Published in final edited form as:
J Sol Energy Eng. 2017 June ; 139(3): . doi:10.1115/1.4035830.

High-Speed Monitoring of Multiple Grid-Connected Photovoltaic Array Configurations and Supplementary Weather Station

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Abstract

Three grid-connected monocrystalline silicon photovoltaic arrays have been instrumented with research-grade sensors on the Gaithersburg, MD campus of the National Institute of Standards and Technology (NIST). These arrays range from 73 kW to 271 kW and have different tilts, orientations, and configurations. Irradiance, temperature, wind, and electrical measurements at the arrays are recorded, and images are taken of the arrays to monitor shading and capture any anomalies. A weather station has also been constructed that includes research-grade instrumentation to measure all standard meteorological quantities plus additional solar irradiance spectral bands, full spectrum curves, and directional components using multiple irradiance sensor technologies. Reference photovoltaic (PV) modules are also monitored to provide comprehensive baseline measurements for the PV arrays. Images of the whole sky are captured, along with images of the instrumentation and reference modules to document any obstructions or anomalies. Nearly, all measurements at the arrays and weather station are sampled and saved every 1s, with monitoring having started on Aug. 1, 2014. This report describes the instrumentation approach used to monitor the performance of these photovoltaic systems, measure the meteorological quantities, and acquire the images for use in PV performance and weather monitoring and computer model validation.

Keywords

data acquisition; photovoltaic; meteorology; inverter; weather station; solar

1 Introduction

Three grid-connected solar photovoltaic (PV) arrays were constructed on the National Institute of Standards and Technology (NIST) campus in Gaithersburg, MD, with construction finished around July 2012. This location is in a mixed-humid climate zone [1]

Contributed by the Solar Energy Division of ASME for publication in the Journal of Solar Energy Engineering:Including Wind Energy and Building Energy Conservation.

Assoc. Editor: Geoffrey T. Klise.

having four distinct seasons. Skies are variable, with only a couple days of cloudless skies per month, and the solar resource for PV is about 1600–1800 kWh/m^2 per year [2].

The three arrays on campus use the same monocrystalline silicon module, but all are mounted in different configurations: the canopy array (Fig. 1) is mounted on east/west facing canopies over a parking lot, the ground array (Fig. 2) is mounted on tilted ground supports in an open field, and the roof array (Fig. 3) is mounted on tilted, weighted racks on a flat building roof. There is a single inverter at each array, which is connected to the NIST campus grid, and subsequently the local grid. The characteristics of the arrays are summarized in Table 1.

In addition to the basic monitoring systems that the PV integrator installed, research-grade sensors have been installed at each array to measure various electrical, temperature, and meteorological values, with monitoring commencing on Aug. 1, 2014. These data acquisition systems (DASs) were created to address the needs for long-term, high accuracy, subminute data sets from large-scale, calibrated, well-maintained and documented systems in a variable weather environment, as expressed in Refs. [3–6]. The only other known arrays instrumented to a comparable level with public to semipublic data sets in the northeast of the U.S. are the 65–907 kW arrays at the Northeast Solar Energy Research Center (NSERC) [7] and the 32 MW Long Island Solar Farm [8], both installed at Brookhaven National Laboratory in Upton, NY, on Long Island, and the 6kW and 60 kW Regional Test Center (RTC) arrays installed at an IBM facility in Williston, VT [9]. An onsite weather station was also installed to address the same aforementioned needs and to provide supplementary data to the campus PV array DASs for modeling and validation studies by researchers in and outside NIST.

The DASs on the NIST campus sample and save measurement values, including those from the integrator's systems, every 1 s. The motivation for the high-speed sampling is to allow future research on: inverter maximum power point tracking operation (which is especially of interest during rapid irradiance changes), anti-islanding test perturbations [10], the effects of fast moving clouds, the causes of module and balance-of-system component failures, and cloud irradiance enhancement and transitions along with their dynamic effects on power output and quality. Also, more accurate mean power and energy yield values can be calculated [11], especially during highly variable or low insolation. Other uses include identifying fluctuating direct current (DC) offsets [10] to later filter out of the data, and validation of short-term irradiance forecasting and inverter/grid interaction models for smart grids. These data are currently being used at NIST in research advancing microgrids to increase the penetration of PV and other renewable energy technologies.

In addition to the electrical, temperature, and meteorological values, cameras near each array and the weather station capture still images every 5 min, and a current-voltage (I–V) tracer continually tracks the maximum power point and takes curve traces every 1 min of reference modules installed at the weather station in the orientations of each array.

