SHADING ON PV SYSTEMS: ESTIMATING THE EFFECT

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ABSTRACT

Shading of photovoltaic (PV) panels can significantly reduce system performance. When an array of PV panels are connected in series, shading on even one panel in the array can reduce the performance of the array as if all panels were shaded. This article studies the effect of shading on one system consisting of two arrays of four PV panels connected in series. The two arrays are connected in parallel and shaded by a flagpole. Shading effects are estimated in two manners. First, by looking at the percentage of the sky blocked by the nearby flagpole and another more comprehensive method looking at the spatial movement of shadow from the flagpole as it moves across the panels during the day. The method and tool used in the more comprehensive evaluation are discussed along with insight into when the spatial methodology should be used.

1. INTRODUCTION:

Shadows on photovoltaic (PV) panels can significantly curtail the performance of the PV system. In fact, when one panel in a series is shaded, the output of the panels connected in series reacts like all panels are shaded. A simple test of a PV module is to shade one cell in the module and see what happens to the output. If all the cells are connected in series, the production of the modules drops to basically to zero. Now this is may not be true for all types of PV modules and some modules may have by-pass diodes that reduce this problem, but there are many modules being installed that exhibit this behavior.

Therefore is it important to install PV panels so that shading is minimized. In practical applications, shading cannot be avoided. Therefore it is important to know how much the shading will affect the system performance and develop designs to minimize the affects of shading.

Sun path charts have been developed that show the degree to which shading affects system performance when the sun is in various quadrants of the sky (see http://solardata.uoregon.edu/SelectShadeForm.html and [1]). There are also siting tools now coming onto the market with which sun paths are superimposed on photographs and the effect of shading is calculated automatically.

These tools are very useful and give a good first estimate of the shading problems likely to occur. However, detailed evaluation of PV system performance on a 5 minute basis has shown limitations of the current practices. Basically, shadows move across the array and a single snapshot of the shading problem does not fully reveal the potential shading problem.

To demonstrate the problem with shading, an extreme example is examined where the shadow from a nearby flagpole moves across two arrays of panels, each array of four panels is connected in series and the two arrays are connected in parallel. A solar angle calculator is used to trace the movement of the shadow across the arrays and the corresponding output of the PV system is compared to standard estimates of shading and the more detailed spatial analysis.

While each situation differs, the methodology used in the example can be applied to a variety of situations and a better understanding of the effects of shadowing can be obtained. The article is organized as follows. First, the system used in this example is described. Next the output of the system during the day is shown to illustrate the

Fig. 1: Flagpole located to the east of a 1.3 kW photovoltaic system. The system is tilted at 45° and an azimuth of 200°, a little west of true south. The pyranometer is mounted on the top of the panels between the third and fourth panel from the east.

shading problem. A brief description of a first order shading analysis is given followed by a detailed spatial analysis as the shadow moves across the array. The summary of the results are then presented along with recommendations of when a more detailed spatial analysis is needed.

2. PV SYSTEM BEING EVALUATED

The photovoltaic system in Salem consists of two arrays of 4 Sharp 165 Watt panels. The panels in each array are connected in series and the two arrays are connected in parallel to a PV Powered 1100 inverter. The panels are tilted 45° facing southwest with an azimuth of 200° (Fig. 1). The system is nominally a $1.32\text{kW}_{\text{peakDC}}$ system. There is a global pyranometer (SP Lite Pyranometer) on the roof of the building and a similar pyranometer mounted in the plane of the array between the third and fourth panels from the east. A flagpole is located just east of the system.

Ambient temperature, wind speed, solar cell temperature are also measured along with DC current and voltage and AC power output. A Campbell Scientific data logger reads the inputs every 2 seconds and output averaged 5-minute data. The data from this system are available from the University of Oregon Solar Radiation Monitoring Laboratory Website at http://solardata.uoregon.edu/SelectArchival.html. Click on Salem, specify the months of interest, and then click on “select files” to download the data.

