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## **AC 2011-2652: INVESTIGATIONS ON SOLAR DATA AND A GRID-TIED SOLAR PHOTOVOLTAIC ARRAY**

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# **Investigations on Solar Data and a Grid-tied Solar Photovoltaic Array**

## **Abstract**

The purchase and installation of a grid-tied solar photovoltaic (PV) system in our institution for supporting a course titled “Alternative Energy Systems and Applications” provided us opportunities to develop new tools to support hands-on engineering education as well as carry out research in the area of renewable energy sources, particularly solar energy. This paper deals with the research we recently carried out on solar data availability and performance analysis of the grid-tied solar PV system. The academic goal of these investigations was developing tools and methods for analyzing available solar irradiation for assessing the performance of solar PV and solar thermal systems at the location of interest. One of the ultimate objectives was to accurately assess the availability of solar radiation and predict the performance of our grid-tied array of PV panels, and to compare the predicted performance with the actual one based on measured energy generated.

For solar radiation we investigated both locally measured data as well radiation databases based on measured data as well as data from theoretical models and hybrid models. Based on the different sources of data examined, different models were established for analyzing the performance of the PV panels and predicting their output power based on the manufacturer’s specifications. We have obtained different degrees of agreement between the actual measured performance of the system and the predictions of different models we developed. This paper will discuss in detail the approach we followed in our investigations, the models developed and the results obtained. Educational tools developed will also be discussed.

## **Introduction**

Use of solar energy as a renewable energy source has recently gained a lot of attention again due to the energy crises that appear to be repeating again and again. The performance of solar photovoltaic (PV) panels as well as solar thermal collectors will be highly dependent on the availability and strength of solar irradiation they are exposed to. Therefore, in order to predict their performance extensive and reliable data on the availability of solar irradiation at the location of installation is of paramount importance. The ideal situation would be having instruments such as pyranometers and pyrheliometers installed at the location of interest for collecting solar data for extended periods of time much like the practice of collecting wind data through the use of anemometers in order to perform feasibility studies on wind generator systems. The more data collected the more reliable the predictions of solar irradiation availability would be from a statistical point of view. However, this is simply not a practical solution for a project of arbitrary size and location. It is, therefore, necessary to use more practical methods for assessing the availability of solar irradiation for any particular application at an arbitrary location. Solar radiation data that can be obtained from various sources that provide extensive statistical data for numerous selected locations in the country might prove to be very useful for

this purpose. In this paper we discuss studies conducted along this line and give some examples of the results obtained and tools developed for analysis.

### Solar Data Analysis

For a particular location solar data may be available from a database that is based on either measured solar data or data generated by semi-empirical models at a local weather station or airport which may be a designated location for the National Solar Radiation Data Base (NSRDB). NSRDB stores statistical data for some 1020 locations in the United States and one can access this database via the Department of Energy's National Renewable Energy Laboratory<sup>1</sup> (NREL). In the absence of any of these resources one can opt to use a theoretical model for generating data for a clear day by using certain simplifying assumptions. A good source of the necessary sun-earth geometric relationships and those for an arbitrary flat plane surface can be found in Duffie and Beckman<sup>2</sup> or Goswami et al.<sup>3</sup> One starts with the solar constant,  $G_{SC}$ , which represents the extraterrestrial solar irradiance and determines that on a surface normal to the sun's rays on any day of the year using

$$G_{on} = G_{SC} \left( 1 + \frac{0.33 \cos \left( \frac{360n}{365} \right)}{365} \right) \quad (1)$$

where  $n$  represents the  $n$ th day of the year. This equation accounts for the fact that the earth-sun distance changes continuously throughout the year. The fact that the axis of rotation of the earth around itself is tilted  $23.45^\circ$  from the axis of the orbital plane of the earth around the sun requires the use of the solar declination angle,  $\delta$ , given by

$$\delta = 23.45^\circ \sin \left( 360 \frac{284+n}{365} \right) \quad (2)$$

At a particular location on the surface of the earth for an arbitrary plane surface the angle of incidence,  $\theta$ , can be obtained from

$$\begin{aligned} \cos \theta = & \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma \\ & + \cos \delta \cos \phi \cos \beta \cos \omega + \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega \\ & + \cos \delta \sin \beta \sin \gamma \sin \omega \end{aligned} \quad (3)$$