Technical details of the PV arrays, sensors, and data acquisition systems can be found in NIST Technical Notes 1896 [12] and 1913 [13].

2 Measurements

2.1 PV Arrays

The sensors and instruments installed at each array measure the following values:

- global horizontal irradiance (GHI)
- plane-of-array (POA) irradiance
- wind speed and direction
- ambient temperature
- module backsheet surface temperature
- array DC voltage
- source circuit DC currents
- various DC and AC measurements (by the inverter)
- various AC measurements

The GHI and POA irradiance are measured using secondary standard pyranometers, as shown in Fig. 4 at the canopy array. Two additional measurements of the POA irradiance are taken using a flat-plate silicon irradiance sensor and a domed diffused silicon-cell pyranometer. Additional GHI measuring pyranometers are installed at the roof array, spatially dispersed to capture the effects of the 14 story building directly north of the array. This tower blocks a fraction of the diffuse irradiance and reflects and augments the irradiance during sunny conditions [14]. Also installed at the roof array are two GHI measuring flat-plate silicon irradiance sensors to quantify the level of soiling: one is regularly cleaned and the other is not.

Pyranometers were installed to most accurately measure the irradiance incident on the array, and flat-plate silicon irradiance sensors were installed to capture the irradiance under fast changing conditions at nearly instantaneous speeds. While pyranometers are more accurate than the silicon irradiance sensors, their response times are on the order of seconds. The flat-plate irradiance sensors also better approximate the array's effective irradiance, or that absorbed by the PV cells (compared to the pyranometers, which measure the *incident* irradiance), because they have similar reflective properties and spectral responses. All pyranometers installed by the researchers are aligned to within half a degree of the nominal array tilt.

The module backsheet temperatures are measured using fourwire, class "A," thin-film resistance temperature detectors (RTDs), which were calibrated [15] and installed according to best practices [16]. Four sensors are installed on one central module in positions according to IEC 60891 [17], with the rest installed behind a center cell on separate modules throughout the array to capture the temperature gradients in the array and for calculating a single representative array temperature. The ambient temperature outdoors and inside the inverter is also measured at each array.

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The wind speed and direction at each array is measured using a heated ultrasonic wind sensor positioned above and in a position that does not shade the array.

Current shunts were installed either in the inverters, as shown in Fig. 5, or in a separate enclosure to measure the output circuit currents from each combiner box. Custom voltage divider circuits were also installed to accurately measure the array voltage. Current shunts and voltage dividers were chosen instead of current transformers (CTs) or Hall effect sensors, or other types of DC voltage transducers, because they are much more accurate and stable. All inverter measurements and error codes are saved, along with the measurements from a revenue grade AC meter at each array near the connection to the grid.

The basic monitoring system that the integrator installed at each array includes a domed diffused silicon pyranometer, an RTD measuring a single module temperature, and an RTD probe measuring the ambient air temperature. The integrator also collects data from the inverters and the AC meters. Having both of these data sets will allow a one-to-one comparison of the two monitoring systems.

Cameras were installed at each array, which take images every 5 min of both the entire array and multiple close-up sections. These images are taken to capture the shading, snow, rain, and frost, and any other obstructions or damage to the arrays. An image of the ground array and plot of the day's output circuit powers and efficiencies during a period of partial snow coverage are shown in Figs. 6 and 7, respectively.

2.2 Weather Station

The sensors and instruments installed at the weather station measure the following meteorological quantities:

- direct normal irradiance (DNI)
- diffuse horizontal irradiance (DHI)
- global horizontal irradiance (GHI)
- infrared (IR) irradiance (net and total)
- ultraviolet (UV) irradiance (A, B, and total)
- spectral irradiance curves
- snow depth
- wind speed and direction
- humidity
- precipitation
- barometric pressure
- hail count
- ambient temperature

The weather station is located on an unobstructed rooftop, as shown in Fig. 8, 300–750m (1000–2500 ft) from the PV arrays. It is arranged to optimize the placements of the instruments and reference modules, resulting in virtually no shading of either.

The installed instrumentation includes stationary and tracking radiometers. The stationary radiometers include multiple spectroradiometers and UV radiometers, and the same, or functionally the same, type of thermopile and silicon pyranometers installed at the arrays measuring the GHI, as shown in Fig. 9. On the tracker are first class pyrheliometers measuring the DNI, black and white pyranometers measuring the DHI, and a pyrgeometer measuring the IR irradiance. There are redundant DNI, DHI, and GHI measuring radiometers on separate data loggers to maximize data availability and to provide comparative checks of the measurements.

