PROVIDING HIGH QUALITY DATA TO DEVELOP AND VALIDATE PV MODELS

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ABSTRACT

The National Renewable Energy Laboratory created a PV module testing facility that is being located at different sites around the country to provide high quality data to test and validate PV performance models. The facility will be located in Eugene, Oregon from December 2012 to February 2014. The rationale for the PV module test facility and activities planned while it is at the University of Oregon are discussed. Spectral data will be included along with global, beam, diffuse, and tilted data. Data will be averaged over five-second intervals and IV curve traces will be run every five minutes on 15 modules.


Fig. 1: NREL's PV module test facility at the University of Oregon.

1. INTRODUCTION - BACKGROUND

Utility scale photovoltaic installations require considerable financing that can run to $500,000,000 or more. As the cost of these large scale installations decreases, the incentives will be reduced and money necessary to pay back these loans will increasingly come from the sale of electricity being generated. The amount of electricity generated and the availability of this electricity depend on the solar resource as well as the efficiency of the modules and amount and type of storage available. Therefore understanding the amount and characteristics of the solar resource is very important when evaluating the economics of the solar electric facility.

Just as important is the knowledge of how well the photovoltaic (PV) modules perform in the field and the rate of degradation in performance over time. Many models have been created that estimate the solar radiation in the plane of the array from global horizontal irradiance (GHI) and/or direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI). PV performance models can use GHI values and/or the DNI and DHI components of the incident radiation to calculate the irradiance incident on the plane of array (global tilted irradiance [GTI]). Correlations between GHI and DNI and/or DHI have been a subject of research for years and are used to obtain the DNI and DHI components of radiation. Models also exist to project the DNI and DHI components onto tilted surface. Given the GTI and other meteorological values and PV module characteristics, models can be used to determine the amount of electricity generated. It is therefore important to know precisely how well each of these models works and if they will work equally as well in different locations, specifically various climate zones, around the world.

There has been a considerable amount of testing of photovoltaic modules in the laboratory and in the field. The methodologies used vary considerably. For example, photovoltaic modules are tested in the lab with artificial solar lamps and during production with flash test using artificial light. These tests are great during development stages for evaluating relative performance of solar cells or on the manufacturing line certifying the solar module specifications. However, field operating conditions can be significantly different from those in the lab and it is the electricity generated by the modules in the field that determine the kilowatt hours (kWhrs) that are used to pay the loan used to design and build the facility.

There are many products on the market that do predict the performance of photovoltaic systems from PVWatts (rredc.**nrel**.gov/solar/**calculators**/PVWATTS/version1/) and PVsyst (*www.pvsyst.com)* to NREL Systems Advisor Model (*https://sam.nrel.gov/)*.

These models were developed and tested using existing dataset that typically had uncertainties on the order of 5% and utilized models for estimating solar radiation on tilted surfaces that were develop from similar datasets. It is possible with the best instruments and quality maintenance to obtain much better results that can be used to validate, improve, or develop new PV performance models.

2. STATUS OF SOLAR INSTRUMENTATION

With billions of dollars being invested in solar electric facilities, more accurate and expensive pyranometer and pyrheliometers are being installed and improved instruments and monitoring techniques are being developed and tested. Most pyrheliometers have an accuracy of ±2% or better and the absolute cavity pyrheliometer such as the Hickey-Frieden Absolute Cavity Pyranometer (AHF) has an accuracy of better than ±0.5%. The absolute cavity radiometer is used to test and validate the accuracy of other pyrheliometers and is helping solar instrument manufactures to obtain a more accurate understanding of the systematic errors in their instruments and to develop improved models.

Using the shade/unshade method of calibration for pyranometers along with an absolute cavity radiometer for the direct normal measurement provides the best method of pyranometer calibration. Using the absolute cavity radiometer and a pyranometer with minimal thermal offset for diffuse measurements provides the most accurate calibration for pyranometers. Secondary standard pyranometers such as the Kipp and Zonen CM 22 have an uncertainty of ±2% or better if temperature compensation algorithms are used. Diffuse measurements made with a secondary standard pyranometer mounted on a tracker and shaded by a disk or ball provides highly accurate diffuse measurements.

