Geographic Smoothing of Irradiance

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Solar Variability and Smoothing

Solar irradiance is variable due to:

- **Long-timescale**
  - Movement of sun through the sky
  - Seasonal changes: length of day, composition of clear atmosphere, etc.

- **Short-timescale**
  - Cloud shadows passing over PV modules

Two types of variability smoothing:

- **Smoothing due to spatial diversity**
  - Short-distance (< a few kms), short timescale smoothing due to different incidence times of cloud shadows.
  - E.g., smoothing within a PV plant.

- **Smoothing due to geographic diversity**
  - Long-distance (10s to 100s of km), all timescale smoothing due to different cloud patterns at different locations.
  - E.g. smoothing when aggregating multiple PV plants many miles apart.
Impact of Solar Variability

Spatial Diversity:

- Small impact on annual energy estimates for PV plants.
  - When averaged over 1-year, little spatial variation in energy.
- Large impact on short-timescale (e.g., <1-hour) ramp rate estimates.
  - Affect interconnection decisions such as storage sizing, especially in locations with utility imposed RR restrictions such as Puerto Rico.\(^1\)

Geographic Diversity:

- For annual energy estimates, must accurately represent local variability
  - E.g., San Francisco and Santa Clara may have different cloud patterns (fog); must account for this in energy estimate.
- Large impact for transmission-level balancing.
  - Over long distances, PV fluctuations are typically uncorrelated, reducing variability and uncertainty in load balancing.

\(^1\) Puerto Rico Electric Power Authority Minimum Technical Requirements for Photovoltaic Generation (PV) Projects (2012)
Spatial Variability: Point vs. Plant

To simulate the power output of a PV plant, we often start with an irradiance point sensor.

- At long timescales (e.g., > 1-hour), point sensor and PV plant produce similar relative power output profile.
- But, at short timescales point sensor variability > PV plant variability.
Gradual Cloud Movement

- Single point sensor has a sharp ramp down around 15:42.
- Aggregate of all point sensors ramp down at a much slower rate.
Impact on Power Output

Different amount of spatial smoothing for 1 inverter vs. whole plant.
Impact on Energy and Ramp Rates

Daily/Annual Energy:
- Very small differences between point sensor, 1 inverter, and whole PV plant.

Short-timescale variability:
- Very large differences between point sensor and 19MW PV plant.
- Moderate differences between point sensor and one 500kW inverter.
Variability Scaling

Spatial smoothing depends on area aggregated.
Quantifying Spatial Smoothing

To quantify spatial smoothing, define the variability reduction (VR):

\[
VR(\bar{t}) = \frac{\text{variability point sensor}}{\text{variability PV system}}
\]

\(VR = 1\): no smoothing
larger VR => more smoothing

**VR depends on:**

- **Timescale**
  \(\bar{t} \uparrow, VR \downarrow\)

- **Average distance between PV modules**
  \(\bar{d} \uparrow, VR \uparrow\)

- **Daily cloud speed**
  \(CS \uparrow, VR \downarrow\)
PV Plant Variability Simulation

- To appropriately simulate PV plant variability, need a method to smooth point sensor irradiance
  - One method: Wavelet Variability Model (WVM)

### WVM Inputs
- PV Plant Footprint/Density of PV
- Point Sensor Timeseries
- Daily Cloud Speed

### WVM Outputs
- Plant Areal Average Irradiance
- Irradiance to power model
- Plant Power Output

- Other methods exist:
  - pv.sandia.gov
  - “PV Publications”
PV simulations w/WVM match the RR distributions much better than the simulation from the un-smoothed point sensor.
On an annual basis, WVM simulations are very accurate.

Ex: for RRs > 10% of capacity

<table>
<thead>
<tr>
<th></th>
<th>$P(\text{RR} &gt; 10% \text{ of capacity})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>measured</td>
<td>4.13%</td>
</tr>
<tr>
<td>no smoothing</td>
<td>7.30%</td>
</tr>
<tr>
<td>time avg.</td>
<td>5.06%</td>
</tr>
<tr>
<td>Marcos</td>
<td>3.47%</td>
</tr>
<tr>
<td>WVM</td>
<td>4.08%</td>
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</table>
Geographic Differences

Variability statistics can vary significantly across different locations.

Cumulative distributions

Magnitude of Variability
Geographic Variation in Puerto Rico

### August, 2013

<table>
<thead>
<tr>
<th></th>
<th>Sun</th>
<th>Mon</th>
<th>Tues</th>
<th>Wed</th>
<th>Thurs</th>
<th>Fri</th>
<th>Sat</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHI</td>
<td>[500][700]</td>
<td>[500][700]</td>
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</tbody>
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**Mayaguez, PR**

**Carolina, PR**
Geographic Smoothing Within Puerto Rico

WVM simulated RRs for 40MW plants in August 2013

|                | $P(|RR| > 10\%)$ | $\max(|RR|)$          |
|----------------|------------------|------------------------|
| Mayaguez       | 3.4%             | 31% of capacity        |
| Carolina       | 7.2%             | 34% of capacity        |
| aggregate of both plants | 1.3%             | 20% of capacity        |
Summary

- Smoothing depends on timescale and geographic separation.
- Spatial smoothing: short timescales (< 1-hr), short distances (< a few km)
  - Clouds edges cross PV modules at different times, lead to smoothed aggregate output.
  - Point sensor relative variability > PV plant relative variability.
- Long timescales (>1-hr), short distances (< a few km)
  - All PV modules see similar cloud patterns, little smoothing.
  - Annual energy of a PV plant can be well approximated from a point sensor
- Geographic smoothing: long distances, all timescales
  - PV modules see different cloud patterns, fluctuations uncorrelated.
  - Aggregate variability reduced significantly.
  - Annual energy estimates should be performed separately for each location.
Thank You!

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