SAND2013-4151P

Exceptional service in the national interest

Sandia National Laboratories

Irradiance and Solar Plant Variability Modeling

Sandia/CanmetENERGY Collaboration

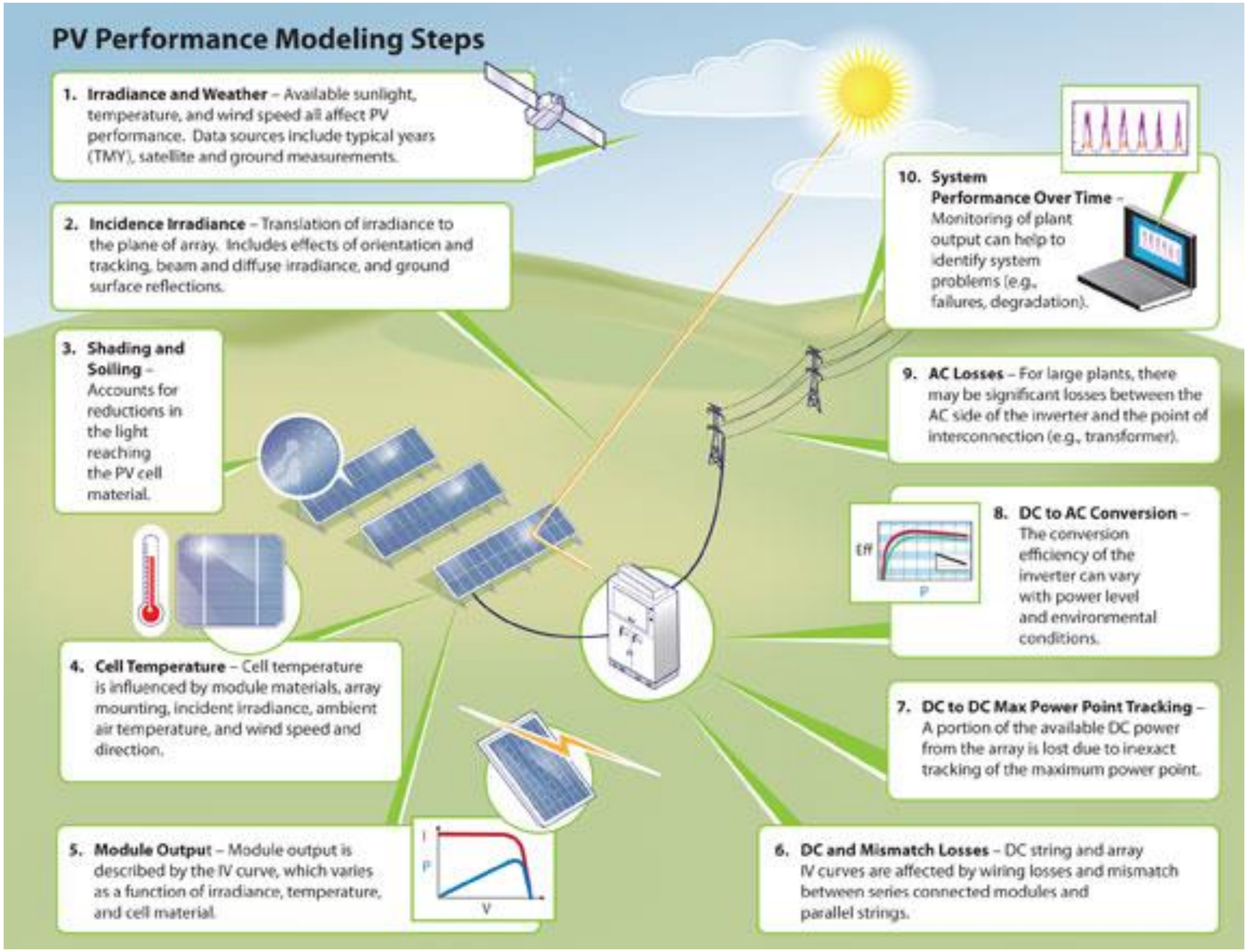
Thursday, May 2, 2013

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.