The solar radiation data have an absolute accuracy of about 5% except for incident angles greater than 70°. The voltage, current, and power readings have an accuracy of better than 1% at full scale. Ohio Semitronic transducers are used for these measurements.

3. SYSTEM PERFORMANCE

When examining the data, two problems readily appear. The first is the inverter drop outs that occur from time to time. According to the inverter manufacturer, these dropouts are related to fluctuations in utility voltage. Some credence can be given to this because the dropout problem tended to disappear when the inverter was “re-calibrated” to match the voltage window as seen from the utility.

The other problem had nothing to do with the performance of the PV system components, but rather with the shading of the system by the flagpole as its shadow passed across

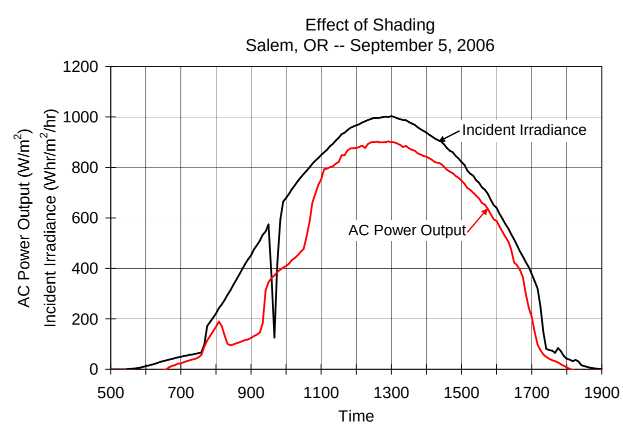

Fig. 2: Output of the PV system in Salem, Or. on September 5, 2006. The bottom red line is the AC power output of the system during the day. The top black line is the incident solar radiation. Note the drop in incident solar radiation as the shadow of the flagpole passes over the pyranometer at around 9:45 am. The effect of shading from about 8:00 am to nearly 11:00 am is much more severe for the AC output.

the face of the panels. A typical plot of system performance on a clear day is shown in Fig. 2.

During the morning, around 8:00 am in this example, the system output drops dramatically and only increases slightly as the incident energy increases. Then around 9:30 am, the AC output takes a big jump, but still doesn't achieve maximum the expected output. From 9:30 am to around 11:00 am, the AC output increases at a rate much closer to the rate of increase of the incident solar radiation than measured between 8:00 am and 9:30 am. It still falls short of the "expected" rate of increase. Then around 11:00 am, the production of the system jumps to a more expected rate and the system output follows the incident solar radiation for the rest of the day.

Also plotted in Fig. 2 is the incident solar radiation from the pyranometer mounted in the plane of the array between the 3rd and 4th panel. The shadow of the flagpole passes over the pyranometer at about 9:45 am. There is a significant drop in incident solar radiation when the flagpole shades the pyranometer and all the pyranometer sees is the diffuse radiation from the rest of the sky.

At first glance, one might expect that the performance lost from the shadow is just equal to the percentage of shading on the array. This is a classic example where an intuitive assumption about the performance does not match what actually happens.

3.1 Explanation of system performance

What physically happens is that at about 8:00 am in the morning the sun comes into position to cast a shadow from the flagpole across both arrays. Just as with putting a hand over one solar cell can basically shut down the output of the whole panel, the shading significantly degrades the performance of the whole system. Both strings of four panels are affected.