Reference PV modules from the same production batches as those in the arrays are also installed at the weather station, orientated the same as those at the arrays, and arranged to ensure virtually no shading. Five temperature sensors are installed on each module and flat-plate silicon irradiance sensors of the same model that are used at the arrays are installed next to each module in their respective planes. Flashing is installed around select modules to simulate the effect of the respective installations on the modules' temperatures.

These reference modules provide baseline measurements without the significant wiring, mismatch, soiling, snow, shading, and other losses inherent to the modules in the arrays. These reference modules also provide data on their aging, and their true average cell temperature and absorbed/effective irradiance from their measured I–V curves, which can be correlated with the measured backsheet surface temperature and POA irradiance, respectively.

Cameras are also installed at the weather station that capture images of the instruments and reference modules every 5 min. An additional all-sky camera takes horizon-to-horizon 2 megapixel images approximately every 8s, with an example image shown in Fig. 10.

3 Data Acquisition and Control

The data loggers at each array measure and save data every 1 s, excluding the RTDs which are measured every 10 s. Measurements at the weather station are sampled at the same rates except for the spectroradiometers and reference modules; the spectroradiometers are measured and the curves saved every minute, and the reference modules are maximum power tracked and traced every minute, with the maximum power data averaged every minute from 1 s samples. Time synchronization occurs at the start of each day to ensure all data loggers and computer clocks are accurate to within 0.5 s.

Electrical shielding, grounding schemes, measurement techniques, settling and integration times, excitation, etc., have all been carefully chosen and optimized to minimize noise, uncertainty, and lost data, which is challenging given the 1 s sampling rates. The battery backups for each of the data acquisition systems will last at least three days with automated optimized control of the heaters, ventilators, and data acquisition devices needed exclusively for daytime measurements. The solar tracker also has a three-day power backup via a wet-cell battery bank.

4 Data Archiving, Monitoring, and Maintenance

All data are continually transferred to a central server and database. Between Aug. 1, 2014 and the time this paper was written, data availability from all of the DASs is greater than 99%. There were also periods where sections of or a whole array were down, usually due to problems with the inverter or a combiner box, or scheduled outages in the buildings where these inverters connect.

All of the pyranometers are calibrated at the National Renewable Energy Laboratory (NREL) according to their Broadband Outdoor Radiometer Calibration (BORCAL) procedure [18] every 12–24 months. This calibration provides net-IR corrected responsivities (μV/(W m^{-2})) at every 2 deg in the measured solar zenith angle range, which can be easily implemented using freely available software [19]. All radiometers are cleaned three times per week and the reference modules are cleaned on an as-needed basis. Logs of instrument replacements and cleanings, array failures, and general maintenance have been kept and are available.

5 Summary

NIST has instrumented three monocrystalline grid-connected PV arrays on the Gaithersburg, MD campus with high-accuracy solar, temperature, electrical, and other meteorological sensors, in addition to cameras capturing still images. A weather station has also been installed that includes supplementary solar and meteorological instrumentation, reference modules, and an all-sky camera. Most measurements are recorded every 1 s and data availability is greater than 99% between Aug. 1, 2014 and the time this paper was written. A public data portal will eventually be made available, but in the interim, interested modelers and analysts can directly contact the author.

Acknowledgments

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Fig. 1.
Canopy array

Fig. 2.
Ground array

Fig. 3.
Roof array

Fig. 4.

The canopy array weather instruments at the north end of the center canopy, showing the irradiance sensors and mounts as well as the ambient temperature sensor, wind sensor, and wind sensor surge protector

Fig. 5.

The inverter DC combiner compartment at the ground array with the installed DC measurement components, showing three of the seven current shunts, and, left-to-right on the upper DIN rail: the ambient temperature sensor, shunt remote terminal unit (RTU), analog transmitter, voltage divider, and fuse holder for the DC busbar voltage taps

Fig. 6.