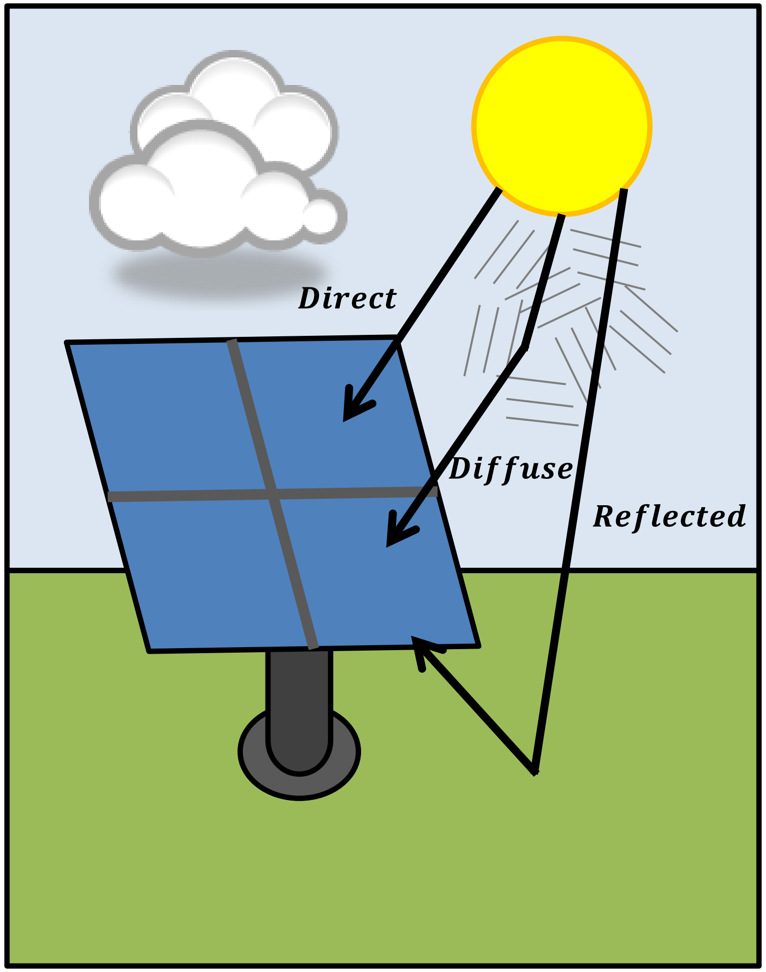
Modeling A PV Plant End to End



For more information on Sandia PV performance modeling, visit **pvpmc.org**

Modeling Irradiance Part of Process

- Global Horizontal Irradiance (GHI): GHI = direct horizontal + diffuse horizontal irradiance
- Plane of Array Irradiance (POA): POA = direct + diffuse + reflected irradiance incident on the plane
- Direct Normal Irradiance (DNI): direct irradiance when plane is pointing directly at the sun (i.e., 2-axis tracker)

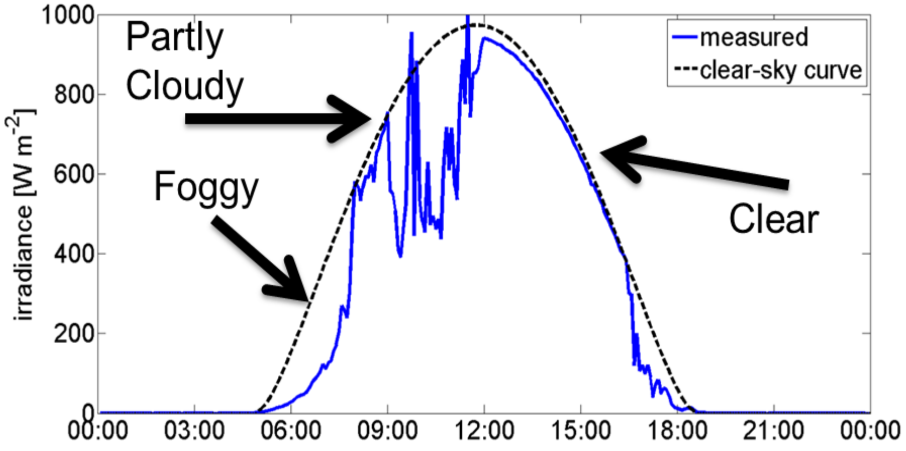


Irradiance Variability Characteristics

- Variability refers to change from one time interval to another, and the result is interval-specific (sec-by-sec is vastly different than hr-by-hr)
- Clear-sky irradiance curve can be determined based on solar angles and aerosol estimates, then used to classify states:
  - Clear: irradiance follows clear-sky curve
  - Cloudy/Foggy/Rainy: irradiance consistently less than clear-sky curve
  - Partly Cloudy: irradiance fluctuates significantly
- One of many way to measure irradiance variability: Variability Index (VI)

$$VI = \frac{\sum_{k=2}^{n} \sqrt{(GHI_k - GHI_{k-1})^2 + \Delta t^2}}{\sum_{k=2}^{n} \sqrt{(CSI_k - CSI_{k-1})^2 + \Delta t^2}}$$

  - Clear: $VI < 2$
  - Variable: $5 < VI < 10$
  - Highly Variable: $VI > 10$

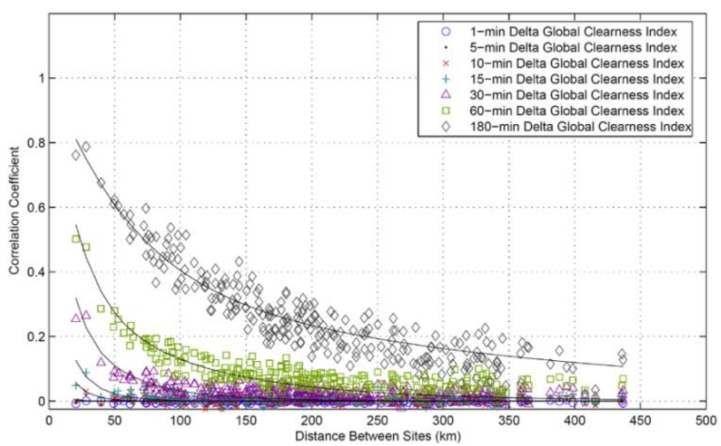


Ref: "The Variability Index: A new and Novel Metric for Quantifying Irradiance and PV Output Variability", by Stein, Hansen and Reno, Presented at 2012 ASES conference.