Some electricity is actually produced because the diffuse irradiance still strikes the panels. Slowly the number panels shaded in the west array is reduced. Then around 9:30 am, there is no longer any shading on the four panels

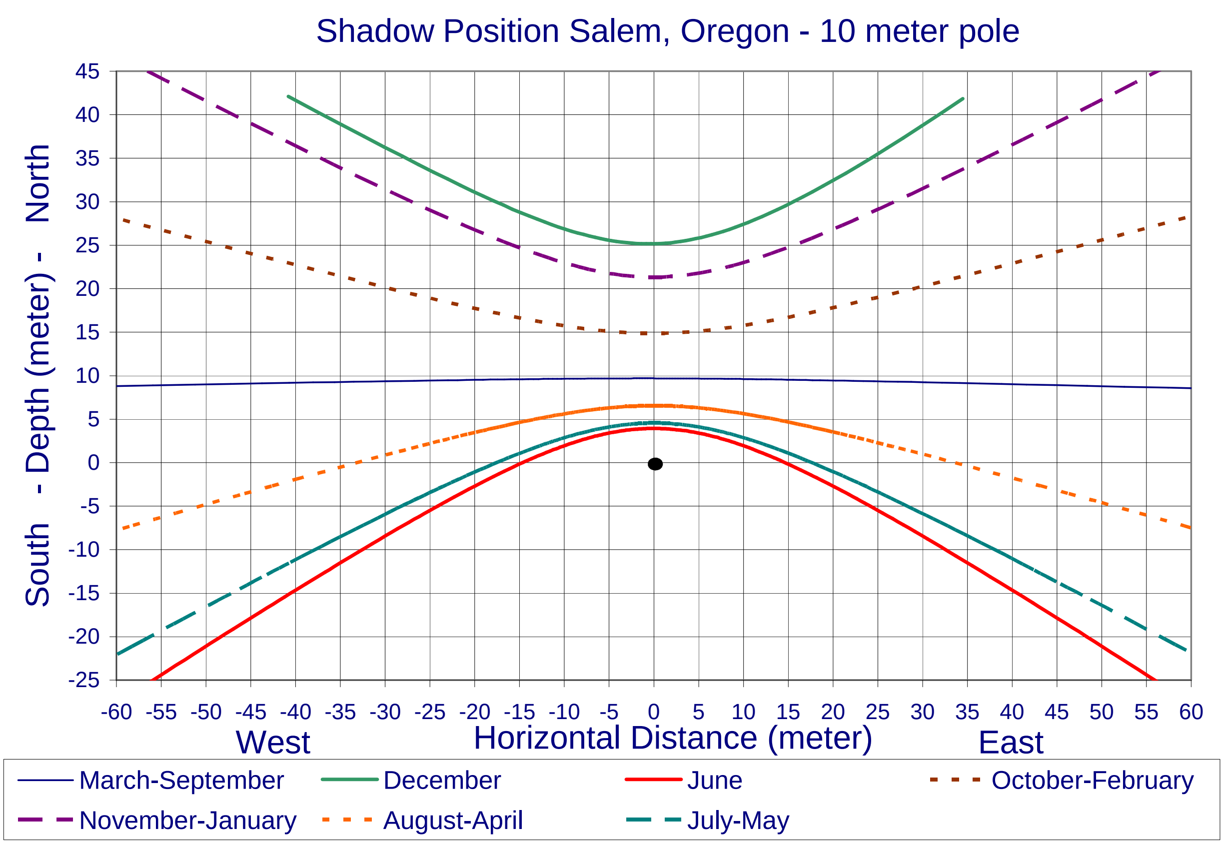

Fig. 3: A plot of the end of the shadow cast by a 10 meter pole for the 21 of each month. The paths are shown until the sun gets within 10º of the horizon. Note that for March 21, the shadow from a 10 meter pole does not extend more that 10 meters in front of the pole. This is because the latitude of Salem, Oregon is near 45°. Plots for different latitudes would look different.

in the west array. So the west array goes into full production but the east array is still shaded. Note that only when the nearly all the shading is removed from all four panels connected in series does the production for that array return to normal.

From 9:30 am to 11:00 am the shading on the east array decrease. Note that the production of the system increases in proportion to the solar radiation on the west array and the diffuse irradiance on the east array. Around ll:00 am, the last of the shading from the flagpole ends and the system production returns to normal.

