High Penetration Solar Forum
March 2011

Solar Variability, Forecasting, and Modeling Tools

Jan Kleissl, Byron Washom*,
Chi Chow, Peter Cottle Matt Lave, Jennifer Luoma, Patrick Mathiesen,
Anders Nottrott, Bryan Urquhart, Johnny Zheng

Mechanical & Environmental Engineering, http://solar.ucsd.edu

*Director, Strategic Energy Initiatives, UC San Diego
Kevin Meagher, Silviu Darie (Power Analytics)

CSI Solar RD&D Program
www.calsolarresearch.ca.gov

Program Manager

Itron CSI RD&D
Focus Areas

• Solar Resources for California
• Solar irradiance variability
  – How likely are extreme ramps?
  – Does geographic dispersion help?
  – Case study at UC San Diego
• Irradiance input for power flow models: EDSA Designbase (Kevin Meagher)
• Solar Forecasting
  – Sky Imagery
Key Deliverables

CPUC-CSI
• More accurate CA solar resource map at high spatial and temporal resolution with online calculator
• Solar forecast model

DOE
• Open source simulation application for power system designers for distribution feeder design
• Characterization of PV variability
• Cloud tracking and forecast model
• Utility command / control interface
NSRDB Overpredicts GHI near Coast

MBE between SUNY model and CIMIS GHI measurements

CIMIS #111 – Green Valley, Santa Cruz Co. 7.5 km from the coast

CIMIS #008 – Gerber, Tehama Co. 93.0 km from the coast

\[(\text{SUNY} - \text{CIMIS}) / \text{CIMIS}\]

Units $\rightarrow [\% \cdot 10^{-2}]$

Nottrott & Kleissl (2010)
Corrected Solar Maps for CA

• Applied correction algorithm to generate a corrected GHI data set for California
• Visualized using Google Earth (free software)
• GIS tool facilitates accurate solar resource assessment and economic analysis

solar.ucsd.edu
Improve NSRDB

• Accuracy (similar to CIMIS analysis, now with 1000s of systems)

• Spatial scale: detect fine spatial gradients in areas of high PV penetration to get 5 km resolution

• Temporal scale:
  – 1 hour → 15 minutes using PV data
  – Given clearness index, develop probabilistic timeseries down to 5 minutes. Calibrate model using UCSD 1 second data

• Publish in Google Earth, other formats on demand
  • survey
Optimum azimuth angles for PV
Working the Magic

15 minute PV AC output

azimuth, tilt, rated efficiency, shading, location

GHI, DNI

DJI
PV Variability
Integration Costs of Solar Dramatically Impacted By Geographic Diversity, and May Be Less than for Comparably Sited Wind

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Increased Reserve Costs ($/MWh)</th>
<th>Solar</th>
<th>Wind</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reserves Constant Throughout Year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-min Deltas (Regulation)</td>
<td></td>
<td>$14.7</td>
<td>$5.0</td>
<td>$1.6</td>
</tr>
<tr>
<td>5-min Deltas (Load Following)</td>
<td></td>
<td>$7.0</td>
<td>$2.1</td>
<td>$0.7</td>
</tr>
<tr>
<td>60-min Deltas (Reserve Margin for Hour-ahead Forecast Error)</td>
<td></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>
<td>$2.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Reserves Change with Position of Sun</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Site</td>
<td></td>
<td>$1.1</td>
</tr>
<tr>
<td>5 Sites</td>
<td></td>
<td>$0.2</td>
</tr>
<tr>
<td>25 Site Grid</td>
<td></td>
<td>$0.1</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
PV Systems in San Diego County and UC San Diego: Testbed for Solar Variability

Map courtesy of CCSE
Measurements

- Air temperature and humidity (thermistor, capacitor)
- Global horizontal solar radiation (pyranometer)
- Solar panel temperature (thermistor, rear side), charging current & voltage for large arrays: DC and AC power to obtain inverter efficiency
1 sec data – partly cloudy day
Spatial Averaging Effect of PV Array

• Irradiance measured by point sensor → spatial averaging occurs for PV array
Effect of PV Array Size on Ramp Rates

Simulating different size PV plants through moving averages:
640 kW: t = 16 sec moving average
(plant at efficiency of 0.1, cloud speed of U = 5 m s⁻¹)

3%/sec change never occurs for 640 kW plant
Ramp Rates of Individual Solar Power Plants

- Misperception of actual ramp rate magnitudes need to be corrected

<table>
<thead>
<tr>
<th>Moving average / Power plant</th>
<th>RR&gt;1% s⁻¹ Probability</th>
<th>#/day</th>
<th>RR&gt;5% s⁻¹ Probability</th>
<th>#/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-sec / 2.5 kW</td>
<td>0.0655</td>
<td>2,359</td>
<td>0.0135</td>
<td>486</td>
</tr>
<tr>
<td>4-sec / 40 kW</td>
<td>0.0590</td>
<td>2,125</td>
<td>0.0081</td>
<td>292</td>
</tr>
<tr>
<td>16-sec / 640 kW</td>
<td>0.4298</td>
<td>1,511</td>
<td>0.0004</td>
<td>15</td>
</tr>
<tr>
<td>64-sec / 10 MW</td>
<td>0.0103</td>
<td>370</td>
<td>0.0000</td>
<td>0</td>
</tr>
<tr>
<td>256-sec / 164 MW</td>
<td>0</td>
<td>0</td>
<td>0.0000</td>
<td>0</td>
</tr>
</tbody>
</table>
Geographic Smoothing
Wavelets – A new tool to quantify variability

- Fit shape to clear sky index data
- Change duration and magnitude of increase to determine best fit

\[ \psi_{j,\tau}(t) = \frac{1}{\sqrt{2^{j+1}}} \psi \left( \frac{t - \tau}{2^{j+1}} \right) \]
Wavelets to Detect and Measure Cloud Events

Wavelet decomposition for one site (EBU2) and the average of 6 sites.