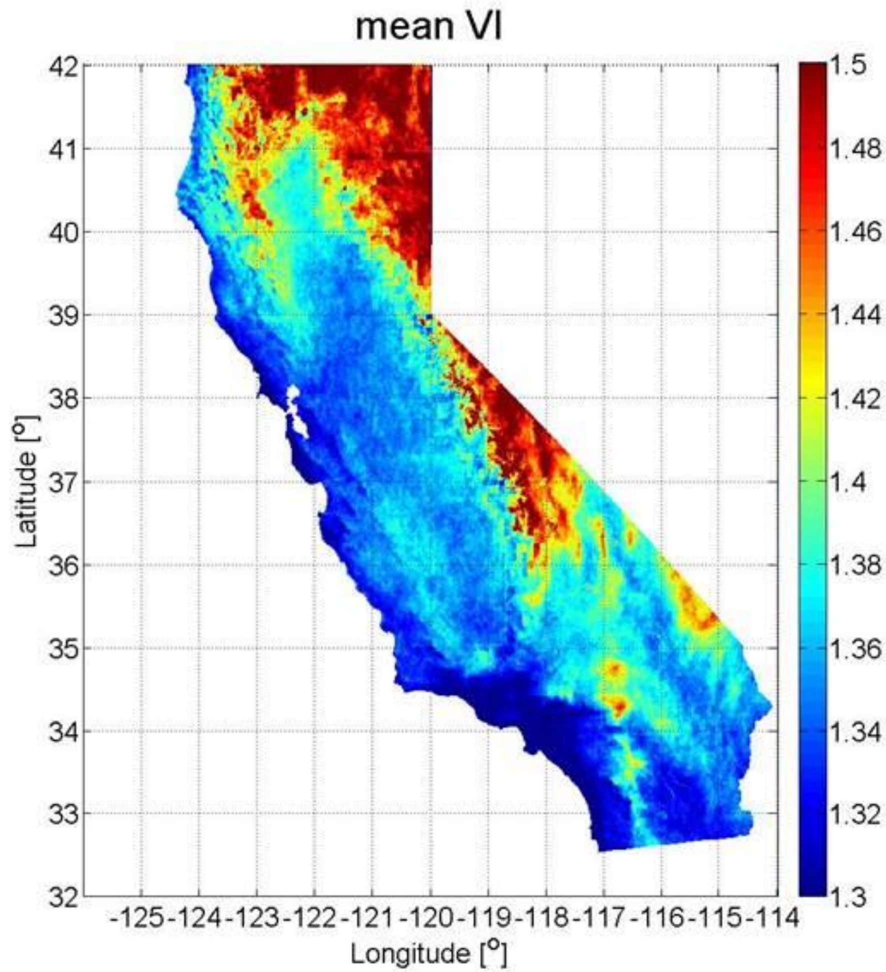
Irradiance Variability by Location

Sandia National Laboratories

- Example: map of the mean variability index for the state of California (based on the Solar Anywhere 1km/30-min satellite data).
- Statistical correlation over large scales



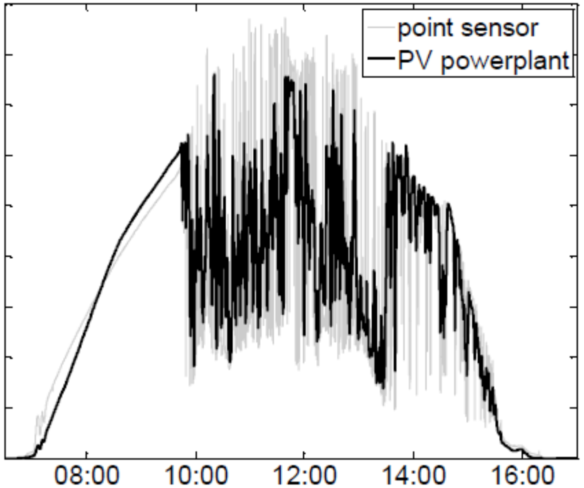
Ref: "Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System," by A. Mills et al, 2009.



Ref: M. Lave, 2012 (unpublished)

Power Versus Irradiance

- For grid studies, power output characteristics are what matter
  - Ramp rate ($\Delta P/\Delta t$) statistics are of interest
  - Choose time interval based on the application!
- Power output ≠ point sensor irradiance
  - Large plant footprint, tracking system, DC/AC ratio
  - Difference is larger if we are interested in short time frames (e.g. sub-minute)
- First approximation for high resolution (≤1 min): Plant-averaged irradiance and plant power output are nearly proportional



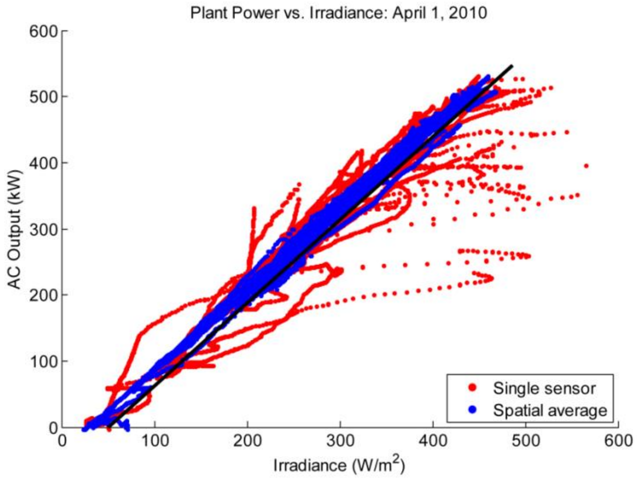


Figure 2. Relationship between irradiance and AC power from the entire La Ola plant for April 1, 2010, a partly cloudy day.

Ref: "Lanai Hig-Density Irradiance Sensor Network for Characterizing Solar Resource Variability at a MW-Scale PV System", by Kuszamaul, Ellis, Stein, and Johnson, presented at 2010 IEEE PVSC Conference in Honolulu, HI