4. <u>METHOD TO ESTIMATE AFFECT OF SHADING</u>

Since the simple method of estimating the amount of sky blocked by an obstacle during certain times of the day (year) does not adequately explain the production loss due to shading, it is necessary to find another method that will help predict the effect of shading.

A program is needed that calculates the angle and extent of shadow on the array over the day. Solpos on the NREL Website (http://rredc.nrel.gov/solar/codes_algs/solpos/#solpos) and the solar angle calculator on the University of Oregon Solar Radiation Monitoring Laboratory (UO SRML) Website (http://solardata.uoregon.edu/DownloadExcelAddin.html) are two programs that will calculate the solar angles necessary. Solpos is a C program that calculates solar angles and the UO SRML solar calculator is an Excel add-in that is derived from Solpos and PVWatts. The UO SRML solar calculator is also used to estimate the electricity produced during various times of year. The method to estimate the loss of PV system production utilizes the UO SRML solar angle calculator.

The first step in estimating the effect of shadowing on a PV array is knowing how a shadow will track across the PV array. For a simple example, we took a 10 meter pole in Salem, Oregon and traced the end of the shadow as the sun moved across the sky. The shadow cast by the pole on a horizontal surface is shown in Fig. 3. The shadow length is calculated trigometrically knowing the zenith or incident angle. The vertical (north-south axis) and horizontal (east-west axis) distance can be calculated knowing the

