Towards intra-hour solar forecasting using two sky imagers at a large solar power plant

Bryan Urquhart
Chi Wai Chow
Andu Nguyen
Jan Kleissl
University of California, San Diego

Manajit Sengupta
National Renewable Energy Laboratory

Jim Blatchford
California Independent System Operator

David Jeon
Sempra Generation
Sempra Generation at Copper Mountain
- Began with 10MW
- Added 48MW in Solar 1 expansion
- 152MW under construction (Solar 2)
- Transmission nearby
- Was largest PV plant in country
  - Mesquite solar in AZ is largest

Copper Mountain Solar 1

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Plant Size</td>
<td>48 MW</td>
</tr>
<tr>
<td>Inverters</td>
<td>96</td>
</tr>
<tr>
<td>Inverter Size</td>
<td>500 kW</td>
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<tr>
<td>Plant Area</td>
<td>1.3 km²</td>
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Deployment Setup

Sky imager used to generate current forecasts
Sky imager used for cloud height
Inverter House

1.8 km

- Sky imager used to generate current forecasts
- Sky imager used for cloud height
Cloud Tracking

- Clouds detected using red-blue ratio (RBR)
- Clear sky library (CSL) provides detection reference
- Binary image projected to sky (cloudmap)
- Ray tracing provides ground shadows
Mapping the Power Plant

- 2.5 × 2.5 m forecast cell
- 4.0 × 4.0 km domain
- each inverter distinct
  - inverter-level forecast possible

Sky imager used to generate current forecasts
Sky imager used for cloud height
Power Normalization

**List of Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$P$</td>
<td>power</td>
</tr>
<tr>
<td>$P_{nom}$</td>
<td>nominal power</td>
</tr>
<tr>
<td>$\eta$</td>
<td>efficiency</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
</tr>
<tr>
<td>$T_{stc}$</td>
<td>temperature at stc</td>
</tr>
<tr>
<td>$GI$</td>
<td>global irradiance</td>
</tr>
<tr>
<td>$GI_{stc}$</td>
<td>global irradiance at stc</td>
</tr>
<tr>
<td>$stc$</td>
<td>standard test conditions</td>
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**Power to Global Irradiance**

$$P = \eta(T) \ GI$$

$$P_{nom} = \eta(T_{stc}) \ GI_{stc}$$

$$GI = \frac{\eta(T_{stc})}{\eta(T)} \frac{P}{P_{nom}} GI_{stc}$$

**Normalized Power**

$$kt_{poa} = \frac{GI}{GI_{csk}}$$

**Plane-of-Array Clear Sky Global Irradiance**

- Clear sky global horizontal irradiance
  - *Kasten model*
  - Break into direct and diffuse components
    - *Boland et al.*
  - Transpose to plane of array
    - *Muneer model*
  - Plane-of-array clear sky irradiance $GI_{csk}$
Clear Sky Index Selection

- The sky condition is known, but the actual impact of clouds is not.
- How to turn a binary sky condition into a power value?
  - Use observed history at the plant to characterize optical depth of cloud field.
  - Assign a clear sky index to each sky condition.

- Use observed distribution of normalized power (i.e. clear sky index) and look for peaks near 1 and less than 0.875.
- Long term trend in clear sky index indicates variability in cloud types at the plant, especially in the winter.

\[ \text{clear } \text{kt} = 1.07 \]
\[ \text{cloudy } \text{kt} = 0.46 \]
Power Output Determination

Average clear sky index covering each inverter’s panel footprint is used to compute power:

\[ P = \frac{\eta(T)}{\eta(T_{stc})} \frac{G_{I_{csk}}}{G_{I_{stc}}} k_{t_{poa}} P_{nom} \]

where

\[ k_{t_{poa}} = \frac{1}{N} \sum_{i=1}^{N} k_{t_{poa}}^{i} \]
Forecast Evaluation Metrics

### Standard Metrics

\[
MBE = \frac{1}{N} \sum_{i=1}^{N} \frac{P_f^i - P_a^i}{\langle P_a \rangle}
\]

\[
MAE = \frac{1}{N} \sum_{i=1}^{N} \frac{|P_f^i - P_a^i|}{\langle P_a \rangle}
\]

\[
RMSE = \frac{1}{\langle P_a \rangle} \left[ \frac{1}{N} \sum_{i=1}^{N} \left( \frac{P_f^i - P_a^i}{\langle P_a \rangle} \right)^2 \right]^{1/2}
\]

### Time Averages

\[
\langle P_a \rangle = \frac{1}{N} \sum_{i=1}^{N} P_a^i
\]

\[
\bar{P}_x^i = \frac{1}{M} \sum_{i=1}^{M} P_x^i
\]

| \(P\) | Power, plant aggregate output |
| \(f\) | Forecast power |
| \(a\) | Actual power |
| \(N\) | Total samples for a day |
| \(M\) | Number of samples in moving average |
| \(x\) | either \(f\) or \(a\) |
Ramp Timing

- 10-minute ahead forecast
- While there are ramp timing and duration inaccuracies, the causes have been assessed and targeted improvements currently underway address and improve results.
Conclusions and Future Work

Final Thoughts

• Method demonstrates limited skill on days with heterogeneous clouds
  — Requires further improvement for consistent skill on days where a sky imager is expected to add value
  — Methodology not expected to perform better than persistence on clear days
• After about 2 years of development, this is the first major test of the forecast. While the performance is not as good as hoped, it shows much potential
  — Many areas for improvement were identified and we are working to address them.

More to come …

• Stereo “3D” reconstruction for higher accuracy position determination
• Continue working on the optical depth methodology
• Perform more extensive validation
• Use new imaging device
  — Higher resolution, high dynamic range
  — No shadowband, fewer 0-3 minute errors

Final Thoughts

More to come …
**Acknowledgements**

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<td>The authors gratefully acknowledge the help of the <strong>Ron Clabaugh</strong> of Sempra Generation for helping to set up the sky imagers, <strong>Shiva Bahuman</strong> of Sempra Generation for networking the sky imagers at the plant and helping to provide real time images and power data, and <strong>Darrel Lopez</strong> of El Dorado Energy for providing support in setting up this project.</td>
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<td>The authors would also like to thank <strong>David Zeglinkski</strong> and <strong>Megan Fox</strong> of OSISoft, and <strong>Jo Frabetti</strong> of the San Diego Super Computer Center for helping to integrate the power data into the University smart grid database.</td>
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Thank you for your time