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SOLAR FORECASTING AND GRID INTEGRATION
Project Sponsors and Partners

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

DOE
U.S. Department of ENERGY
Energy Efficiency & Renewable Energy

Costshare:

Itron
CSI RD&D Program Manager
Key Deliverables

- Solar variability model for distributed or utility scale solar power plants
- Marine Layer Forecast Models
- Sky imager forecast model
- Solar inverter model for dynamic simulations
- Gadgets:
  - Topographic horizon data for California
  - Downscaled 1 sec PV output data from 80 systems
  - Cloud speed sensor

- For more details: March 2013 CPUC CSI I Webinar
Wavelet Variability Model (WVM)

**Inputs**
- PV Plant Footprint
- Density of PV
- Point Sensor Timeseries
- Location/Day Dependent “A” Coefficient

**Outputs**
- Plant Areal Average Irradiance
  - irradiance to power model
- Plant Power Output

Determine variability reduction (smoothing) at each wavelet timescale.
Cloud Simulator: Smoothing Depends on Cloud Speed

Scaling depends on cloud speed

For sufficiently large cloud speeds and sizes,

\[ A = \frac{1}{2} \times CS \]
Puerto Rico
Mayagüez

10% Ramp / Minute Rule

Collecting 1-second irradiance measurements at the University of Mayaguez, PR.

> Arrangement of 4 sensors allows for cloud speed measurement.
> Data input to WVM to simulate PV plant power output.

Daily Irradiance

RRs and violations

Number of violations varies significantly by day.

60MW Plant 1-min. RRs

Sun Mon Tues Wed Thurs Fri Sat

Sun Mon Tues Wed Thurs Fri Sat

September, 2012

GHI [W m⁻²]
Occurrence and Severity of Violations

> Large number of violations
> WVM allows simulating PV ramp rates, but also the impact of mitigation measures such as solar forecasting and battery storage.
> WVM run for >10 developers during prospecting.
How do Extreme Ramps Scale with System Size?
Maximum Aggregate Solar Ramp Rates for California IOUs

**Objective:** Analysis of aggregated distributed PV power output in SDG&E, SCE, PG&E, CAISO territory

- Ramp rates of aggregate measured power output of the PV systems
  > Implications for intra-hour load following / balancing
- Compare PV power output against ground measured and satellite-derived irradiation
  > What metering for PV systems is necessary to be able to follow output in real time?
Ramp Rates for SDG&E

- Weather-induced RRs are wrt 30 day average daily cycle
- Largest ramp events are weather-induced
Two Days with the Largest Ramp Rates

Aggregate modeled & measured power of all 45 PV sites and Aggregate GHI of 5 CIMIS stations for the day with the largest 1-hour ramp rate in 2010

- Largest aggregated hourly ramp: 60.4% of PV PTC capacity
- 2\textsuperscript{nd} largest ramp: 44.5%.
  - Marine layer cloud “burn-off”, like many other large ramps.
Largest Ramps for all California IOUs

<table>
<thead>
<tr>
<th></th>
<th>SDG&amp;E</th>
<th>SCE</th>
<th>PG&amp;E</th>
<th>CAISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance between sites</td>
<td>28 km</td>
<td>101 km</td>
<td>186 km</td>
<td>332 km</td>
</tr>
<tr>
<td>Largest absolute hourly ramp</td>
<td>60.4%</td>
<td>30.7%</td>
<td>29.9%</td>
<td>29.9%</td>
</tr>
<tr>
<td>Largest weather induced ramp</td>
<td>55.5%</td>
<td>29.8%</td>
<td>27.6%</td>
<td>20.3%</td>
</tr>
</tbody>
</table>

- Largest ramps in SCE, PG&E, CAISO driven by changing sun angle in early morning and late afternoon during clear skies.
  - Highly predictable.
  - Anti-correlated to evening load peak.
- Relative Ramp rates do not decrease for areas beyond 60 miles.
- Weather-induced ramp rates decrease with area (56% for SDG&E versus 20% for CAISO).
Largest Ramps in CAISO
Marine Layer Solar Forecasting

- Logistic Regression (GPLI)
- High Resolution Numerical Weather Prediction (UCSD)
- Evaluation period May – October 2013
Statistical Marine Layer Forecast Model

- Goal: Predicting the likelihood of marine layer (ML) development along the southern California coast.
- ML Classification: Automatic ML classification algorithm from satellite data.
- Multivariate logistic day-ahead ML forecast given real time weather observations and NWP.