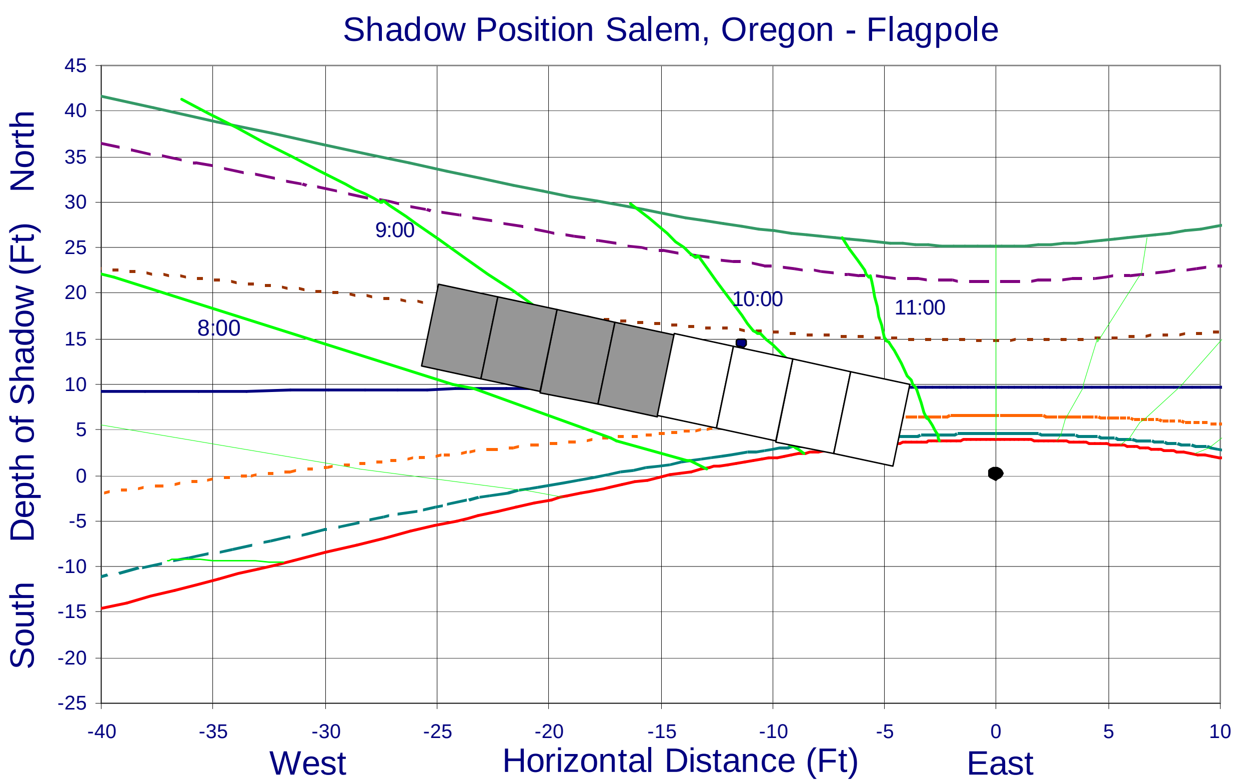

Fig. 4: Photovoltaic array overlain on shadow plot for Salem, Oregon. The black circle marks the flagpole and the dark blue line at about 10 feet is the shadow length for a 10 foot pole on September 21. Note that the pole shades the arrays from just after 8:00 am to about 11:00 am. The x-axis is in the east west direction and the y axis is in the north south direction.

azimuthal angle. The traces stop when the sun gets within 10º of the horizon because very little of the electricity is generated for this location when the sun is within 10° of the horizon.

There is also a lot of useful information in Fig. 3. First, note that from the spring to the fall equinox, the shadow does not extend more than 10 meters in front of the a 10 meter pole. Of course Salem is located very close to 45º north latitude and at the equinoxes, the solar declination is zero. The sun path would be different for different latitudes.

With knowledge of the shadow's path, one can next calculate the time period when the panels will be shaded. Using the Salem example (Fig. 1), the solar system array is superimposed on the shadow diagram (Fig. 4). The scale is not exact because the height of the flagpole was not measured. Also the times shown on the plot are solar times whereas the times in Fig. 2 are local standard time (about 10 minutes ahead of solar time for September 5 in Salem).

As discussed in section 3.1, as the shadow from the flag pole starts to shade the PV system, all panels are shaded shortly after 8:00 am. Then about 9:30 am, the shading on the west array ends and around 11:00 am all shading from the flagpole has ended.

Fig. 4 confirms that the shading of the arrays causes the decrease in performance and also helps to confirm that the shading of one panel connected in series in an array affects the performance of the entire array that is connected in series.

4.1 Estimating the Shadow's Effect on Performance

A spatial representation of the movement of the shadow across the PV system has been demonstrated in Fig. 4. The next step is to use this graphical representation to estimate the affect of shading on the system performance. This can be done much in the same way as sun path charts are used to estimate production loss due to shading. Instead of using just the area of the sky blocked by the obstruction (the

