USING SUN PATH CHARTS TO ESTIMATE THE EFFECT OF SHADING ON PV ARRAYS

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ABSTRACT

Site Evaluation Forms developed for the Energy Trust of Oregon are discussed, particularly the estimation of the effects of shading on PV system output. Preliminary results from monitoring of six PV systems in Oregon are also discussed. A systematic difference between measured data and and PVWatts based modeled values as been found for low irradiance values.

1. INTRODUCTION

As the novelty of solar electric systems wears off, more users are becoming concerned about the amount of electricity being generated by the system. Tools, such as NREL's PVWatts http://rredc.nrel.gov/solar/codes_algs/PVWATTS/, already exist to estimate system performance. However, these programs do not take shading into account and treat the system as having near ideal performance. As more solar electric systems are being installed and the infrastructure is being established for more widespread use of these systems, the demand is increasing to get a better estimate of the actual performance of solar electric systems.

Three factors are important in getting better estimates of PV system performance:

- Knowledge of the solar resource at the specific location
- Talking account of tilt, orientation, and shading on electricity production
- Improved estimates of inverter and module performance

Working with Richard Perez at the Atmospheric Research Science Center at the University at Albany who produced solar irradiance values from satellite measurements, the University of Oregon Solar Radiation Monitoring Laboratory (UO SRML) has produced a solar radiation data base on a 0.1° grid for the Pacific Northwest. Work is now going on to update the National Solar Radiation Data Base and hopefully this density of information will become available nationwide.

The Energy Trust of Oregon (ETO), funded by system benefit charges, has a goal of replacing or reducing a percentage of electricity produced by fossil fuels. In initial discussions, the idea of paying incentives for electricity produced by photovoltaic systems was discussed. Because of the improvements being made in inverters and overall system performance and the wide variance of performance of installed PV systems, it was decided to base the incentive on installed kilowatts (peak DC) and require systems losses due to non-optimum tilt and orientation, and shading be less than 75% of the optimally oriented non-shaded system. In the meantime, the UO SRML is monitoring the performance of six PV systems in Oregon for the Trust to more accurately estimate the actual amount of electricity being produced by these systems.

The purpose of this paper is to talk about two aspects of this ETO project. The first section will discuss the Site Evaluation Form that was developed to aid solar contractors and the Trust in estimating the impact of surrounding objects that shade the PV array. The second section shows some of the initial results of the monitoring the PV system performance and will illustrate the effects of shading on the PV system performance.