Simulated Solar Data Requirements

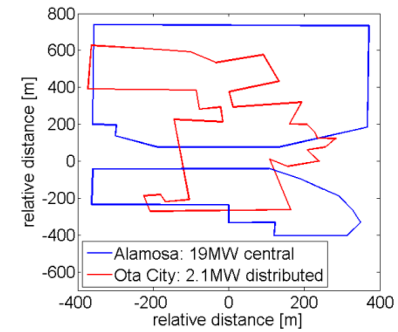
Sandia National Laboratories

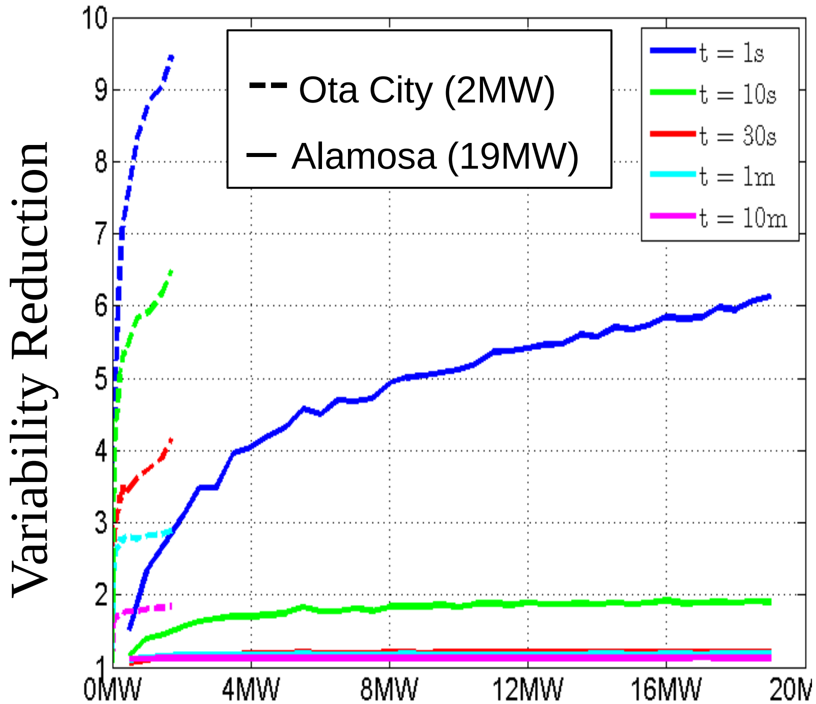
- Generally, power (not irradiance) data for a single plant of a fleet of plants is needed for grid integration analysis
- Type of data depends on the application

Application	Attributes of interest	Resolution	How much data
Flicker and power quality	Fast changes and their frequency	<1 sec	Representative periods (hrs?)
Local voltage impacts such as voltage regulation and frequency impacts (island grids)	Largest ramps	1 sec	Several sample days
Distribution feeder voltage control and LTC/VR impacts	Sample variability pattern time synchronized	1 sec	Several sample days for each season
High load / low load voltage profile along distribution feeder	Sample of daily/seasonal profile, time synchronized	1-15 min	Representative season
Integration cost, including reserves calculation for a BA	Power and forecast time series, time synchronized	1-15 min	1 year, multiple locations
Capacity value calculation	Sample daily/seasonal profile, time synchronized	15-30 min	1 year
Energy production	Seasonal pattern	1 hr	1 year

Variability as Function of Plant Size

- Variability Reduction (VR) = $\frac{Variability_{point\ sensor}}{Variability_{whole\ plant}}$
- Large values indicate larger reductions in variability.
- VR = 1 means no smoothing.





Variability Reduction depends on:

1) **Geographic diversity of the plant**

Both an increase in area and a decrease in density (GCR) can reduce the relative variability.

2) **Daily meteorological conditions (i.e., cloud speed)**

Variations in the spatial correlations of clouds lead to different reductions in variability on different days.

Ref: "Analyzing and Simulating the Reduction in PV Powerplant Variability Due to Geographic Smoothing in Ota City, Japan and Alamosa, CO," by Lave, Stein, and Ellis, Presented at 2012 IEEE PVSC Conference, Austin, TX

How to Model Plant Output

Proxy Plant

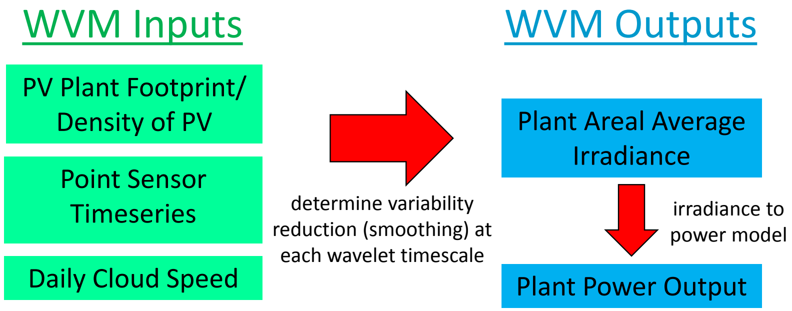
Plant output data is hard to find! If available, measured data from one location and apply to the location of interest.

Start from Satellite Data

Satellite data is low temporal/spatial resolution. Need to model sub-hour characteristics statistically (e.g., SolarAnywhere)

Start from Measured Irradiance

High temporal resolution irradiance is commonly available. Need way to systematically translate to power output (e.g., Lave's Sandia/UCSD WVM)