Here  $\omega$  is the hour angle,  $\phi$  is the latitude of the location,  $\gamma$  is the azimuth angle and  $\beta$  is the slope (inclination) of the plane surface. Figure 1 illustrates these angles and others. In the equations above all angles are in degrees, and  $\omega$ , which represents solar time can be determined from standard time by using

$$\text{Solar time} - \text{standard time} = 4(L_{st} - L_{loc}) + E \quad (4)$$

where  $L_{st}$  and  $L_{loc}$  are the standard time meridian and the longitude of the location of interest respectively and  $E$  is the equation of time in minutes and is given by

$$E = 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B) \quad (5)$$

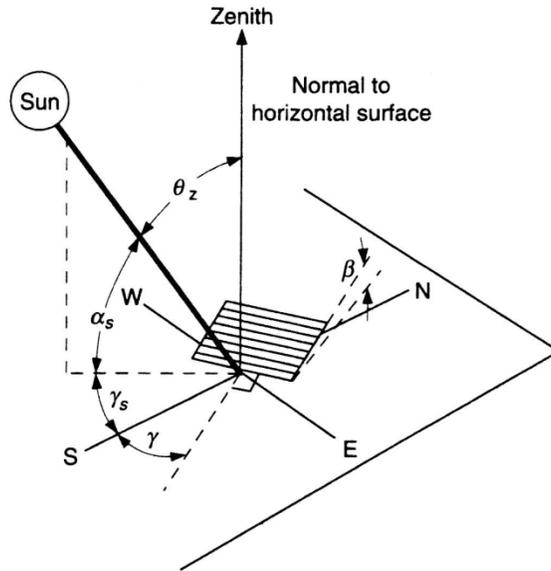


Figure 1. Different angles illustrated<sup>2</sup>.

where  $B$  is

$$B = (n - 1) \left( \frac{360}{365} \right) \quad (6)$$

and is in degrees. The radiation on a horizontal surface can be determined using the solar zenith angle,  $\theta_z$ , which is given by

$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \quad (7)$$

This is the angle of incidence of solar rays on a horizontal plane surface. The solar irradiance on a horizontal surface can then be found from

$$I_T = G_{on} \cos \theta_z \quad (8)$$

whereas the solar irradiance on any arbitrary flat surface can be found from

$$I = G_{on} \cos \theta \quad (9)$$

The last piece of the model has to deal with accounting for the attenuation of solar radiation as it propagates through the atmosphere. This can be done by using the concept of air mass and a model for attenuation given by the Beer-Lambert-Bouguer law. Equations (8) and (9) will also be particularly important in manipulating the measured data or modeled data in data bases to be evaluated for an arbitrary inclined surface.

As part of our studies conducted in the School of Engineering at Grand Valley State University (GVSU), we had access to solar radiation data collected and recorded at a weather station located on our main campus which is approximately 10 miles away from the location of our grid-tied

solar PV arrays, downtown Grand Rapids. Two strings of Unisolar model ES 124 PV panels are connected in parallel with 6 panels in series in each string. They are tilted at a fixed slope of approximately  $45^\circ$ , which is close to the latitude of our location. We wanted to compare first how the Grand Valley State University weather station data compared with those from NSRDB. NSRDB has published a large amount of data pertaining to solar availability. This includes hourly data, daily statistics, hourly statistics and typical meteorological year data. One of the 1020 designated locations throughout the US is the Grand Rapids Airport which is approximately 9 miles from our campus where the solar panels are installed. The hourly data from NSRDB that is needed contains entirely modeled data. That it is constructed through indirectly measured data. There are two different models used. The first is the meteorological-statistical model (METSTAT) and the second is the model from the State University of New York at Albany (SUNY). The METSTAT model was developed using National Weather Service (NWS) observations of total and opaque cloud cover and measured data from the Solar Radiation Network (SOLRAD). The improved METSTAT model utilized satellite imagery for total cloud cover estimates, and cloud height information. From this and the fact that opaque clouds usually occur at lower altitudes, total and opaque cloud cover estimates were developed for the METSTAT model. The SUNY model uses Geostationary Operational Environmental Satellite (GEOS) imagery to estimate solar radiation. This model relies on the inverse relationship between reflected irradiance from the clouds and atmosphere back into space and ground irradiance which is the radiation that reaches the surface of the earth. For more details one can refer to the users' manual of NSRDB<sup>4</sup>.