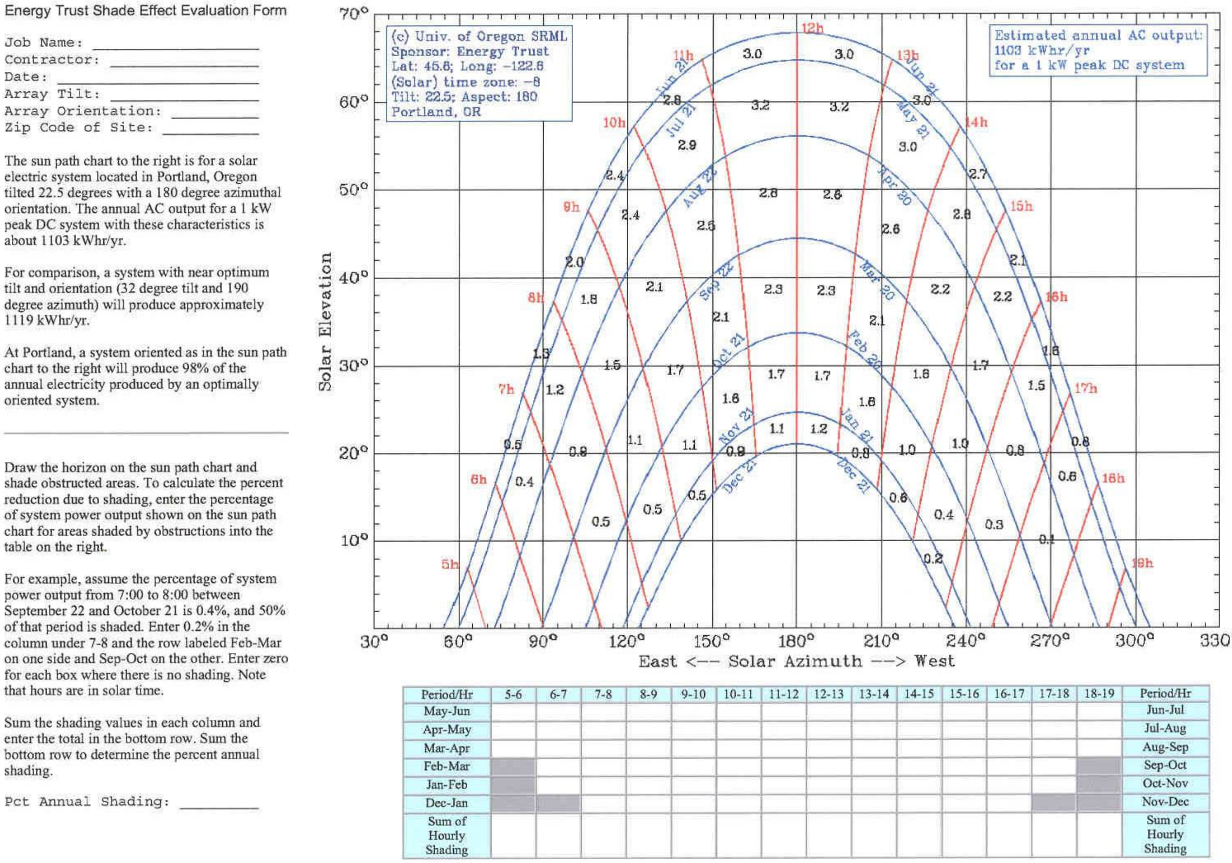
2. SITE EVALUATION FORM

The Site Evaluation Forms used by the Energy Trust of Oregon can be found near the bottom of their Web pages (See Fig. 1 for the address). The purpose of this form is two fold. The first is to estimate the effect of tilt and orientation on the output of the array by comparing the estimated output of an optimally oriented array with the estimated output of the planned tilt and orientation of the array. The second is to provide a method to estimate the loss of power generated resulting from shading of the array.

These Site Evaluation Forms were created for locations in Oregon with TMY 2 data sets for a variety of tilts and orientations. First the optimum orientation is found by using PVWatts to determine the orientation and tilt that produced the maximum output. This information was put on the form along with the estimated annual output of a system at the given tilt and orientation. Those filling out the Site Evaluation Forms can either use the information on the form or the calculated result for the tilt and orientation using PVWatts.

Next a sun path chart was produced to show the path of the sun across the sky from the summer to the winter solstices. Next hourly PV production was calculated using a program based on PVWatts. The percentage of electricity produced between the each hour for the given period was then calculated. For example, the power produced was calculated between December 21 and January 21 for each hour. This was also done for the November 21 to December 21 time period. The total electricity produce each hour was then divided by the annual electricity produced.

Two forms are required if local standard time is used because the hour lines during the first half of the year are different from those during the second half of the year (this is the result of the equation of time). By using solar time, the hour lines during the first half of the year are identical to the hour lines during the second half of the year and only one form is required. The percentage PV system performance between hours in solar time was obtained from the values calculated in local standard time. The percentage of each hour that occurs in the solar time hour interval was used to multiply the performance estimate in the local standard time interval and the value in the solar time interval is the sum of the apportioned values local standard time intervals. Next the values from times in other month period that were in the



Energy Trust Shade Effect Evaluation Form

Job Name: ____________
Contractor: ____________
Date: ____________
Array Tilt: ____________
Array Orientation: ____________
Zip Code of Site: ____________

The sun path chart to the right is for a solar electric system located in Portland, Oregon tilted 22.5 degrees with a 180 degree azimuthal orientation. The annual AC output for a 1 kW peak DC system with these characteristics is about 1103 kWhr/yr.