For measurements on a tilted surface, secondary standard pyranometers provide for the most accurate measurements. First class pyranometer provide good tilted measurement but are not as accurate as secondary standard pyranometer. Photodiode base pyranometer, such as the LI-COR Li-200, don’t have any tilt affect but are subject to the spectral distribution of the incident radiation. Ground reflected irradiance alters the spectral distribution of the incident global irradiance and this in turn adds uncertainty to tilted surface measurements made using photodiode based pyranometers.

The most accurate measurements of global horizontal irradiance (GHI) are made with high quality pyrheliometers and quality diffuse measurements made on automatic trackers with shade disks. However, secondary pyranometers make the most accurate measurements of global tilted irradiance (GTI) because the ground reflected and partially obscured diffuse sky irradiance have to be modeled. The GTI is calculated by projecting the direct normal irradiance (DNI) onto the tilted surface, adding the portion of diffuse horizontal irradiance (DHI) seen by the tilted surface, and estimating the amount of ground reflected radiation incident on the tilted collector. The modeling of the portion of DHI seen by the collector and the amount of ground reflected irradiance are often done using crude geometric assumptions and have large uncertainties. Since these contributions are generally small compared to the DNI tilted component, these models are hard to validate, especially with size of uncertainties in the data assumed to be “true”.

3. ESTIMATING PHOTOVOLTAIC PERFORMANCE

Electrical measurements of PV module performance can be made to 0.5% or better. **The limiting factor in testing photovoltaic performance models is the measurement accuracy of the incident solar radiation**. This uncertainty results in models that have performance predictions that can differ by several percent and also prevents a determination of which model might be more accurate. In addition, attempts to improve model predictions are hindered by the lack of accurate irradiance measurements.

Further complicating matters is the fact that the output of photovoltaic (PV) cells is dependent on the spectral distribution, much like the photodiode pyranometers. This means that atmospheric aerosols and ground cover can affect model predictions. Therefore models that work well in one location might not work as well in another location where the aerosols and ground cover result in different spectral distributions.

The best quality solar radiation measurements are expensive. In addition, maintenance at solar monitoring sites may not be consistent and calibrations are not always performed in a uniform manner. Therefore the quality and accuracy of irradiance data are not consistent and likely to vary from one station to another.

4. SOLUTION TO THE PROBLEM

The National Renewable Energy Laboratory (NREL) has undertaken a multi-year project to solve this problem. Under the Technology Validation effort of DOE's Systems Integration program, NREL has develop a PV model testing facility using the highest quality solar radiation measurement instruments and quality IV curve tracing equipment to monitor the performance of a variety of photovoltaic modules of different technologies. The plan is to locate the test facility at climatically diverse locations around the country. The operators at each location are responsible for high quality maintenance of the equipment and provide onsite technical assistance to help the facility to run smoothly to ensure a more complete dataset. The test facility will be located at chosen sites for 14 months and then returned to NREL for calibrations before it is sent to another location. The first location chosen was at the Florida Solar Energy Center and the second location was at the University of Oregon Solar Radiation Monitoring Laboratory (see Fig. 1). Data for these locations, in addition to NREL's in Golden, CO will provide a diverse data set for PV model development and validation.

The resulting dataset will be created with a consistent set of highest quality irradiance monitoring instruments tended five days per week with uniform, documented maintenance. All calibrations will be performed on a regular basis at NREL. This reduces uncertainty brought about by use of different instruments operating under a variety of maintenance routines and calibration schedules. With this minimum of uncertainty, the strengths and weaknesses of the models will be easier to identify. In addition, the data will likely provide useful information for improving the models or developing new photovoltaic performance models.

5. PV TEST FACILITY

The PV test facility consists of an 8x8x20 shipping container with PV models mounted on the south side tilted at latitude and solar irradiance and other meteorological equipment mounted on the roof (see Fig. 1). PV monitoring and data logging equipment are mounted inside the temperature controlled trailer.