Satellite Classification:
- Marine layer: light blue
- ML + cloud: purple
- Cloud: orange
- Clear sky: dark blue
Net Load Forecasting – distributed PV generation:

San Diego Gas and Electric:

- 20,000+ distributed PV generation sites
- 300+ substations

Impact of distributed PV sites on grid performance?

- Develop distributed generation cluster profiles
- Develop load forecast parameters for clusters
  - Operational PV forecasting
  - Testing and calibration
High-resolution, cloud-assimilating NWP at UCSD: day-ahead (40 h) solar forecasts across Southern California. 1.3 km and 5 min resolution.
To improve accuracy, clouds are populated in initial conditions

**Direct Cloud Assimilation**
- Cloud hydrometeors are modified in initial conditions

**WRF model simulates cloud evolution**
- Evaporation
- Deformation
- Condensation

**RUC methodology**
- Benjamin, et al., 2004, 2007, etc.
WRF-CLDDA
Simulation of Marine Layer Dissipation

6/13/2011
Integration with Utility Models

- Dynamic system modeling
- Energy storage dispatch for demand charge reduction
- Sky imager forecasting for feeder voltage control
Power Modeling

1. Static and dynamic modeling determines allowable power circuit penetration levels, performance constraints and cost.
2. Specific inverter designs are implemented as hardware options. These inverter modeling capabilities are essential to power system modeling and analysis.
3. Generic inverter attributes are also defined facilitating broad based modeling and analysis.
Power Systems Simulations

Voltage Support.

Frequency Support

Ramp-down

![Voltage Support Graph](image1)

![Frequency Support Graph](image2)

![Ramp-down Graph](image3)
Dynamic simulations using Power Analytics model in Simulink
Secure Bi-Directional Communication - ICCP

- ICCP (IEC 60870)
  - Inter-control Center Communications Protocol
  - OSI structured
  - Mature and accepted bi-directional communications standard
  - Currently supported by SDG&E
- Currently in production
- Power Analytics
- In certification with ERCOT
5 SDG&E Feeders with High PV Penetration

- Climate Zones (coastal to desert)
- Urban and Rural
- 1 mile to 10 mile size
- Goals
  > Examine ramp rates by site and in aggregate
  > Evaluate feeder impacts (losses and voltage regulation)
  > Evaluate mitigation measures enabled through forecasting
Intra-Hour Solar Forecasting With Total Sky Imagery
Feeder Modeling and Control

- Develop highly spatially and temporally resolved solar resource data for the feeders
  - Apply to all PV systems on feeder
  - Also simulate highly resolved load data
- Simulate feeder voltages and voltage regulator actions
- Investigate use of forecasting to reduce potential voltage regulator actions associated with PV
“Gadgets”

- Topographic Horizon Database
- Downscaled 1 sec PV Output Data
- Cloud Speed Sensor
Topographic Horizon Database

- Topographic shading reduces PV output and is commonly not considered by satellite or NWP solar resource models.
- Impact on PV generation generally benign, but can be a few % in mountainous areas.
Case Study – Twin Peaks

- Day length up to 30% shorter than unobstructed
- Annual losses usually less than 1%
- Data available for all high PV penetration regions with topography
Downscaled CA PV Data to 1 sec

- High resolution PV data required for integration studies
  - Voltage variability impacts of PV exacerbated when assuming uniform output profiles for all sites on a feeder
- CSI performance based incentive (PBI) data only available as 15 min average
- Statistical downscaling uses properties of resolved data (e.g. clear versus cloudy) to dynamically introduce fluctuations
Downscaling Example

• Request at [http://solar.ucsd.edu/datasharing/](http://solar.ucsd.edu/datasharing/)
• 365 days of 1 sec data per site
• 115 sites in California
Cloud Speed from Pairs of Solar Irradiance Measurements

- Provisional patent filed
- Developing commercializable product
- Integration into meteorological measurement systems at utility scale solar power plants

<table>
<thead>
<tr>
<th>Pair #</th>
<th>Direction [°]</th>
<th>Regression Coef.</th>
<th>Time gap [s]</th>
<th>Speed [m s⁻¹]</th>
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<td>0</td>
<td>0.7140</td>
<td>1.65</td>
<td>3.6</td>
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<td>7</td>
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