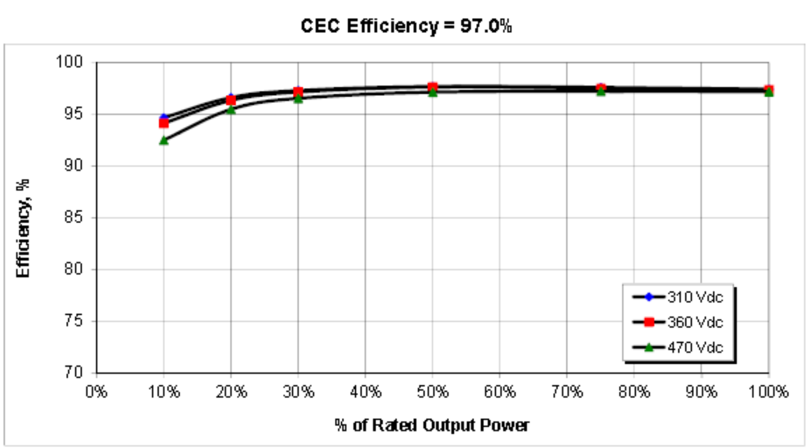
$$P_{dc} = \frac{I_{tr}}{1000} P_{dc0}(1 + \gamma(T_{cell} - T_{ref}))$$

Other models

- Module mismatch losses : ~1% for well-designed arrays
  - Even with substantial variation among modules over time
- Wiring losses : static engineering calculations
- MPPT tracking efficiency : model as a constant (very small loss)
  - Challenging measurement, inverter standards are evolving
- Inverter conversion efficiency : California Energy Commission (CEC) model is nearly universal
- Negligible uncertainty for all, relative to irradiance



Source: S. MacAlpine, 2012

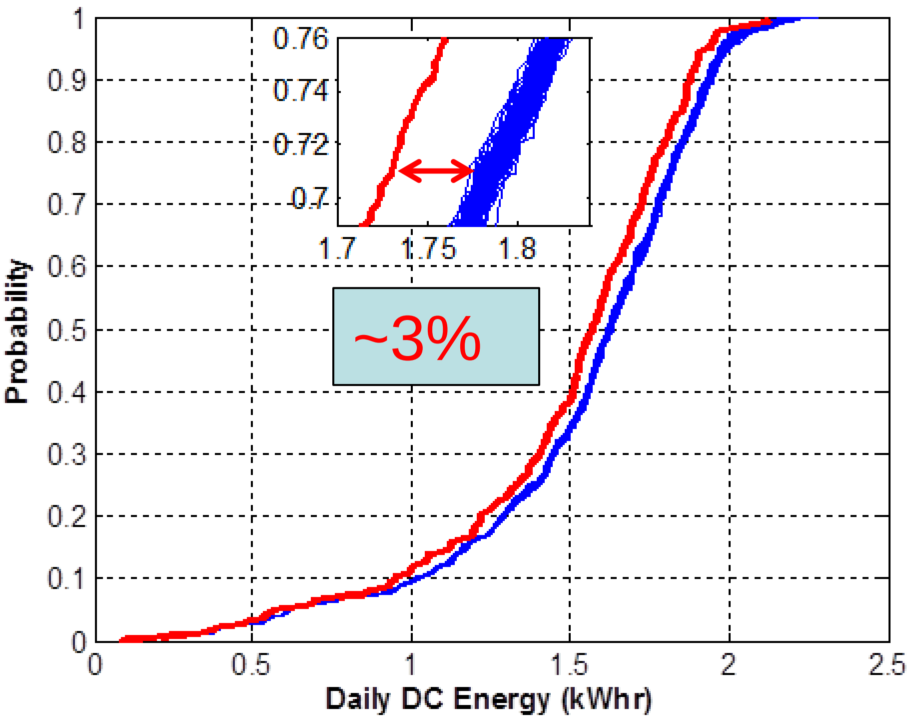


Example: Uncertainty in daily energy

- Analysis does NOT consider uncertainty in GHI/DNI/DHI values
- Uncertainty in each modeling step is quantified, propagated in a Monte Carlo procedure
- Blue curves are estimates of true but unknown value
- Red curve is 'baseline' model prediction

- **Shift indicates an overall bias toward overestimating energy from POA model uncertainty**
- **Small variation among blue curves – little effect from uncertainty in other models**

Distributions of daily energy: cSi module, isotropic sky model, Albuquerque data (other module, models, and data similar)



Source: Hansen, 2014

Summary of contributions to uncertainty in model predictions

Model Step	Point in time (Power)	Time averages (Energy)
Irradiance values	5 – 10 % depends on data source	0 – 5 % depends on data source
POA irradiance	+/– 5%	+/– 2%
Solar spectrum	+/– 3%	Unknown
Shading	Site and time dependent	Site dependent
Soiling	Site and time dependent	Site dependent
Reflections	Low	Low
Cell temperature	Smaller than module output	Low
Module output	+/– 2%	Approaches 0
Other models	Low	Low

Source: My Professional Judgment

Related IEA PVPS Task 13 Research

- Subtask 3.1: Effects of measurement uncertainty on model parameters and on module power ratings (Hansen, Sandia Nat'l Labs, USA and Dirnberger, Fraunhofer ISE, Germany)
- Subtask 2.3: Overall uncertainty framework for data acquisition and modeling (Reich, Fraunhofer ISE, Germany)
- Subtask 2.4: The PV Performance Modelling Collaborative www.pvpmc.org (Stein, Sandia Nat'l Labs)

References

Stein et al. (2010), Validation of PV Performance Models using Satellite-Based Measurements, Proc. of ASES National Solar Conference, 2010

Lave et al. (2014), Evaluation of GHI to POA Models at Locations across the United States, Proc. of the 40th IEEE PVSC, 2014

King et al. (2004), Photovoltaic Array Performance Model, Sandia National Laboratories SAND2004-3535

MacAlpine et al. (2012), Beyond the Module Model and Into the Array: Mismatch in Series Strings, Proc. of the 38th IEEE PVSC, 2012

Hansen et al. (2014), Which Models Matter: Uncertainty and Sensitivity Analysis for Photovoltaic Power Systems, Proc. of the 40th IEEE PVSC, 2014

Thank you