For comparison, a system with near optimum tilt and orientation (32 degree tilt and 190 degree azimuth) will produce approximately 1119 kWhr/yr.

At Portland, a system oriented as in the sun path chart to the right will produce 98% of the annual electricity produced by an optimally oriented system.

Draw the horizon on the sun path chart and shade obstructed areas. To calculate the percent reduction due to shading, enter the percentage of system power output shown on the sun path chart for areas shaded by obstructions into the table on the right.

For example, assume the percentage of system power output from 7:00 to 8:00 between September 22 and October 21 is 0.4%, and 50% of that period is shaded. Enter 0.2% in the column under 7-8 and the row labeled Feb-Mar on one side and Sep-Oct on the other. Enter zero for each box where there is no shading. Note that hours are in solar time.

Sum the shading values in each column and enter the total in the bottom row. Sum the bottom row to determine the percent annual shading.

Pct Annual Shading: ____________

Period/Hr	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	Period/Hr
May-Jun															Jun-Jul
Apr-May															Jul-Aug
Mar-Apr															Aug-Sep
Feb-Mar	▨													▨	Sep-Oct
Jan-Feb	▨													▨	Oct-Nov
Dec-Jan	▨	▨											▨	▨	Nov-Dec
Sum of Hourly Shading															Sum of Hourly Shading

Fig. 1: Site Evaluation Form for a south facing system tilted 22.5 degrees in Portland, Oregon. Forms can be found on the Energy Trust Web page at http://www.energytrust.org/Frames/Frameset.html?mainFrame=http%3A//www.energytrust.org/Pages/renewable_energy_programs/index.html

same range of solar elevation and azimuthal angle were added. For example the electricity produced from 11 to 12 o'clock solar time for November 21 to December 21 was added to the electricity produced from 11 to 12 o'clock solar time for December 21 to January 21.

With this form, it is now possible to estimate the reduction in system performance resulting from shading. First one has to determine the horizon using standard site evaluation tools (for example, Solar Path Finder™ or a Solar Site Selector™) and then transfer the information to the sun path chart on the Site Evaluation Form. When the sun is blocked by an obstruction, the contribution is set to zero and when the sun is unobstructed, the full percentage of electricity generated is credited. By adding the percentage loss due to shading in each interval, the amount of electricity lost to shading for the year can be calculated. To give an idea of the magnitude of the shading affect, let's say that an obstruction was 10° high all around and on a difference system the obstruction was 20° all around. In the case of the 10° obstruction, the shading would cause less that 1% loss for a south facing system tilted at 22.5°. In the case of a 20° obstruction, the lost would be about 8%.

The shading loss for systems with different orientations and tilts are different. An example of a shading calculation is shown in Fig. 2 and given in Table 1 for an east facing vertical surface. The shaded area in Fig. 2 shows the obstructions on the horizon. Table 1 uses the horizon diagram of Fig. 2 to estimate the effect of shading on the solar electric array.

On has to estimate the amount of shading in each interval. For example, between 5 and 6 about ¼ of the area is shaded and the percentage loss during that time is 1.4*2.4% or 0.6%. Table 1 gives examples for other periods.

Another way do identify the effects of obstructions is to use the Clean Power Estimator™ Obstruction Analysis.

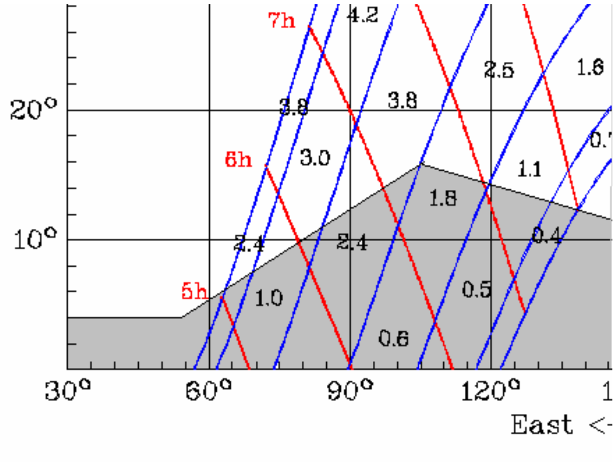


Fig. 2: Shading for an east facing vertical array. The shaded area is the horizon.