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

1700-1800: Strong peaks of duration 256 sec (~4min) are detected at a single site, but much smaller peaks for the AVG of 6 sites.

→ Wavelets provide time scale of variability
Reduction in Variability at 6 sites vs 1 site: Fluctuation Power Index

Reduction in variability over all timescales, but especially over shorter timescales.
Conclusions Variability

- Unless PV systems are co-located or when examining long time scales (\(\geq 1\) hour):
  - PV system output uncorrelated
  - Standard deviation increase as \(\sqrt{n}\), not \(n\)
- % Ramp rates decrease for large solar power plants
- Research needs: uniform framework and parameters for each climate zone
Irradiance Input for EDSA Designbase

(And anybody else)
Sample Worst 4-min Period

1-sec $K_c = \text{clear-sky index, representative of home installation (2.5kW)}$

63-sec $K_c = \text{clear-sky index filtered by 63-sec moving average (10MW)}$

RR = change in PV output in 1 second.

Average 2.5kW RR

Average 10MW RR
More Worst 4-min Examples

- Mean(abs(1-sec RR)): 6.1% 0.47%
- Mean(abs(63-sec RR)): 5.3% 0.48%
- 1-sec K 63-sec K
- 1-sec RR 63-sec RR

- 5.6% 0.41%
- 5.4% 0.44%
- 5.3% 0.55%

- 6.3% 0.33%
- 5.7% 0.34%
- 5.7% 0.31%

- 06/28 13:39:37
- 07/18 15:08:04
- 06/28 12:35:53
What $kt(\text{time})$ to use?

- Assume: transient power flow model
- Duration of event: 60 seconds
- Create 60 seconds GHI time series from
  - One ramp event based on cdf
  - One ramp event based on conditional average
  - Worst 60 seconds in 1 year timeseries
- Other factors:
  - Size of solar power plant (filters fluctuations), central or distributed
  - Goal of analysis (steady state power model, inverter frequency support, load following)
**Flowchart for Transient Stability Model**

**Product**
- 1 sec clearness index: $kt$

**Input:**
- Table of 1 sec clearness index $kt$ from $t = 1$ to $60$ sec
- Who: Raw data from UCSD

**STEP 1**
- Filter($kt$): Filtered 1 sec $kt$ for particular array
- Equation: filter size [sec] = $A^{1/2} / U = DC^{1/2} / (\eta^{1/2} U)$; DC power rating [kW], atmospheric velocity $U = 10$ m/s and $\eta = 15\%$ PV efficiency.

**STEP 2**
- $GI_{SKC}$: Clear sky global irradiance at panel tilt
- User OR 1107 W m$^{-2}$

**STEP 3**
- $GI$: Global irradiance input to EDSA model
- $GI = GI_{SKC} * kt$ (time)
- none

**STEP 4**
- Flowchart for Transient Stability Model
Solar Forecasting

Kevin Meagher Presentation
Total Sky Imager: Cloud Detection
Final Cloud Detection

2010-03-10 15:53:00.000

RBR > Sunshine parameter = 0.83343

RBR > Clear Sky Library (CSL)

RBR > CSL | RBR > SP

Red blue ratio

Simple threshold

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>
30 sec Forecast

- Actual $t_o$
- Forecast $t_{o+30s}$
- Actual $t_{o+30s}$
- Error

### Cloud Speed
- E-W
- N-S

### Cloud Fraction
- $0$ to $1$

### Matching Error
- $0$ to $15$

### Cap Error
- $0$ to $100$

Time [HH:MM]: 08:00 to 17:00
### 1 to 5 minute forecast

Mean total matching error and total cap error for 30-sec to 5-min ahead forecast. Since errors during overcast and clear conditions are zero, the errors in the table are biased high.

<table>
<thead>
<tr>
<th></th>
<th>30 sec</th>
<th>1 min</th>
<th>2 min</th>
<th>3 min</th>
<th>4 min</th>
<th>5 min</th>
<th>Time until advection out of scene [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sept 14, 2009</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>45.0</td>
<td>51.5</td>
<td>63.9</td>
<td>70.0</td>
<td>76.5</td>
<td>123</td>
<td>4 - 27</td>
</tr>
<tr>
<td><strong>Oct 4, 2009</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>47.2</td>
<td>49.8</td>
<td>55.6</td>
<td>61.5</td>
<td>66.6</td>
<td>70.3</td>
<td>8 - 18</td>
</tr>
<tr>
<td><strong>Mar 4, 2010</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>54.6</td>
<td>55.3</td>
<td>59.3</td>
<td>63.4</td>
<td>67.7</td>
<td>71.8</td>
<td>9 - 24</td>
</tr>
<tr>
<td><strong>Mar 10, 2010</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>48.8</td>
<td>53.9</td>
<td>62.3</td>
<td>68.8</td>
<td>75.1</td>
<td>78.0</td>
<td>9 - 15</td>
</tr>
</tbody>
</table>

Error increases with forecast horizon, but 25% better than persistence after 5 minutes.

After 10 to 25 minutes the scene is advected out of the field of view.
Conclusions

• Total sky imager forecasting at UC San Diego and CAISO Henderson, NV 48 MW PV plant; SDG&E territory

• Deterministic sky imager forecast valuable up to 5-15 minutes
  – For longer time scales use probabilistic sky cover fraction
  – Hardware limitations

• Integration of solar forecasting products will further reduce forecast error