SATELLITE-BASED SOLAR GENERATION BACK-CAST FOR PJM

14 March 2017

METHOD OVERVIEW

To estimate PV electrical generation from PJM's various zones, we use satellite imagery to estimate solar radiation at all of PJM's Behind-the-Meter (BTM) solar sites. We estimate both actual generation (using the history of installation of solar panels at each site) and potential generation (using the present solar generation infrastructure).

Our method had us proceed as follows:

- Acquire 24 years (1993-2016) of visible satellite imagery at 15-minute intervals on a 2-km grid cropped around the PJM Service area.
- Estimate Global Horizontal Irradiance (GHI) and Clear Sky Index (CSI) from the visible geostationary satellite image data using the AWST adaptation of the Perez (2002) technique.
- Assemble a set of quality controlled GHI and solar generation observations from PJM and other sources.
- Use our previously-developed technique to correct biases in the satellite-based GHI estimates (satGHI – groundGHI) based on parameters that can be derived from ground-based observations, satellite data, geometry, topography and time.
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METHOD OVERVIEW

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- Interpolate the GHI to each BTM solar installation listed in the GATS data available from PJM in early December, 2017.
- Correct the bias at each BTM site and time in the 24-year history to generate a 24 year GHI time series at each site. Bias correction is performed using a machine-learning technique (described in slides 8 & 9) to capture the relationship between estimated and observed GHI at reliable observation sites, including the effects of elevation, satellite viewing angle and season. This relationship is then applied to all PV generation sites.
- GHI is then passed through a power curve and assembled into TO Zone totals to produce an aggregate power time series for each TO Zone.
  - The power curve is a function of GHI only (we don't explicitly correct for temperature), but since temperature and GHI are related, we believe that errors associated with this relationship are small compared to other sources of error (e.g. the imperfection of estimating GHI from satellite data).
  - The GHI-power relationship was derived from data at well-calibrated PV generation sites around the US
  - These relationships were derived for panels deployed at a mix of tilt and azimuth angles, but mostly facing south at typical roof pitch angles of about 25 degrees.
  - We would be happy to work with PJM to develop a better calibrated power curve using PV sites within PJM

METHOD OVERVIEW

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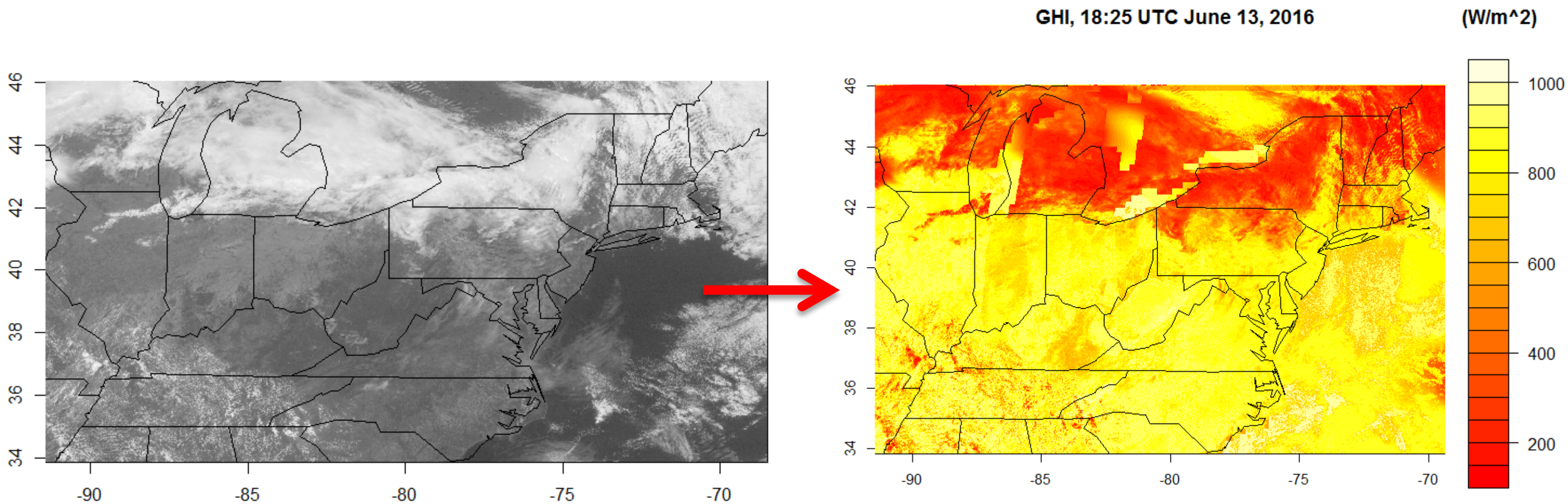
- Separate time series are produced with the following assumptions:
  - All BTM sites were operational throughout the period, no panel degredation.
  - BTM sites come on line as of their installation date and are then subject to panel degradation.
  - The power curve accounts for degradation loss assuming a linear decay rate that increases with increasing average plane-of-array irradiance, but is typically about 0.2% in the first year, and 0.4% in all following years
- Unlike our past operational back-cast product, this product produces historically consistent generation records over the entire period, since we use a single bias-correction procedure. We have revised this product, and are working through the past few months so that all past generation records and all future operational generation records will use historically consistent calibration.