The amount of electric production lost by orienting a system away from an optimal orientation can be calculated using PVWatts or other solar electric system calculators. The overall system annual performance is then estimated by multiplying the amount of production lost from shading by the amount lost by orientation. Current the Energy Trust of Oregon required that the system produces more than 75% of an ideal optimally oriented system to qualify for funding.

3. SYSTEM PERFORMANCE

As photovoltaic systems continue to contribute to the energy mix, it will become more and more important to know or forecast the actual electricity generated. Some incentives such as the Oregon Solar Tax Credit are based on estimated system performance and green tags require measured system output. While there are tools to estimate system production, actual field experience is needed to refine these estimates and more accurately assess the electricity generated.

TABLE 1: SAMPLE CALCULATION OF SHADING. ANNUAL SHADING IS 6.7%

Period\Hr	5-6	6-7	7-8	8-9	9-10	10-11
May-Jun	2.4*(1/4)=.6	0	0	0	0	0
Apr-May	1.0*(.7)=.7	3.0*(.1)= 0.3	0	0	0	0
Mar-Apr	0	2.4*(2/3)=1.6	3.8*(.1)=0.4	0	0	0
Feb-Mar		.6*(1)=0.6	1.8*(.7)=1.3	0	0	0
Jan-Feb		0	.5*(1)=0.5	1.1*(1/3)=.4	0	0
Dec-Jan			0	.4*(.8)=.3	0	0
Sum of Hourly Shading	1.3	2.5	2.2	.7	0	0

Fig. 3: PV Power inverter meter at the Oregon Office of Energy in Salem, Oregon.

Table 2: PV MONITORING STATIONS

Station\Components	Inverter	Modules	Size
Bend	Sunny Boy 1800	BP 140	1120 W_p DC
Cannon Beach	Advanced Energy 5000	Siemens ST 20 ST 40	5200 W_p DC
Grants Pass	Sun Vista 3500	Sharp 185	3330 W_p DC
Klamath Falls	Sunny Boy 2500	Sharp 165	2970 W_p DC
Portland State	Advanced Energy 1000	Photowatt 100	1200 W_p DC
Salem	PV Power 1100	Sharp 165	1320 W_p DC

Fig. 4: SP-Lite pyranometer in plane of array at Portland

The Energy Trust currently bases it solar electric incentive on system size but in the future would like to evaluate the effects of the incentives in terms of kWhrs generated. While the Site Evaluation Form is used to more accurately estimate the system predicted performance, there is a desire to know the amount of electricity that is being generated. Therefore, Energy Trust is funding the UO SRML to monitor six PV systems in Oregon to determine how well the Site Evaluation Forms and the current models predict actual performance.

The goal of the monitoring project is to evaluate several different inverters and solar cell modules to see how close the systems perform compared to calculations using system specifications. In addition, effects such as shading and buildup of dirt on the arrays over time can be evaluated.

The sites monitored and the solar electric system characteristics are given in Table 2. In addition to the AC output of each system, the DC current and voltage output from the arrays are monitored. This helps in the evaluation of inverter efficiency. Incident solar radiation and global solar radiation are measured along with ambient temperature, wind speed, and solar module temperature. A Campbell Scientific data logger averages the data over five minutes and stores the data in memory for retrieval on a nightly basis. Fig. 4 shows the SP-Lite pyranometer that is used at most sites. Figs. 5 and 6 show examples of the transducers and data logging equipment.

A variety of current, voltage, and watt transducers from Ohio Semitronics Inc. were chosen. Where permitted inline transducers were used. The accuracy of the instruments is ±0.5% of full scale. However, the transducers were not designed for the variability of a PV system and readings at lower voltages and currents are not quite as accurate. The zero offset should also be watched. Temperature affects are typically about ±1% of full scale over a -10°C to 40° range. Out of 20 plus transducers that were examined, one sensor had a significant temperature drift and had to be replaced. It is always important to check the calibration of instruments.