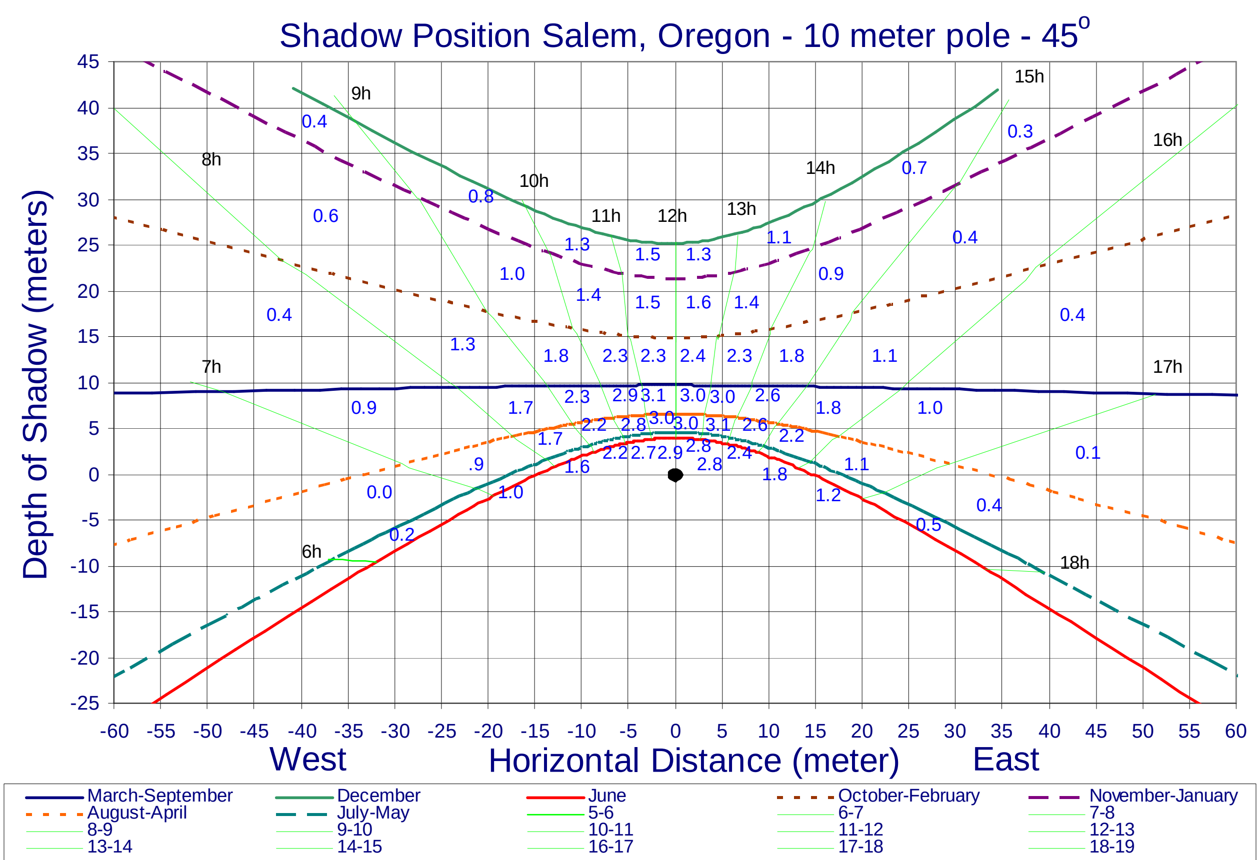

Fig. 5: A special representation of the shadow cast by a 10 meter pole and the percentage of solar energy during each time period and month. For example between 10:00 am and 11:00 between March 21 and April 21 and between August 21 and September 21, a total of 2.9% of the total annual electricity of a south facing system tilted 45° in Salem, Oregon is produced.

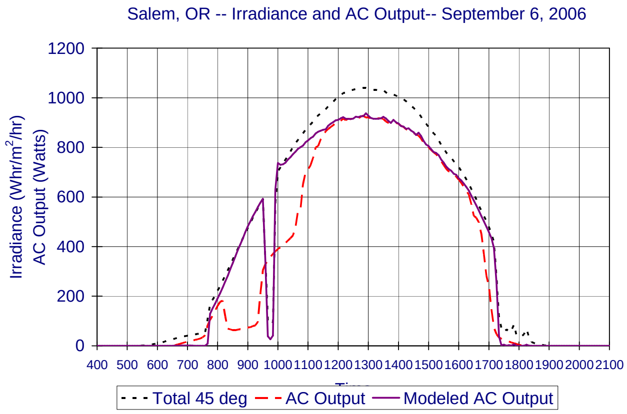

Fig. 6: Model estimate of PV system performance based on incident beam irradiance and PVWatts algorithm. The dotted blue line is the incident solar radiation on the arrays. The dashed red line is the actual PV system performance. The solid purple line is the modeled estimates using incident solar radiation.

flagpole in this example), the areas affected by the shadow are used in the estimate. Inherently this is a more accurate procedure because the effect of the shadow as it moves across the array can be visualized and the effect of panels connected in series can be estimated.