Figure 2 depicts the comparison of total irradiance on a horizontal surface obtained from different models and direct measurements.

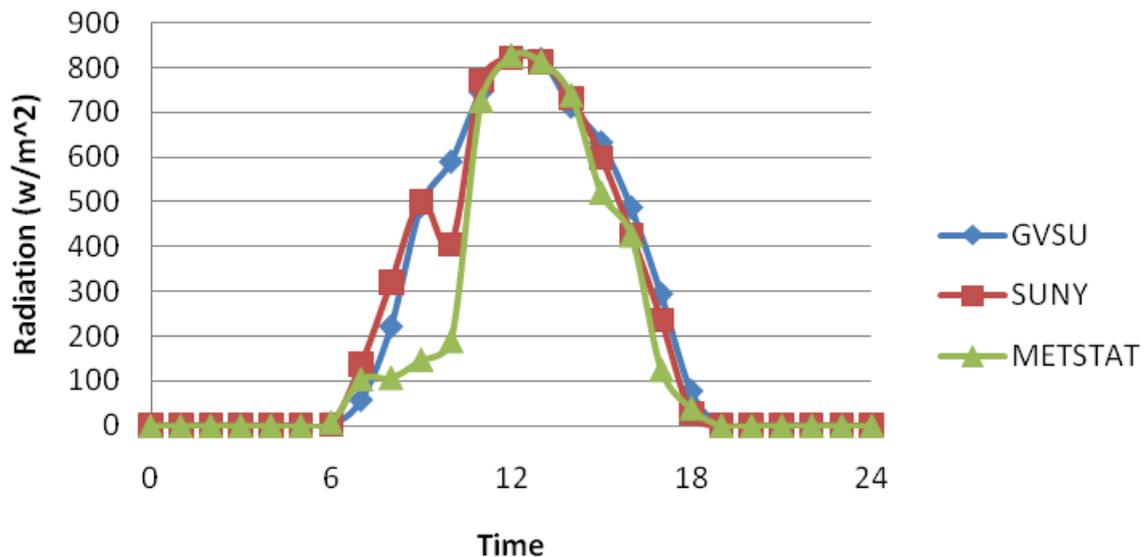


Figure 2 Comparison of total solar irradiance on a horizontal surface.

The direct (beam) radiation component of this is shown in Fig. 3. This was obtained by using the following model for the fraction of diffuse radiation on a horizontal surface<sup>5</sup>

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & \text{for } 0.22 < k_T \leq 0.80 \\ 0.165 & \text{for } k_T > 0.80 \end{cases} \quad (10)$$

where  $I_d$  represents the diffuse irradiance and  $I$  represents the total irradiance. The difference between the two is the direct (beam) component of irradiance. Here  $k_T$  represents the hourly clearness index, which is the ratio of the actual solar irradiance to extraterrestrial solar irradiance on a horizontal surface. The diffuse component of the solar irradiance is also plotted for comparison in Fig. 4.