The pyranometers were calibrated against first class instruments with calibrations to ensure the accuracy of the inci-

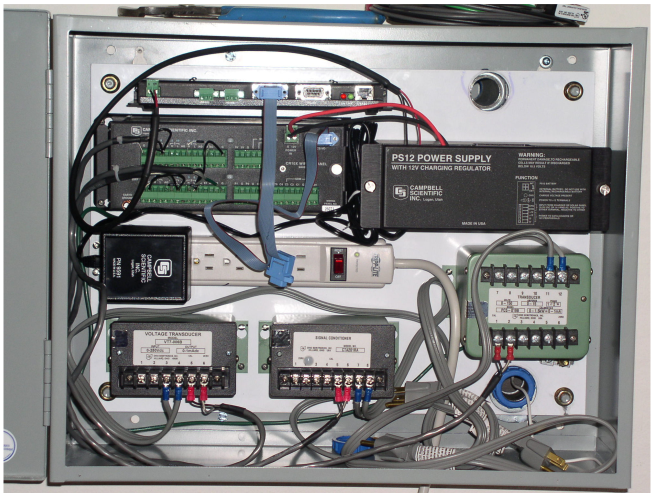


Fig. 5: Data logger and transducers at Salem, Oregon. The transducers are connected to the DC current and voltage into the inverter and the AC power out of the inverter. The transducers are connected to the Campbell data logger (top left) that is to the Internet.

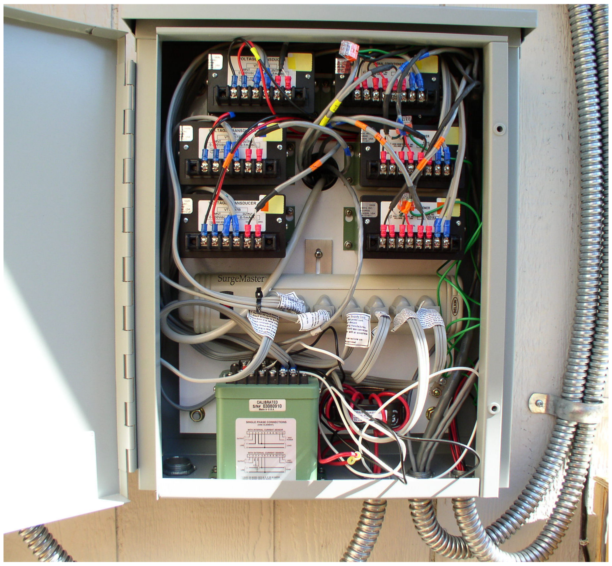


Fig. 6: Transducers for the three different arrays plus the AC watt transducer at Grants Pass, Oregon.

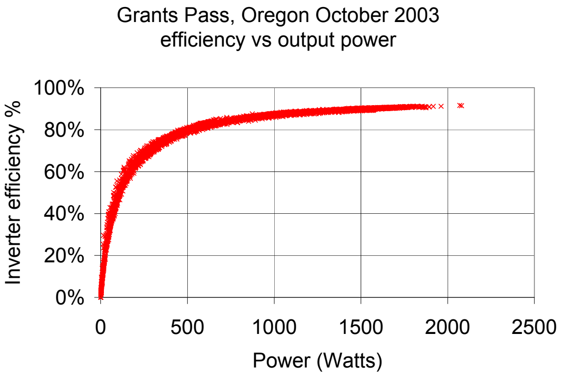


Fig. 7: Efficiency of a Sun Vista Inverter verses power out.