Wavelet Variability Model

Sandia National Laboratories

WVM Inputs

PV Plant Footprint/ Density of PV

Point Sensor Timeseries

Daily Cloud Speed

determine variability reduction (smoothing) at each wavelet timescale

WVM Outputs

Plant Areal Average Irradiance

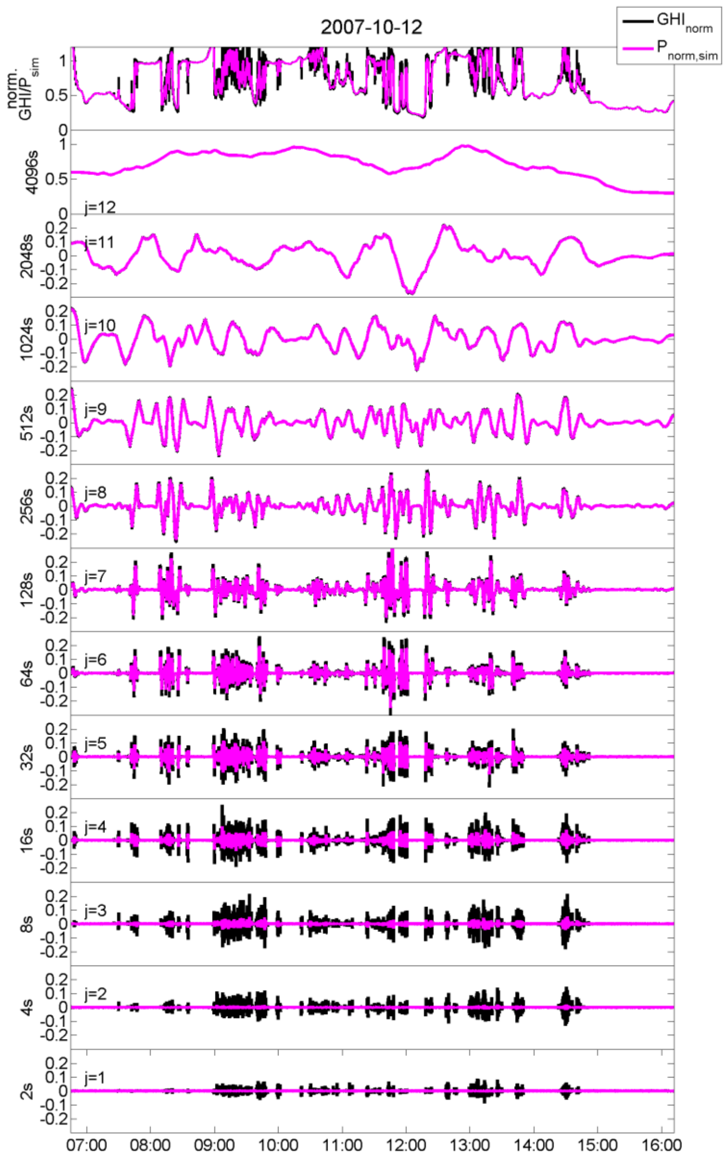
irradiance to power model

Plant Power Output

Ref: "A Wavelet-based Variability Model (WVM) for Solar PV Power Plants", by Lave, Kleissl and Stein

Running the WVM

Sandia National Laboratories

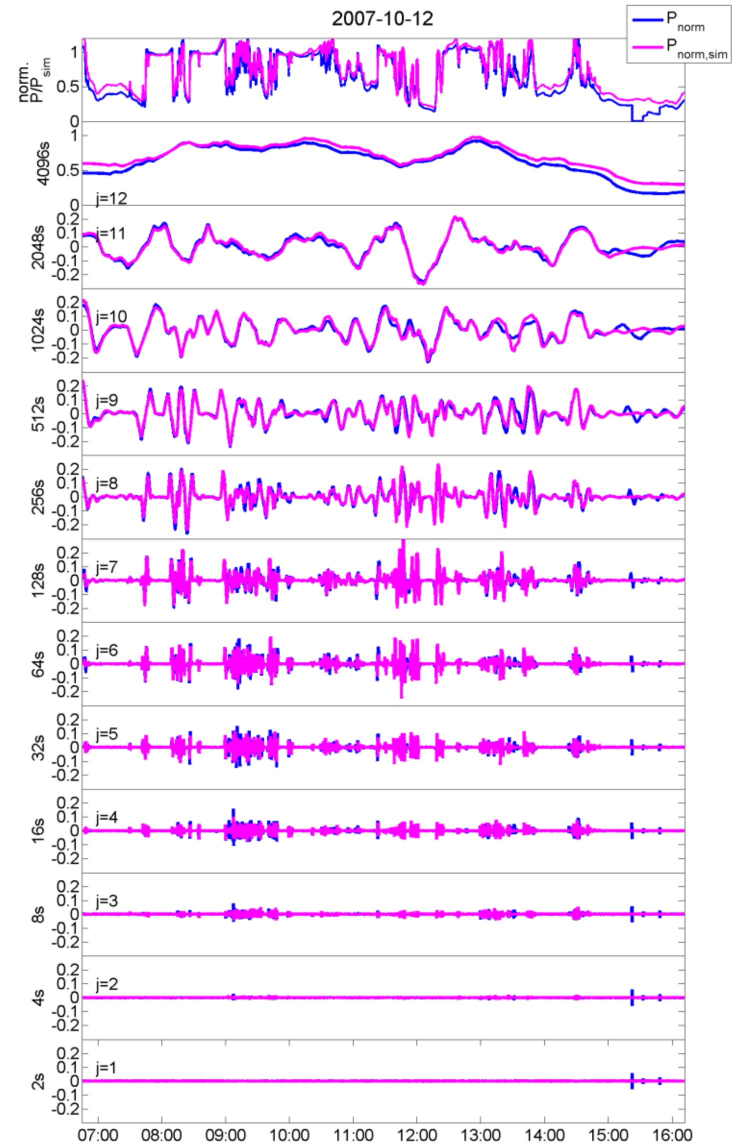


Ota City

Simulated wavelet modes (magenta) derived from GHI wavelet modes (black) by scaling based on simulated VR

Compare well with wavelet modes of the actual power output (blue) of all of Ota City

Ref: "A Wavelet-based Variability Model (WVM) for Solar PV Power Plants", by Lave, Kleissl and Stein



Determining the Variability Reduction

- The Variability Reduction (VR) can be modeled based on correlations between N PV sites (i.e., between N houses or between N sufficiently small groups of PV modules)

$$\mathrm{VR}(\bar{t}) = \frac{\mathrm{N}^2}{\sum_{\mathrm{m}=1}^{\mathrm{N}} \sum_{\mathrm{n}=1}^{\mathrm{N}} \rho(d_{m,n}, \bar{t})}$$

- Correlation equation is dependent on the ratio of distance between two sites to the timescale of interest and the cloud speed