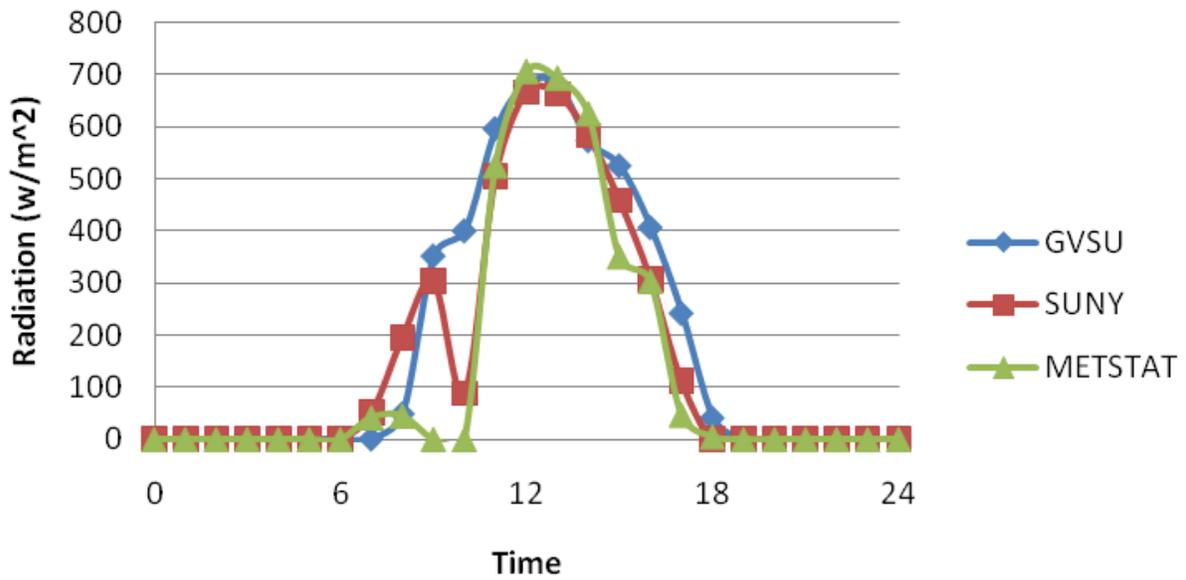


Figure 3 Comparison of the direct component of solar irradiance on a horizontal surface.

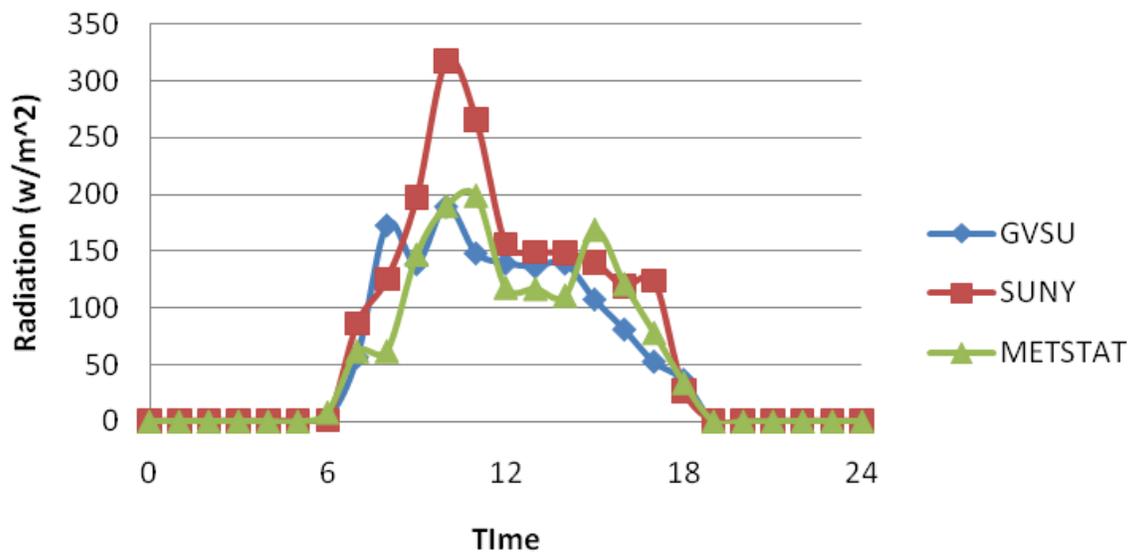


Figure 4 Comparison of the diffuse component of solar irradiance on a horizontal surface.