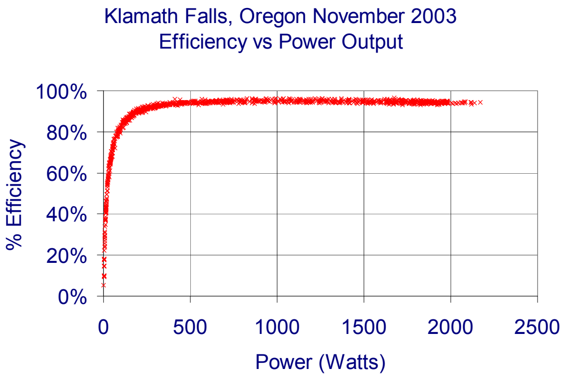


Fig. 8: Efficiency of a Sunny Boy 2500 inverter verses power out.

dent solar radiation measurements. The absolute accuracy of the irradiance measurements is about ±5% but the accuracy starts to fall off significantly at zenith angles above 80°. There are spectral differences between broad band pyranometers and solar cell based pyranometers.

By monitoring the DC current and voltage and the AC watts output, the inverter efficiency can be evaluated by dividing the AC power out by the DC power into the inverter. DC power into the inverter is the product of the DC current times the DC voltage. While this doesn't check how well the max power point software is working, it does give an idea of the conversion of efficiency of DC power into AC power. Figs. 7 and 8 show the inverter efficiency of a SunVista and a Sunny Boy inverter.

The comparison in Figs. 7 and 8 is not straight forward because the SunVista is hook up to three arrays, one facing west, one south, and one east while the Sunny Boy inverter is hooked up to one south facing array.

3.1 <u>Effect of Shading</u>

An example of the effect of shading on system output is shown in Fig. 9. Since the modules of the array are connected in series, the shading of one module will affect the output of the whole array. This is illustrated in Fig. 9 by noticing that the shading affects the solar radiation measurement for only a brief period of time, compared to the decrease in PV system output, and this shadow would also only affect each module for a brief period of time.

3.2 <u>Testing the PV Output Model</u>

An Excel add-in that is used at the UO SRLM for solar angle calculations was modified by including elements of PVWatts program. Since inputs to PVWatts require direct normal irradiance, a routine was also added to calculate beam irradiance from global

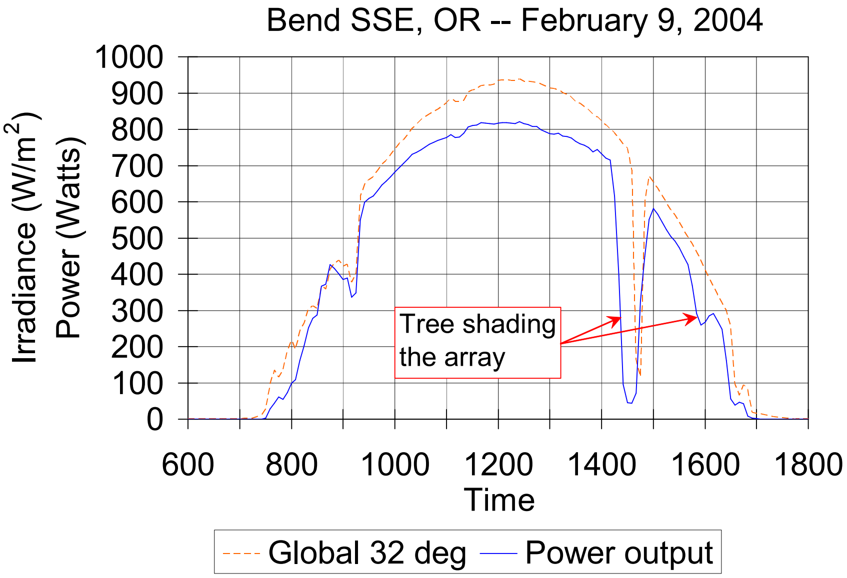


Fig. 9: Plot of PV power output and incident solar radiation for Bend, Oregon. The array consists of a single row of 8 modules connected in series. As the sun sets, a shadow of a tree sweeps across the array.

The dashed line is the incident solar radiation and the solid line is the output power of the array.

While the shadow only affects a small portion of the array, the output drops by about a factor of 10.

irradiance on the horizontal or tilted surface. This beam-global relationship only needs to give an approximate correlation.

With measured global and tilted irradiance, ambient temperature, and wind speed over the surface of the array, the AC and DC power output of the array can be calculated.