SATELLITE IMAGERY

- We processed approximately 450,000 images during daylight hours over the 8766 days from 0000 UTC on January 1, 1993 through 0000 UTC on January 1, 2017 from NOAA’s geostationary operational environmental sensor (GOES) satellites.
  - GOES-7: Jan 1993 through Oct 1994
  - GOES-8: Nov 1994 through May 2004
  - GOES-12: May 2004 through June 2006
  - GOES-13: June 2006 through Dec 2017
  - GOES-14: Mon – Mon 2012, during goes13 outage.
- Mapping Domain: 1600 pixels east-west by 450 pixels north-south.
- Resolution is approximately 1.1 km east-west by 2.6 km north-south.
- Average 50 images per day.
- Missing data:
  - Approximately 5 scheduled outages per day (varied with the 3 different satellites deployed over the period: total: about 43,000
  - Approximately 10,000 additional images are missing, mainly from GOES-7 and GOES-8 – the satellite data was effectively half-hourly during these periods.

GHI ESTIMATE FROM VISIBLE SATELLITE BRIGHTNESS

- Based on the Perez (2002) technique
  1) Compute normalized brightness from raw visible brightness.
  2) Compute clear sky index (0-1) based on the climatological maximum and minimum normalized brightness for that month and hour of the day.
  3) Derive GHI from clear sky index (CSI) and estimated clear-sky irradiance.



PEREZ, R., P. INEICHEN, K. MOORE, M. KMIECEK, C. CHAIN, R. GEORGE and F. VIGNOLA, 2002: A new operational model for satellite-derived irradiances: Description and validation. Solar Energy, 73, 307-317.

SURFACE IRRADIANCE OBSERVATIONS USED IN TRAINING OF BIAS CORRECTION MODEL

Name	Description	Latitude	Longitude	State	Operatror	Start Date	End Date
PSU	Penn State	40.72	-77.93	PA	SURFRAD	19980601	20161231
BON	Bondville	40.05	-87.37	IN	SURFRAD	19950101	20161231
GWN	Goodwin Creek	34.25	-89.87	MS	SURFRAD	19950101	20161231
RUT	Rutland	43.52	-72.95	VT	SURFRAD	20141001	20150915

BIAS CORRECTION MODEL PREDICTOR VARIABLES

Eleven predictor variables are used for bias correction:

1. Decimal year (year + day of year / 365).
2. Hour of day
3. Unadjusted satellite-estimated Clear Sky Index
4. Solar elevation (degrees above horizon)
5. Solar azimuth
6. Clear sky GHI
7. Sun satellite geometry (satellite-based GHI estimate adjustment after satellite navigation, and solar position, assuming clouds are 1.75 km above sea level or 750 m above the surface, whichever is higher).
8. Unadjusted satellite-estimated Clear sky index variability over a 9-pixel box
9. Unadjusted satellite-estimated Clear sky index variability over a 49-pixel box
10. Unadjusted satellite-estimated Clear sky index variability over a 121-pixel box
11. Solar Declination