Fig. 5 shows percentage of energy available during specific times of year between various hours for a 45° tilted system facing due south in Salem, Oregon with respect to a 10 meter pole. The pole can be scaled to any height to represent the actual situation. Multiple poles or other types of obstruction can be constructed from this simple figure. However, these complications will not be discussed here.

Note that the percentage of total energy in each quadrant will vary with the tilt of the array. Typically as the tilt of the array increases, the more energy will be produced when the sun is lower in the sky.

Sketching the PV system on the diagram such as done in Fig. 4 shows when each array is shaded and comparing the areas in Fig. 5 show the amount of production that can be lost during the shading period. To properly estimate the production lost, it is important to know which modules are connected in series. Basically, modules or arrays connected in parallel are considered as independent. Modules connected in series are all affected by the shading of just one panel.

Fig. 6 shows a comparison between an estimate of PV output using the tilted irradiance compared to the actual

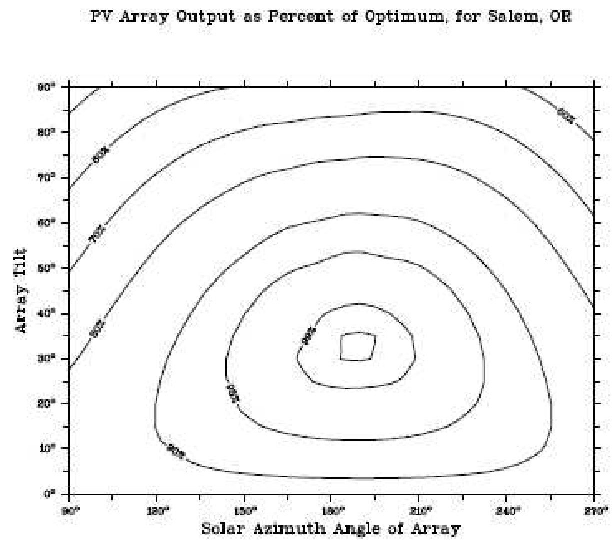

Fig. 7: Performance contour plot for Salem, Oregon. Note the wide range of orientations and tilts that yield performance within 95% of maximum performance.

PV output. This is the method similar to shading analysis using a sun path chart. The shading using the tilted irradiance shows only about 2.5% decrease in PV production. In actuality, the shading produces about a 14% decrease in PV production on September 6.

To estimate the percentage decrease in performance caused by the shading, use Figs. 4 & 5. Assume that between 8 and 9 am, both arrays are shaded. Therefore from Fig. 5 a loss of about 1.7% of the yearly total is expected. Between 9 and 10 am, about half the production is lost from the west array and all of the production is loss by the east array, or about 1.7% of the yearly production. Between 10 and 11 am, the west array is not shaded and the east array is shaded so about 1.45% of the production is lost. For August 21 through September 21 and March 21 through April 21, about 4.85% is lost out of a total production for that period of 22.4%. This represents about 22% reduction in the power production during this period. If one assumes that diffuse irradiance contributes 20% during the period when the panels are shaded, the loss in performance for the month is about 17%. This compares well with the loss of 14% for September 6 and give a much better estimate than to 2.5% loss from the standard method of estimating losses.

5. ANOTHER COMMON SHADING PROBLEM

One of the most common shading problems encountered is when there are rows of PV panels, one in front of the other. The higher the tilt of the panels, the more likely they will shade the panels behind them. (This problem does not occur in the Salem example.)

Depending on latitude and tilt of panels, problems don't usually occur when the sun is 10° or less above the horizon because very little of the total energy is produced during these periods. As with all generalities, with photovoltaic orientations, there are exceptions that will occur. The comments in this section are for typical situations.

If the spacing between the rows is too close, shading can become a problem. The steeper the arrays are tilted to obtain the most optimal irradiance, the more spacing is needed is prevent shading. If space is limited, then one has to find a comprise between optimum tilt and minimizing losses due to shading. In other words, at what tilt and spacing is the maximum performance obtained. There is no one correct answer and this is when performance estimators become useful, especially ones that calculate hourly performance and solar angles.