## Performance of a Grid-tied Solar PV Array

The second set of studies that were conducted dealt with analyzing the performance of our grid-tied solar PV array mentioned previously. The goal was to compare the actual measured power output with the predicted power output based on the solar radiation availability from two sources: the data from Grand Valley State University weather station and those from NSRDB for Grand Rapids Airport. First the characteristic  $IV$  curves (shown in Fig. 5) of the Unisolar ES 124 panels were obtained from the manufacturer's spec sheets. These curves were digitized by the use of the software named Engauge Digitizer V 4.1<sup>6</sup>. From the digitized voltage-current information the power was calculated from  $P = V \cdot I$ , and the power-voltage relationship was established for the

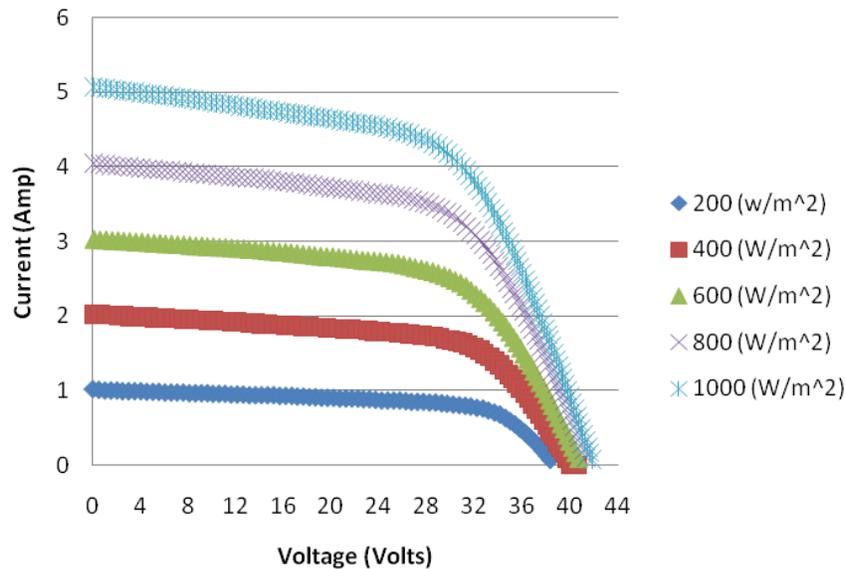


Figure 5 Characteristic  $IV$  curves of the solar PV panels

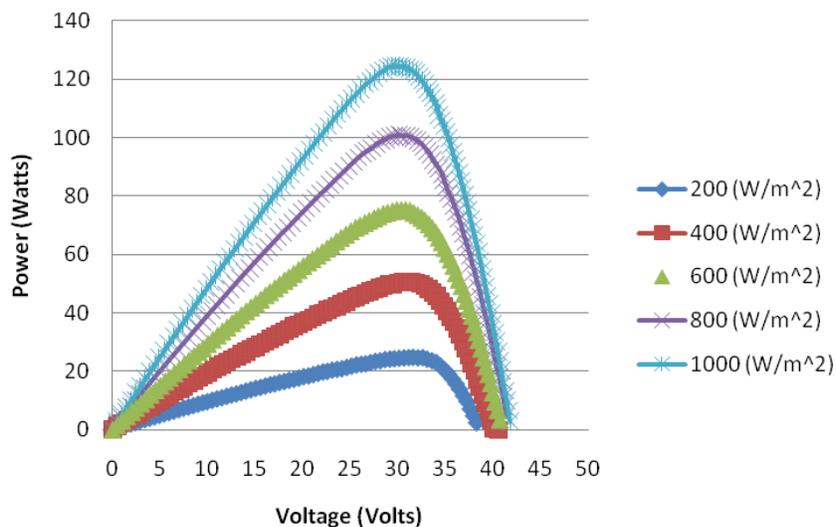


Figure 6 Power-voltage relationship of the solar PV panels.