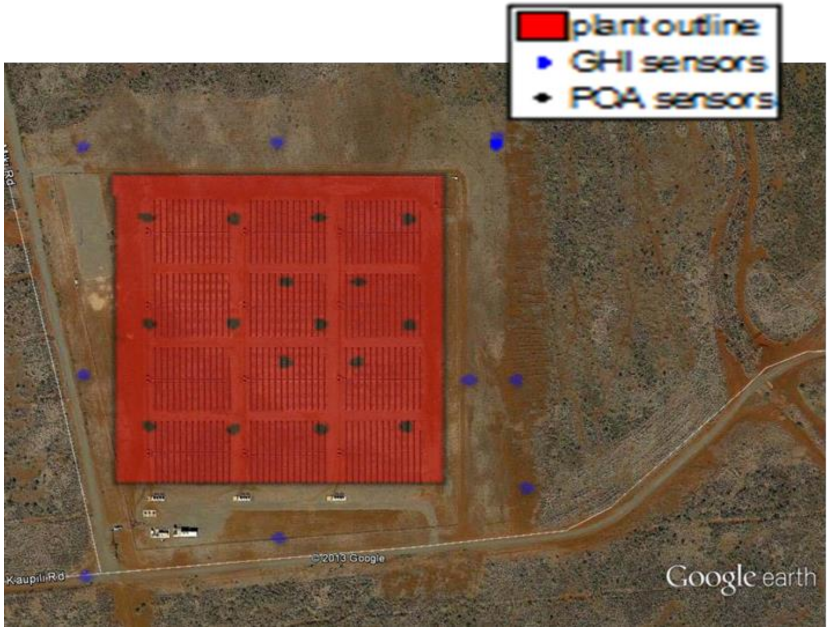
$$\rho(d_{m,n}, \bar{t}) = \exp\left(-\frac{d_{m,n}}{\frac{1}{2} CS\, \bar{t}}\right)$$

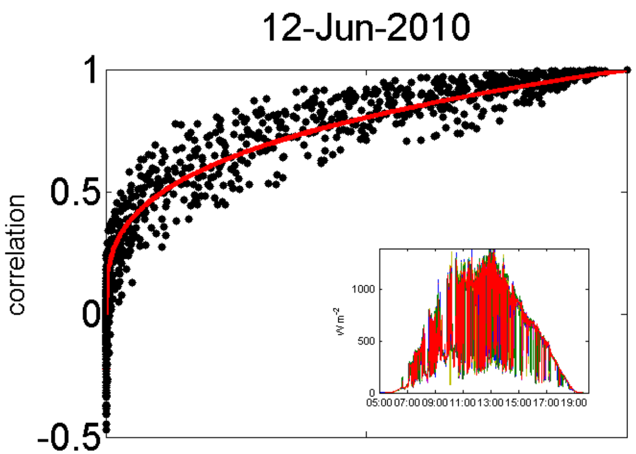
  - $d_{m,n}$ is distance between two sites, m and n, and $\bar{t}$ is the timescale
  - $\rho = 0$ when $d_{m,n}$ is very large or $\bar{t}$ is very small
  - $\rho = 1$ when $d_{m,n}$ is very small or $\bar{t}$ is very large

- Cloud speed (CS) varies from day to day

Ref: "A Wavelet-based Variability Model (WVM) for Solar PV Power Plants", by Lave, Kleissl and Stein

Irradiance sensor network for CS





Best to determine CS from an irradiance sensor network:

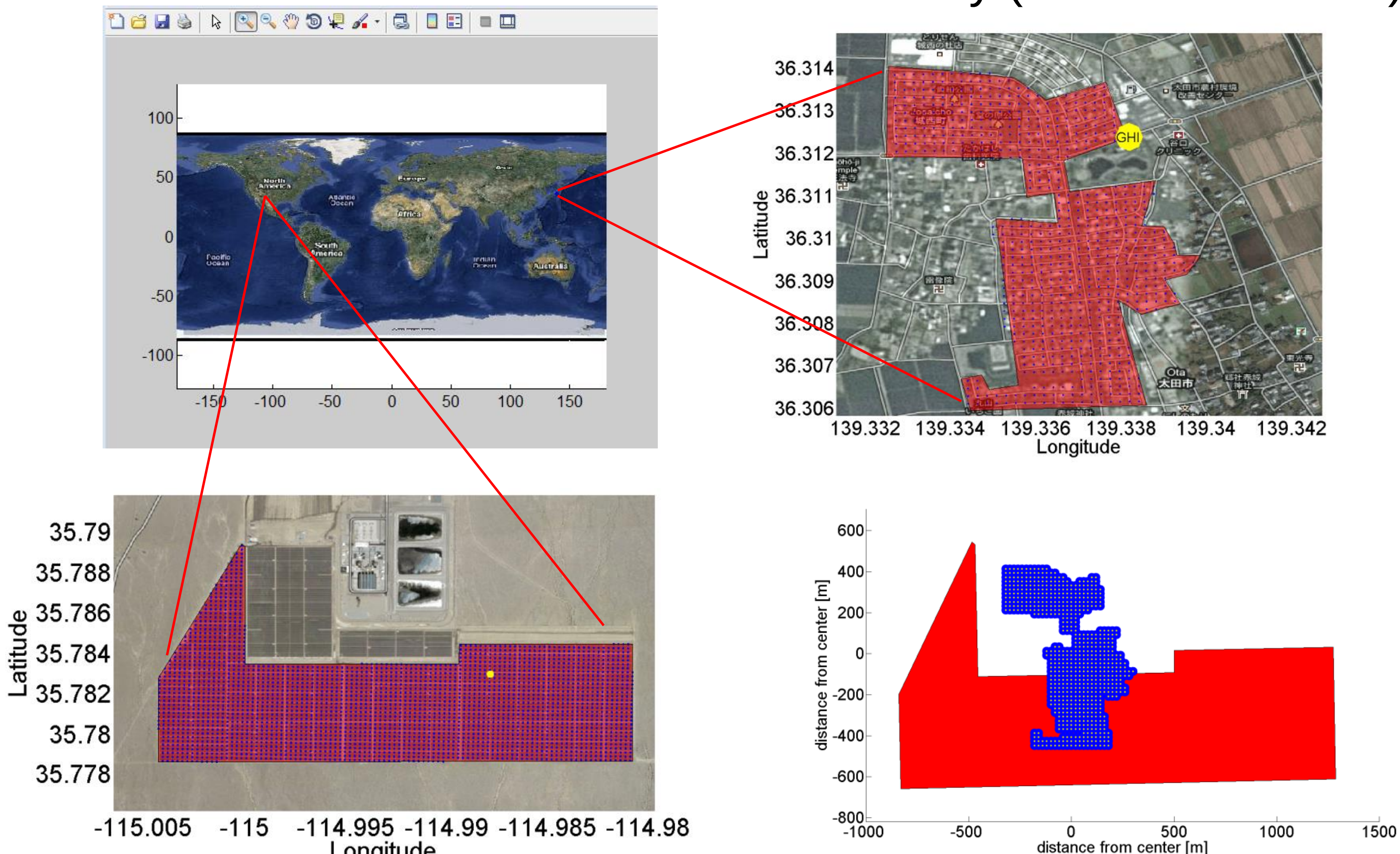
- Can determine correlations between wavelet modes at each sensor pair (black dots).
- Best fit (red line) determines the empirical cloud speed.