Fifteen solar modules are mounted on the south side of the trailer tilted south at 44°. Each module has a T-type thermocouple on the backside to measure module temperature. A Kipp and Zonen CM 22 pyranometer is mounted in the plane of array along with a LI-COR Li-200 pyranometer to measure incident solar irradiance. The modules are connected to a Raydec Multitracer MT-5 unit that takes I-V curves every five minutes with modules loaded at the max power point voltage in between measurements.

Two Kipp & Zonen CM 22 pyranometers and a CHP1 pyrheliometer are mounted on a Solys2 2-Axis tracker on the roof of the trailer. One of the pyranometers is shaded by a disk to obtain DHI measurements. No ventilators are used with the pyranometers. A Vaisala WT-520 weather station is used for the meteorological measurements of ambient temperature, wind speed and direction, relative humidity, air pressure, and precipitation. Data are collected in five-second averages along with standard deviations of the irradiance measurements.

6. PURPOSE OF THE MEASUREMENTS

All the measurements from the PV test facility are designed to test and validate PV performance models and to supply other information necessary to evaluate and emulate the PV module performance. PV performance models require, at minimum, the GHI and ambient temperature. Other parameters such as wind speed and direction and relative humidity play a secondary part in the models, but are often used to improve model estimates. Precipitation has proved useful in estimating the cleaning effect of rain to reduce soiling on photovoltaic modules. DNI and DHI measurements are used to more accurately estimate the solar radiation incident on the modules and the DNI component helps estimate the amount of light transmitted through the glazing.

The DNI and DHI components can be estimated from GHI measurements. However, these estimates are considerably less accurate than the actual measurements. The high quality data collect by this project can be used to more thoroughly evaluate models that estimate the DNI and DHI components from the GHI measurements. Once the DNI and DHI components of radiation are determined, models exist that can be used to estimate the irradiance on the plane of array. The tilted surface measurements can be used to test the model used to estimate the tilted surface irradiance.

The incident solar radiation, along with DNI measurements, and other meteorological measurements are used to predict the PV module performance. With the highest quality data available, the various PV performance models and their component models can be tested to a degree that was not previously possible.

The data collected at the various sites provide an extensive dataset with consistent instrumentation that is well

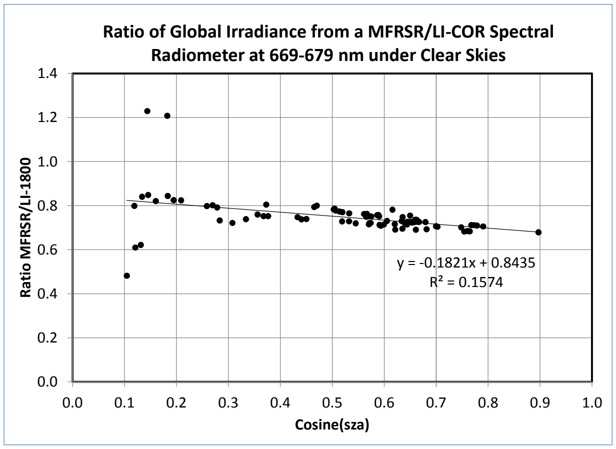

Fig. 2: Plot of the ratio of global irradiance between 669 and 679 nm from a MFRSR and a LI-CORR Spectral Radiometer. Data was taken under clear sky conditions during 2012 and the ratio is plotted against the cosine of the solar zenith angle that includes refraction of the atmosphere.

calibrated, well recorded maintenance at each location, and highest quality field instruments available.

7. AUXILIARY SPECTRAL MEASUREMENTS

Co-located at the PV test facility is a Yankee Solar Multi-Filter Rotating Shadowband Radiometer (MFRSR-7) that records global, diffuse, direct normal irradiance at six wavelength once a minute. The six wavelengths are obtained using 10 nanometer wide filters. Some of these filters deteriorate with time and adjustments have to be made to these measurements to obtain their true values. Once the true values are obtained, the spectral data can be fit to a spectral radiation model, such as SMARTS2.