solar panels as depicted in Fig. 6. The maximum power point was then found to be related to the available solar irradiation,  $G$ , in the following form:

$$P = 0.1251(G) + 0.2054 \quad (11)$$

where  $P$  is in watts and  $G$  is in  $W/m^2$ . Since this is for a single panel and there were a total of twelve panels in the array the total power output will be twelve times what is predicted by Eqn. (10). The actual measured data from the solar PV system has been collected at fifteen minute intervals since July 2009. GVSU weather station data, which was available as hourly measured data, was provided to us for this study covering the period of June 2008 through July 2010. Typical meteorological year (TMY3) data based on data for 1991-2005 from NSRDB has been used. In the interest of brevity only comparisons for selected months in which actual measured data and data from the GVSU weather station were available will be presented here. It should be mentioned that the theoretical model presented at the beginning of the section titled Solar Data Analysis leading to Eqn. (9) does not take into account the attenuation of solar radiation in the atmosphere and this was corrected through the use of air mass and a simple model for attenuation. However more sophisticated models for attenuation as per Kasten and Young<sup>7</sup> were not explored. Since the recorded time with actual measured data was standard time, solar time had to be determined and used in relevant equations in the model. Moreover, since NSRDB lists data for horizontal surface and latitude  $\pm$  multiples of  $15^\circ$ , and the GVSU weather station lists data for horizontal surface only, it was necessary to calculate the solar irradiance on the fixed panels by using the data available for horizontal surface and using modified form of Eqn. (8), which is

$$G_{on} = \frac{G_T}{\cos \theta_z} \quad (12)$$

that makes it possible to subsequently calculate

$$G = G_{on} \cos \theta \quad (13)$$

Note that  $G$  and  $G_T$  do take into account the attenuation of the solar radiation in the atmosphere. Figures 7-9 show comparisons of the measured and predicted power output of the array of solar panels for the first day of each of the three months selected here. Figure 7 appears to correspond to a clear day while Fig. 8 represents how different models can predict quite different power output from actual measured data for a cloudy day. Figure 9 happens to be a partly cloudy day but the mismatch in the measured data and the predicted data based on the solar data from the weather station shows that a 10 mile difference in the location of the facility and the weather station may make considerable difference in the results.

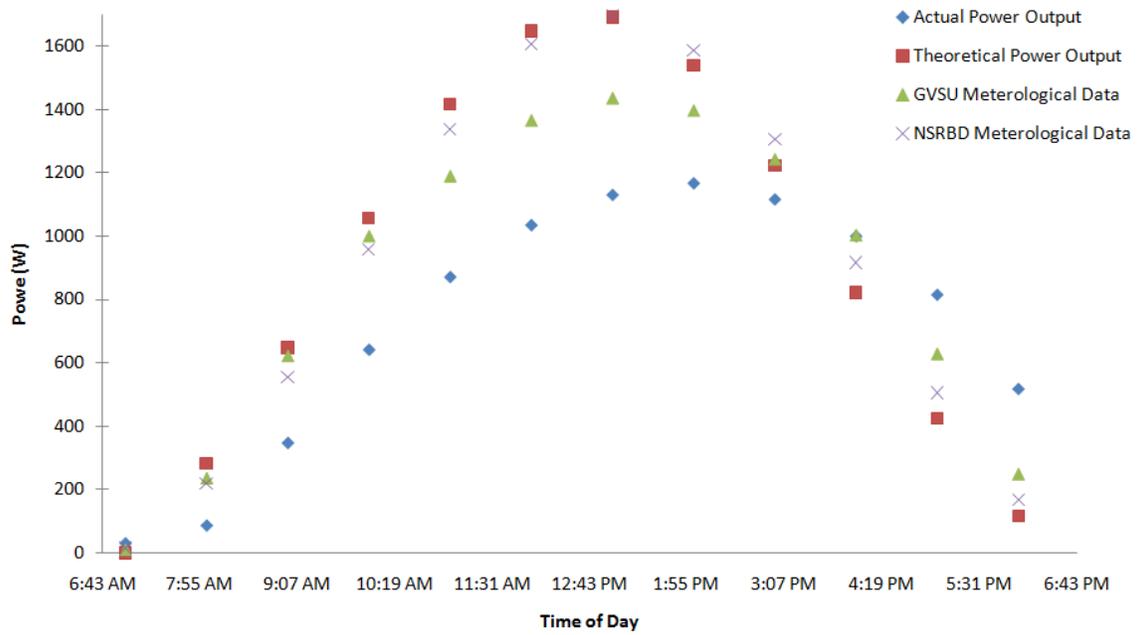


Figure 7 Power output comparison for June 2009.