If no irradiance sensor network, can also determine cloud speed from numerical/satellite data.

Input: PV Footprint

- Input area of interest by drawing one or many polygons on a Google Map

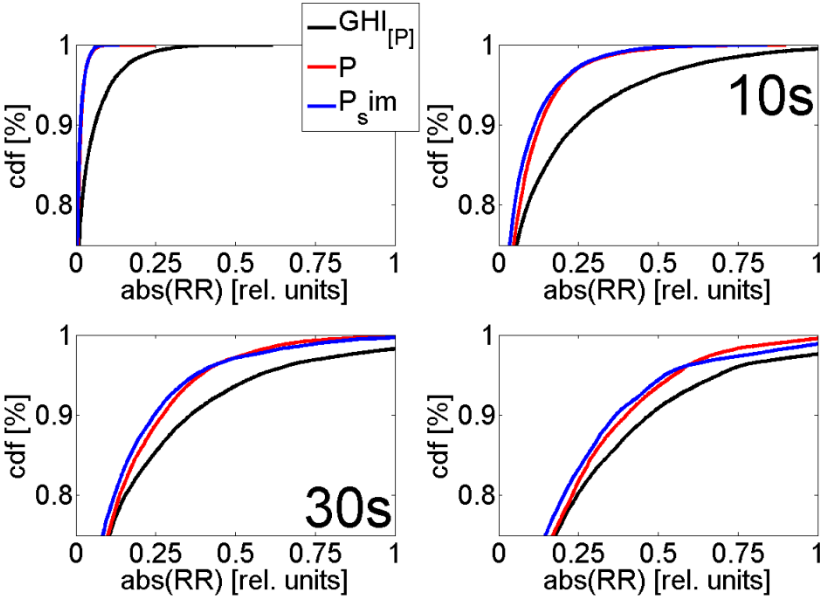
Ota City (2 MW distributed)



Copper Mountain (48 MW plant)

scale comparison

Compare Ramp Rates



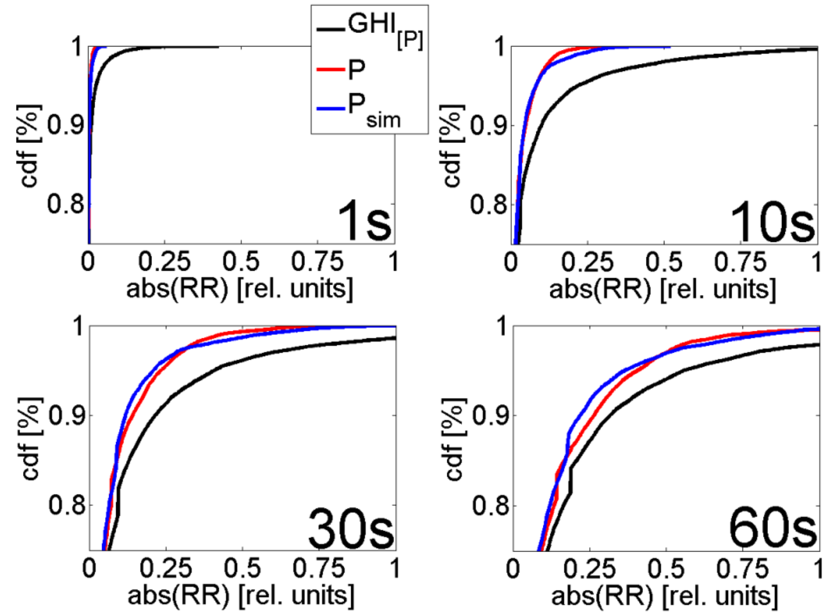
Ota City

The WVM simulation is much better at matching RRs than GHI at short timescales.

For Ota City: through 30s.
For Copper Mountain: through 60s.

Simulated RRs (blue) compare well to actual power RRs (red) at all timescales.

Copper Mountain

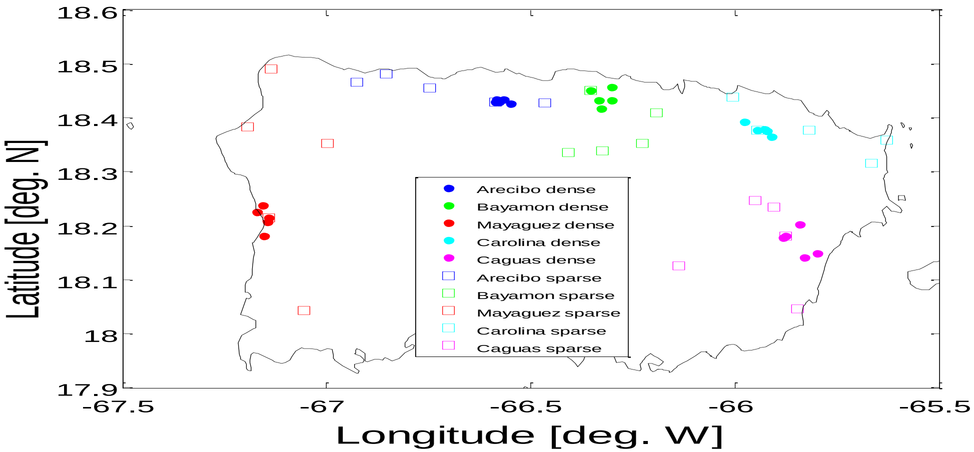


Ref: "Analyzing and Simulating the Reduction in PV Powerplant Variability Due to Geographic Smoothing in Ota City, Japan and Alamosa, CO," by Lave, Stein, and Ellis, Presented at 2012 IEEE PVSC Conference, Austin, TX