In addition to the MFRSR, a LI-COR 1800 spectral radiation is used to take occasional measurements. The spectral radiometer produces 1 nm wide spectral data from 300 to 1100 nm. This spectral radiometer is temperature controlled to obtain stable and consistent measurements in the 800 to 1100 nm region. By using the spectral radiometer that has been calibrated against the LI-COR standard lamp, the MFRSR narrow band measurements can be properly adjusted to their true values (See Fig. 2.)

With the two spectral data sets, the spectral characteristics of the incident solar radiation can be determined. The spectral data can be used to determine if some of the deviations from the model estimates results from changes in the spectral distribution.

In earlier work [2], it has been found that the responsivity of the photodiode based pyranometers depend on the spectral distribution of the incident radiation. It was noted that the responsivity of the pyranometer to global irradiance on clear days is slightly different from the responsivity on totally overcast days. It is expected that PV modules could have similar behavior. Therefore the spectral radiometer will be used to take measurements in the plane of array of the modules and the efficiency of the modules can be tested under a variety of sky conditions. These data will help determine if there is any dependence on the spectral distribution of the incoming irradiance and estimate the magnitude of the effect.

8. OTHER USES OF THE DATA

Since there is very limited availability of five-second data, especially taken with high quality instruments, it is possible to utilize the data for many other purposes. One such example is to compare the data taken over a five-second interval with the average taken over the corresponding minute interval. This information is useful in determining a limit on the accuracy of instruments such as rotating shadowband instruments that make "instantaneous" measurements over a minute interval (see Fig.3).

Most of the data points fall along the zero axis, meaning the five-second data is a good representative of the one minute average data. January is typically very cloudy with many instances of zero DNI, so the results are not surprising. However, there are many times that the different is significant and this difference comes from the DNI value changing rapidly over the minute. If one plots the difference between the five-second data and the corresponding one-minute data against the standard

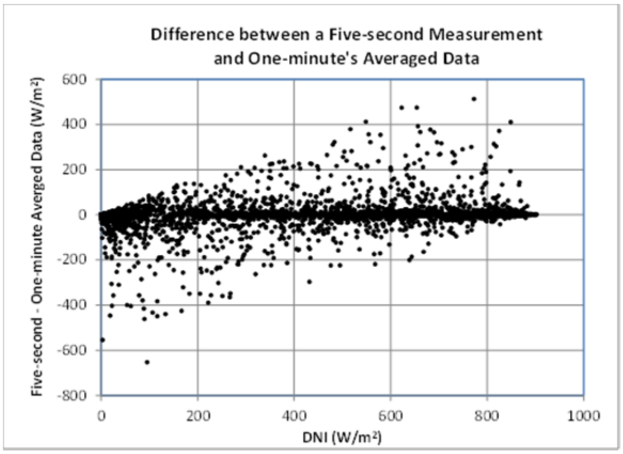

Fig. 3: Plot of the difference between five-second DNI data and the average minute data, January, 2013, Eugene, Oregon.

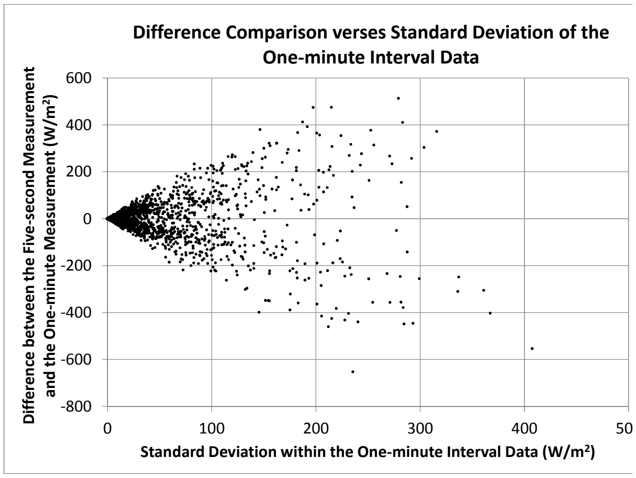

Fig. 4: Plot of the difference between the five-second DNI data and the corresponding one-minute averaged data against the standard deviation of the one-minute data.

deviation of the one-minute data, the difference shows a clear trend (Fig. 4). The standard deviation of the one-minute data is directly related to the accuracy of the five-second data in matching the one-minute data.