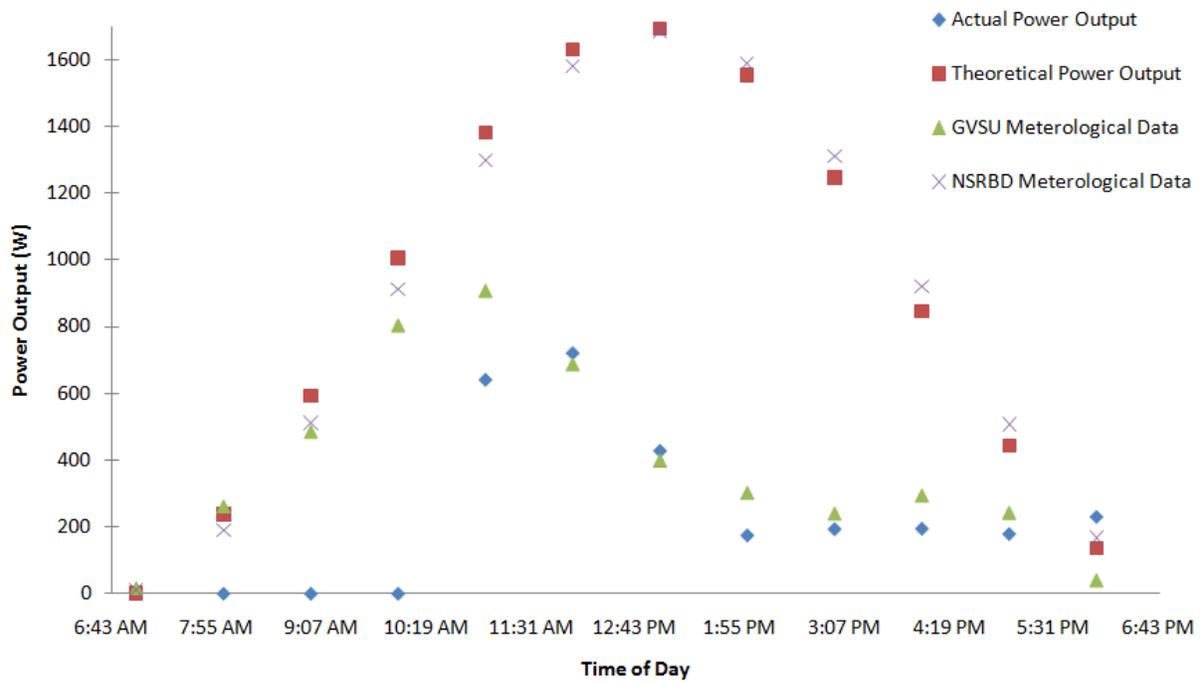


Figure 8 Power output comparison for August 2009.

