Solar Variability and Forecasting

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http://solar.ucsd.edu
Variability of GHI
Figure 3 – 35% renewables have a minor impact on other generators during an easy week in July, 2006. WestConnect dispatch - no renewables (left) and 30% case (right).

Figure 4 – 35% renewables have a significant impact on other generation during the hardest week of the three years (mid-April 2006). WestConnect dispatch - no renewables (left) and 30% case (right).
Why does variability matter?

### Integration Costs of Solar Dramatically Impact by Geographic Diversity, and May Be Less than for Comparably Sited Wind

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Solar 1 Site</th>
<th>Solar 5 Sites</th>
<th>Solar 25 Site Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserves Constant Throughout Year</td>
<td>$14.7$</td>
<td>$5.0$</td>
<td>$1.6$</td>
</tr>
<tr>
<td>Reserves Change with Position of Sun</td>
<td>$1.1$</td>
<td>$0.7$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>1-min Deltas (Regulation)</td>
<td>$7.0$</td>
<td>$2.1$</td>
<td>$0.7$</td>
</tr>
<tr>
<td>5-min Deltas (Load Following)</td>
<td>$5.2$</td>
<td>$2.2$</td>
<td>$1.3$</td>
</tr>
<tr>
<td>60-min Deltas (Reserve Margin for Hour-ahead Forecast Error)</td>
<td>$5.2$</td>
<td>$2.2$</td>
<td>$1.3$</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$26.9$</td>
<td>$9.3$</td>
<td>$3.5$</td>
</tr>
</tbody>
</table>

Example costs based on 10% penetration of solar or wind on capacity basis.

**Why are solar costs lower?**

- Reserves can be held in proportion to clear-sky insolation for solar.
- Reserves are held at the same level all year for wind.

Source: Andrew Mills, Lawrence Berkeley National Lab
The plight of Solar Data
Variability of Solar Irradiance

- Variability of Irradiance
- Variability of spatially averaged irradiance
- Variability of PV power plant

PV Systems in San Diego County and UC San Diego: Testbed for Solar Variability

Map courtesy of CCSE
Average 1-sec **irradiance** ramp event look like?

Cloud edge enhancement

**Cloudy to clear**

**Clear to cloudy**
Spatial Averaging Effect of PV Array

- Irradiance measured by point sensor → spatial averaging occurs for PV array

PV size $A^{1/2} <$ shadow / clear size: decrease of ramp rate, but same amplitude

PV size $A^{1/2} >$ shadow / clear size: decrease of ramp rate and amplitude
Effect of PV Array Size on Ramp Rates

Simulating different size PV plants through moving averages at timescale $t$. $t \sim A^{1/2}$ / Cloud speed $U = DC^{1/2} / (\eta^{1/2} U)$, where DC: power rating in kW.

10 MW plant, at $\eta = 0.1$, $U = 5 \text{ m s}^{-1}$: $t = 63 \text{ sec}$

1% change per sec never occurs for $\geq 128 \text{ sec}$ moving average

Cumulative distribution function

Increasing moving average interval
Wavelets – A new tool to quantify variability

- Fit shape to clear sky index data
- Change duration and magnitude of increase to determine best fit
Wavelet decomposition using a “top-hat” wavelet for EBU2 and the average of 6 sites.

Strong peaks of duration 2048 sec (~34min) are detected at 1030 and 1100.

Strong peaks of duration 256 sec (~4min) are detected between 1700-1800 for EBU2.

Shorter durations have much smaller peaks for the AVG of 6 sites.

→ Identify time scale of variability
Reduction in variability over all timescales, but especially over shorter timescales.

Reduction in Variability at 6 sites vs 1 site: Fluctuation Power Index

Timescale of variability (t) allows estimating:
- ramp rates: if \( \frac{\text{PV size / cloud speed}}{t} \) > t, reduction in amplitude of variability
- necessary storage capacity to smooth out ramps: \( P \times t \)
- Effect of PV variability: voltage flicker (t small) vs load following (t large)
Other Solar Variability Research Needs

- Validated methods to estimate and predict single and aggregated PV plant output profiles for historical periods with minimal ground based measurements
  - Irradiance at a point to 2D irradiance
  - 2D irradiance to PV output (Kuszmaul et al., 2010)
- High time resolution (minute or less) \(\rightarrow\) downscaling in time and space

Why?
- Link average solar forecasts to high frequency ramp rate forecasts estimates
- Provide inputs to grid integration studies that can help determine how large amounts of PV can be accommodated most cost-effectively

Stein, 2010
Solar Forecasting

Total Sky Imagery and Cloud Tracking
Solar Forecasting Benefits

Use of state-of-art wind and solar forecasts reduces WECC operating costs by up to 14%, or $5 billion/yr, as compared to not using wind or solar forecasts for day-ahead unit commitment ($12-20/MWh of wind and solar generation). WECC operating costs could be reduced by an additional $500 million/yr in the 30% case if wind and solar forecasts were perfect.

Source: Hobbs et al. (1999). © 1999 IEEE. Used with Permission
Total Sky Imager: Cloud Detection
Final Cloud Detection

- \( RBR > 0.6 \)
- \( \text{RB ratio} \)

- \( RBR > \text{Sunshine parameter} = 0.83343 \)
- \( RBR > \text{Clear Sky Library (CSL)} \)
- \( RBR > CSL \) \( \text{or} \) \( RBR > SP \)

sunshine parameter + clear sky library = final decision
Cloud Motion Vectors

- Apply cross-correlation method to coordinate-transformed sky image.
- Retain only vectors for which high correlation is obtained
- Assume homogeneous cloud velocity

2009-10-04 16:26:30.000

U: -5.8532m/s V: 0.54762m/s
Table 5 Percentage co-occurrence of clear and cloudy conditions for measured/nowcast.

<table>
<thead>
<tr>
<th>Date</th>
<th>CLR/CLR</th>
<th>CLR/CLD</th>
<th>CLD/CLR</th>
<th>CLD/CLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 14, 2009</td>
<td>56.1</td>
<td>20.6</td>
<td>8.1</td>
<td>15.2</td>
</tr>
<tr>
<td>October 4, 2009</td>
<td>55.2</td>
<td>9.9</td>
<td>3.2</td>
<td>31.7</td>
</tr>
<tr>
<td>March 4, 2010</td>
<td>59.2</td>
<td>18.3</td>
<td>7.8</td>
<td>14.6</td>
</tr>
<tr>
<td>March 10, 2010</td>
<td>54.2</td>
<td>12.8</td>
<td>4.2</td>
<td>28.9</td>
</tr>
</tbody>
</table>
Conclusions

• Solar variability analysis tools developed
  – Quantify variability for different array sizes and geographic layout
  – Quantify ramp rates
• Demonstrated sky imagery in testbed at UCSD
• Preparing for online sky imager forecast at UCSD and large PV plant