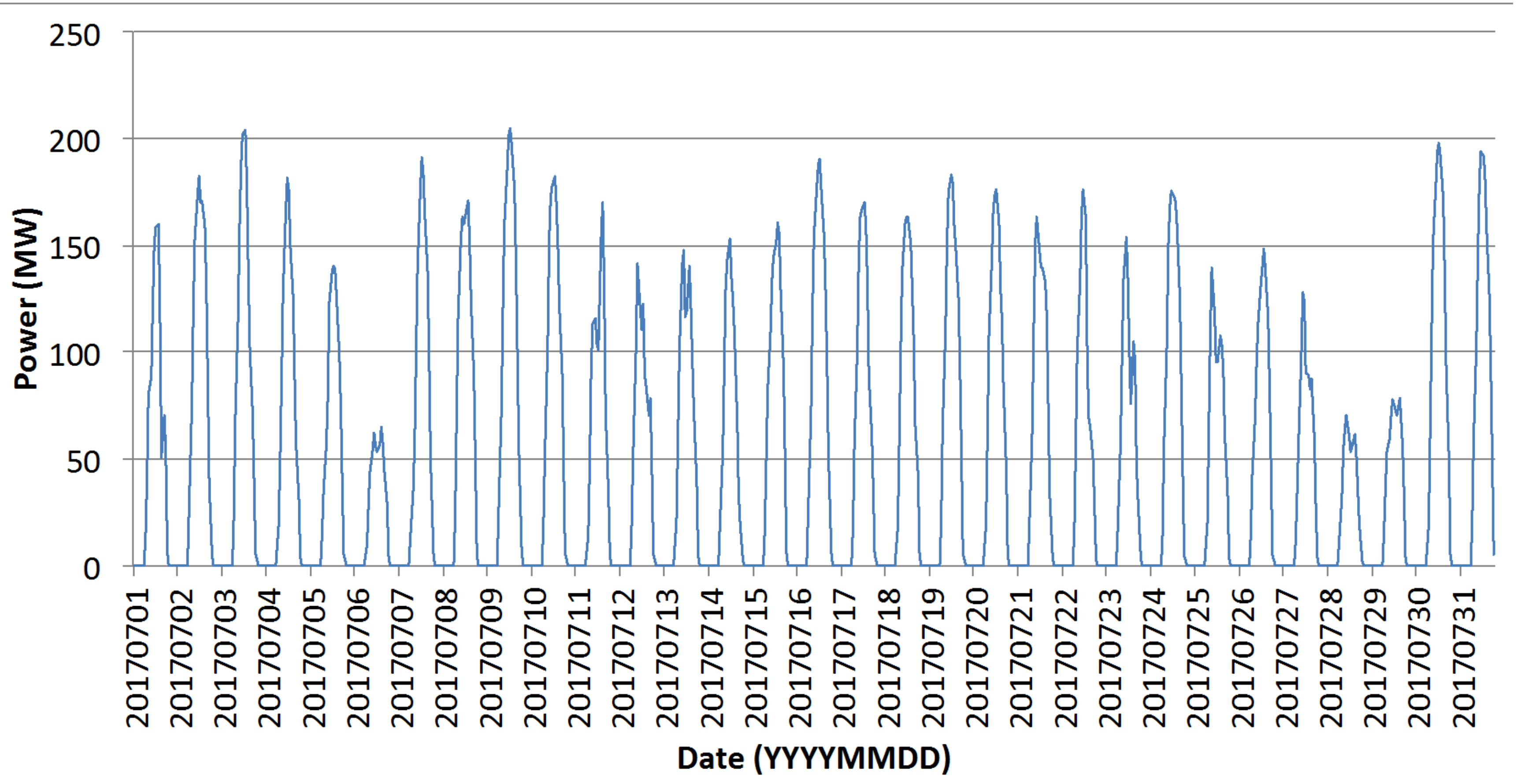
BIAS CORRECTION METHOD AND VALIDATION

Bias correction modeling was accomplished using the commonly used and well-regarded machine learning technique, extreme gradient boosting, or XGBoost (version 0.6a2 currently available at http://xgboost.readthedocs.io/en/latest/).

XGBoost internal parameters were selected using an algorithm that tests a large array of possible settings and selects those that performs best .

SAMPLE MONTHLY AVERAGE POWER

Satellite Estimated Hourly Average Power for July 2017 for the BGE TO Zone (289.0758 MW capacity).



THANK YOU!

Questions?