An Example of WVM Application

Simulated PV Ramp Rates in Puerto Rico

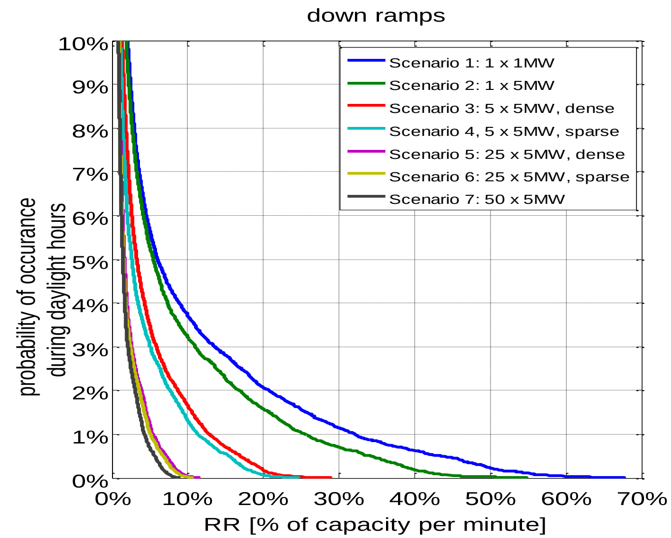
Prepared by Matthew Lave[1,2], Jan Kleissl[1], and Abraham Ellis[2]
[1] University of California, San Diego
[2] Sandia National Laboratories



probability of down ramp exceeding 10% per minute						
Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
3.72%	3.22%	1.64%	1.32%	0.04%	0.01%	0.00%

Scenarios

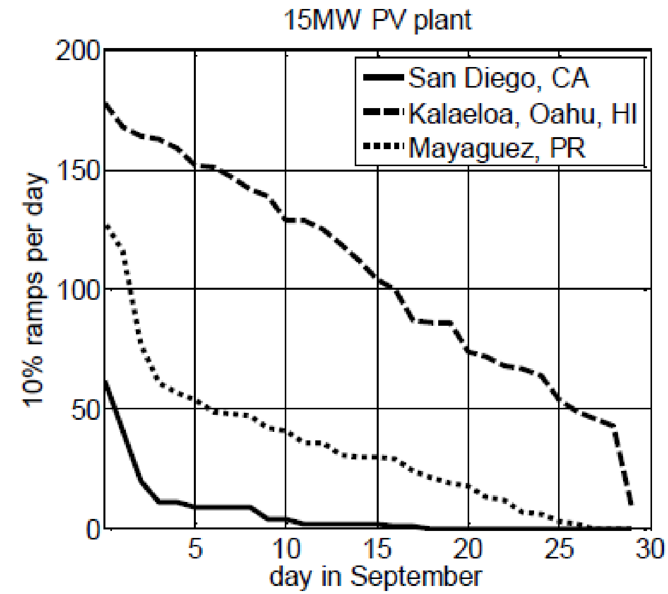
1. 1MW: 1 x 1MW plant
2. 5MW: 1 x 5MW plant
3. 25MW: 5 x 5MW plants in dense clusters
4. 25MW: 5 x 5MW plants in sparse clusters
5. 125MW: 25 x 5MW plants in 5 dense clusters
6. 125MW: 25 x 5MW plants in 5 sparse clusters
7. 250MW: 50 x 5MW plants in 5 dense and 5 sparse clusters

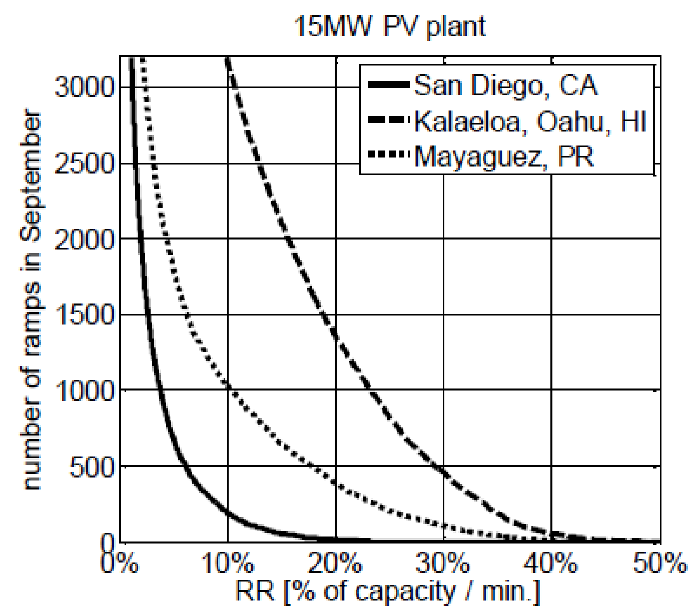


Ref: "Simulated PV Powerplant Variability: Impact of Utility-imposed Ramp Limitations in Puerto Rico", by Lave, Kleissl, Ellis, and Mejia, to be presented in the 2013 IEEE PVSC conference in Tampa, FL.

WVM Applications

- Comparison of variability characteristics for different locations
  - Top: Distributions showing how many days per month each number of RRs greater than 10% of capacity per minute will occur for WVM simulated 15MW PV powerplants in three locations
  - Bottom: Number of large 1-minute RRs in September for WVM simulated 15MW PV powerplants in three locations





These figures are material from a book chapter "Quantifying and Simulating Solar Power Plant Variability Using Irradiance Data" by Lave, Kleissl and Stein, to appear in book currently in preparation.

Contact Information

- Abraham Ellis, aellis@sandia.gov
- Matthew Lave, mlave@sandia.gov