An image taken by the camera at the ground array showing a time of partial snow coverage

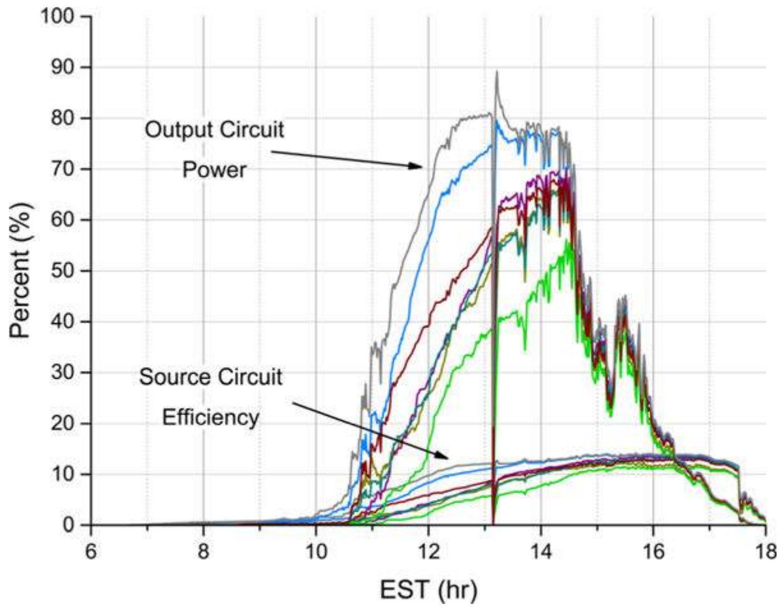

Fig. 7.

The output circuit power as a percent of the standard test conditions (STC) ratings and the efficiencies of the seven source circuits in the ground array during a time of partial snow coverage and later melting

Fig. 8.
The weather station

Fig. 9.
The stationary radiometers installed at the weather station, with the ambient temperature sensor also shown in the upper right

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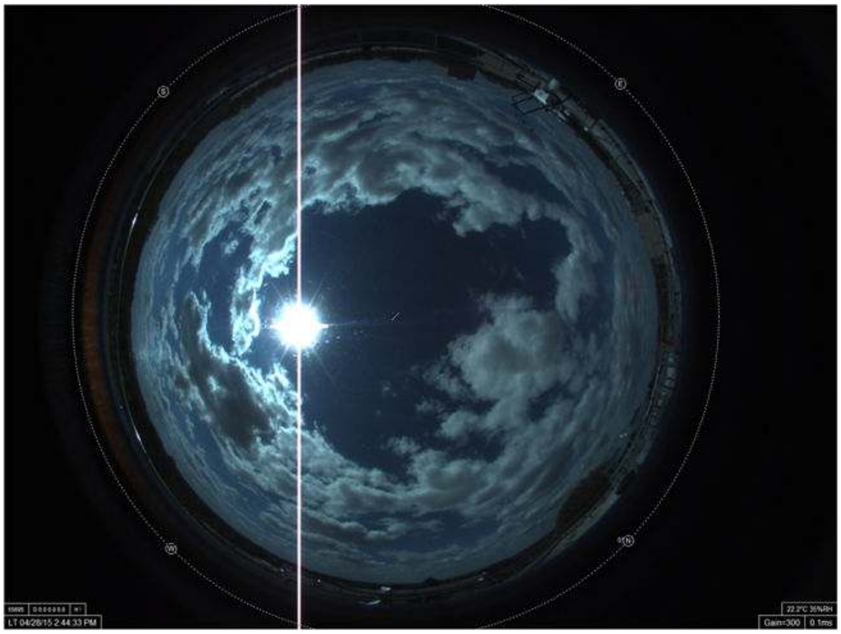

Fig. 10.
An image taken by the all sky camera

Table 1

Summary of the campus PV arrays

	Canopy	Ground	Roof
Array rated DC power (kW)	243	271	73
Latitude (°N)	39.1385	39.1319	39.1354
Longitude (°E)	−77.2155	−77.2141	−77.2156
Elevation[a] (m) (ft)	137 (450)	138 (453)	149 (489)
Height[b] (m) (ft)	5.11 (16.8)	0.67 (2.2)	0.08 (0.3)
Tilt (°)	5	20	10
Azimuth (° CW from N.)	90, 270	180	180
Number of modules	1032	1152	312
Module technology		Monocrystalline silicon—front contact	
Module rated power (W)		235	
Modules per string		12	
Number of source circuits	86	96	26
Number of combiner boxes	7	7	4
Number of inverters	1	1	1
Inverter rated power (kW)	260	260	75

[a]Elevation of the array support (e.g., ground, roof) above sea level.

[b]Height of bottom edge of the bottom module above the array support (e.g., ground, roof).