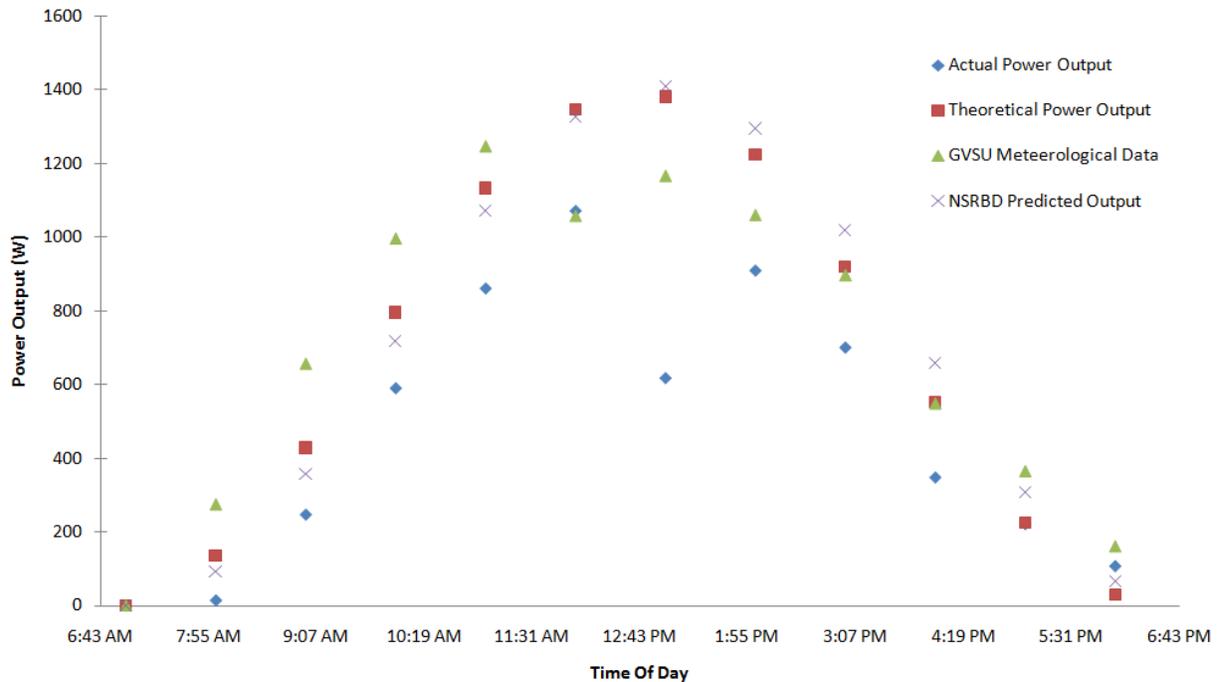


Figure 9 Power output comparison for October 2009.

#### Pedagogical Value of this Work

The students taking the “Alternative Energy Systems and Applications”, a new technical elective course at GVSU, are exposed to the basics of solar thermal and solar electric energy among other topics as described by the first author in previous publications<sup>8,9</sup>. One of the goals of the investigations presented in this paper was to examine different resources that could be utilized by the students in this course for assessing the availability of solar incident radiation at a given location in order to be able to perform technical feasibility analysis of a solar thermal or solar PV system. The second goal was to utilize such resources to conduct performance analysis comparison for an existing monitored solar PV system. Both of these investigations were intended to help determine what kind of realistic extended homework or mini-project assignments could be used in the course for reasonable and meaningful learning experiences for the students who were only exposed to solar thermal and solar electric principles for approximately a total of four weeks. As may be imagined, available resources may be quite varied in source, nature and extent. Therefore, any assignment that is not well thought out and designed may lead to unforeseeable roadblocks that will not result any meaningful outcomes and will be a source of frustration for the students. It was with this motive that such an extensive investigation was undertaken for exploring multitude of resources, their origins, their availability for different locations, the format in which the available data could be obtained, whether the data was purely theoretical, based on measurements or based on semi-empirical models. Most of these studies were conducted by one upper division undergraduate student and one graduate student with varying degrees of supervision and guidance provided by the instructor. The former student worked on an undergraduate assistantship funded through Grand Valley State University’s Faculty Teaching and Learning Center (FTLC) and worked during the summer

semester. The latter student was assigned part of this work as a mini-project that was part of the requirements of the dual-listed course during the semester the course was offered. By this time most of what was realistically doable in a relatively short time period was determined. There was some overlap between the tasks assigned to the two students partly in order to verify the accuracy of the analysis of the important data. Besides generating data from theoretical models, both students had to work with data that was imported from NSRDB or provided by the GVSU weather station. Both students chose to work with Microsoft Excel extensively for data import, modeling and analysis. All the models were implemented in MS Excel and all graphical outputs were generated through the same software.

By carefully planning these heavily student-involved studies/investigations and ensuing mini-project assignment we have established a set of baseline studies that can be carried out by the students as part of extended homework assignments or mini-projects on the topics of solar energy principles in the above mentioned course. The extent to which specifics will be provided to the students and what to expect from their side is quite clear in the instructor's mind. When the students are assigned appropriate work in the future based on these experiences they will be able to make use of our grid-tied solar PV panels as well as the data collected by the GVSU weather station for meaningful hands-on applications.

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