8.1. Long-term effect of cleaning

The fifteenth panel in the PV test array at the UO SRML is an old SolarX HE60 array installed in 1982 that has not been washed for thirty years. During the first six years, it was determined that the short circuit current decreased by about 1.4% from the buildup of dirt (3). The original ratio of short circuit current to incident irradiation was about 1.07 (milliamps/W/m^2). In January 2013, the ratio was 0.84 and this implies a 0.75% decrease in the short-circuit current per year. How much did the performance of the panel deteriorate over the thirty years and how much will the performance of the panel improve when it is finally washed? These are experiments that are planned this year.

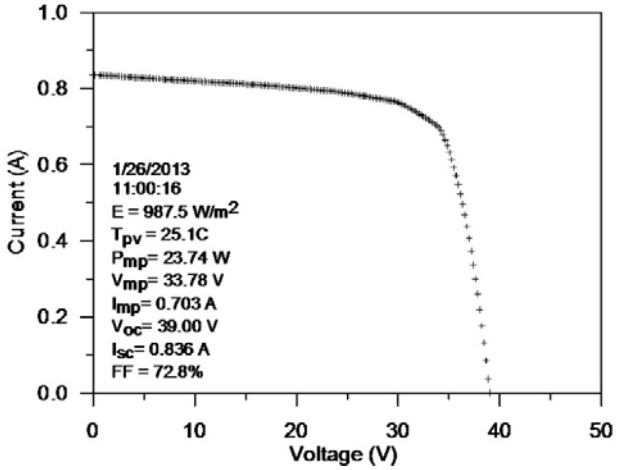

Fig. 5: IV curve from the NREL PV test facility for the SolarX 40 Watt module last washed in 1982, 30 years ago. Note that the environmental conditions are near standard conditions.

Fig. 5 shows the IV (current voltage) curve for the Solar X module. When compared to the IV curves of other panels, the fill factor is not so bad, but the panel only generates about 50% of its original output. During the summer the panel will be washed and then again installed for testing in the washed condition. It will be interesting to see how much of the degradation is related to dirty on the panel, and it is noticeable, and how much relates to the degradation of the panel over the thirty years that it has been exposed to the elements.

For comparison, the IV curve for another crystalline panel is shown in Fig. 6. Note the top of curve is flatter than the curve shown in Fig. 5, but the fill factor is only slightly larger.

9. SUMMARY

The NREL PV module test facility will run at the UO SRML from December 2012 through February 2014. An extensive data set will be obtained that will test various PV models at the Eugene location. The results in Eugene can then be compared with the results obtained at the Florida Energy Center and at future locations as they become available.

Just how well do these PV performance models work? Is

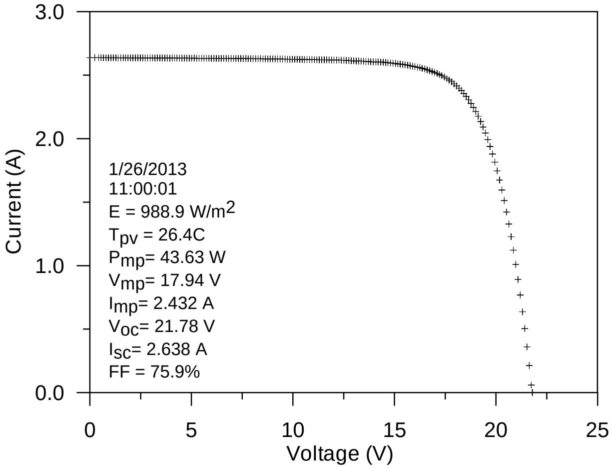

Fig. 6: IV curve from the NREL PV test facility for the newer module that has been out in the field for only 2 or 3 years and the panel has been washed.

the performance of the model site dependent? Are there opportunities to improve the performance of portions of the models with the more accurate data that are now available? Over time, answers to these questions will become available.

As photovoltaic facilities come down in price and incentives decrease, it will become more important to accurately predict how well the facility will perform. This project is one of many that are underway that will provide better answers and help reduce the uncertainty in power production.

10. ACKNOWLEDGEMENTS

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