As input to the calculation, one needs to estimate the conversion of peak DC Watts at standard operating conditions to peak AC Watts at standard operating conditions. For the calculations in the paper a factor of 0.85 was used. This factor helps account for a variety of losses. By seeing the difference between the estimated and actual system performance, the applicability of the model can be tested and the appropriate conversion factor can be obtained. Results of a comparison will be shown for a few selected days, but more tests are needed to confirm these initial checks.

In Fig. 10, the measured output from the photovoltaic array is compared with the calculated output using a modified PVWatts calculation. From 11:00 am to 1:00 pm, the difference between the measure and calculated output is less than 1% for this day. This is well within the uncertainties of the measurements.

Another way to look at the comparison is to plot the ratio of the calculated output to the measured output against the incident solar radiation. Fig. 11 is typical of plots for sites examined to date. The output of the system in Klamath Falls is only about 93% of the calculated system output. The question is why the system in Bend is performing closer to the estimated output than the system in Klamath Falls. Some of the difference can result from the accuracy of the measurements, but there are many other possibilities.

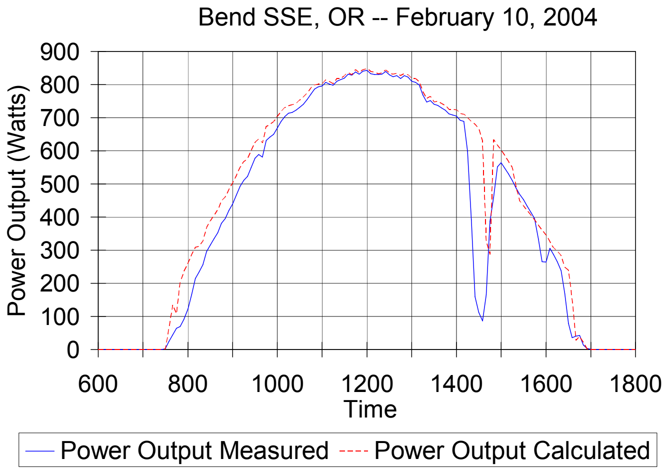


Fig. 10: Comparison of measured and calculated PV power output. The dashed line is the calculated output and the solid blue line is the measured PV output.

4. SUMMARY

Efforts are underway to improve estimates of electricity generated from photovoltaic systems and to better understand and model PV system performance in the field. Three steps are being undertaken to do this in the Pacific Northwest.

- More comprehensive characterization of the solar resource
- Development of tools to take into account the effects of system orientation and the effects of shading
- Evaluating photovoltaic system performance and models that estimate system output

A regional solar radiation data base derived from satellite data has been developed to augment the regional solar radiation data monitoring network. Site Evaluation Forms have been developed for solar installers to evaluate the effects of orientation and estimate the effects of shading. These forms also aid in best location for the modules.

Six photovoltaic systems are being monitored to assess the performance and PV systems in the field and to improve the accuracy of models that assess system performance.

5. ACKNOWLEDGEMENTS

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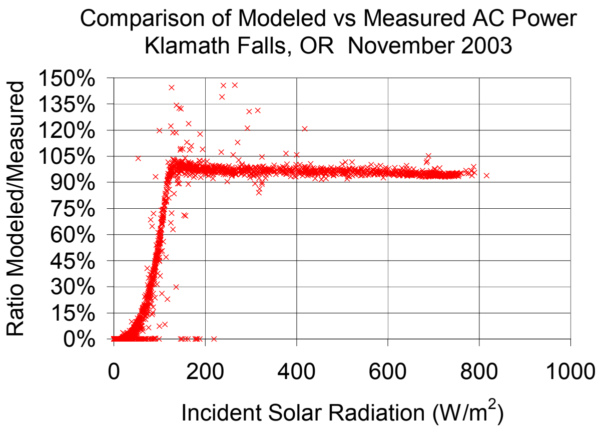

Fig. 11: Comparison of modeled output divided by measured output. Values are in %. For incident solar radiation below approximately 125 Watts/m^2, the modeled irradiance is significantly less than the measured irradiance. This drop off is typical for sites that have