Fig. 7 shows a typical contour plot of performance for solar electric systems. Usually there are a wide range of tilts and orientations that can be used to obtain annual performances close to 95% of the optimum performance. This information is useful when density of solar modules is important and one has to trade off optimum tilt against minimizing shading to obtain the maximum production.

6. DISCUSSION AND SUMMARY

An alternate to sun path charts for evaluating shading is a spatial representation of the shadow as it moves over the PV system. The same methodology used to create performance estimates in quadrants on sun path charts can be used to estimate performance on a spatial plot. Solar angle calculators, such as the one available on the UO Website or on the NREL Website, can be used to create these plots. Right now these have to be done manually, but the procedure can be automated.

Once the plots are created, the arrays can be traced on the plots and the effects of shading can be calculated. While this procedure is more accurate that the ones using sun path charts and diagrams of obstructions, spatial analysis can be time consuming.

Unless shading is extreme, or long rows of panels are connected in series, it is easiest to use current programs that utilize sun path charts.

Any software that produces solar angles and hourly estimates of PV performance can be used for the spatial analysis methodology presented in the paper. The specific

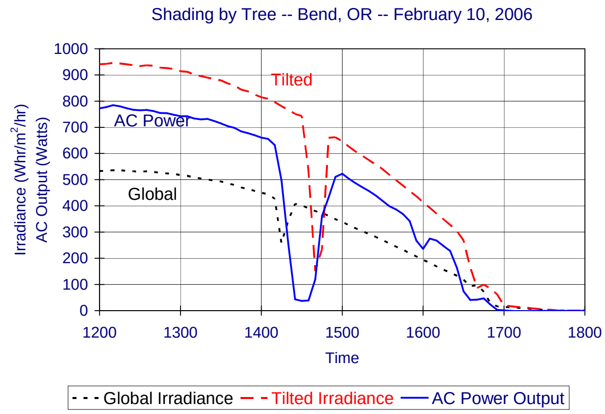

Fig. 8: Tree shading PV array. Global pyranometer is on the West side of the array and the tilted pyranometer is on the East side of the array. The array consisted of 8 panels connected in series.

software used in this article to calculate the solar angles and estimate PV performance is available as Excel add-in shareware on the UO SRML Website. The annual Salem data used in the analysis comes from the TMY2 dataset and has been formatted for easy import into an Excel spreadsheet. The reformatted TMY2 data files for Pacific Northwest sites are available for download on the UO SRML Website under solar data, TMY2 files. The Excel add-in requires that the input data be formatted in the UO SRML format. This format is based on the old research cooperator format and is explained on the Website.

It is not always necessary to use a spatial analysis to estimate the effect of shading. In fact, complex obstruction patterns are most easily analyzed using the traditional sun path chart shade analysis technique. When the sun path shade analysis tool was developed [1], it was understood that the affect of shading would be underestimated. That is why all production during the shading interval was considered lost and no compensation for the diffuse contribution was considered. (The diffuse irradiance contribution should be considered for the spatial analysis method.) The sun path methodology works best if there are not long strings of panels connected in series and if the shading object is not close.

In many cases, slight adjustments to the sun path shading analysis can account for the discrepancy. A typical example of shading is that of a tree with a shadow that will pass from one end of an array to the other (Fig. 8). If the object is far away, then the shadow passes fairly quickly. In this type of situation, if the panels are connected in series, a typical sun path analysis of the effects of shading will underestimate the performance decrease by a factor of about two. One way to overcome this problem is to do shade analysis at both ends of the array and combine the results. More severe cases of shading, when the object is near, a spatial analysis approach could prove useful and should provide a more accurate analysis of the effects of shading.

For the solar industry to thrive, solar systems must be installed well and with good planning. Proper installation and proper configuration of solar modules for the inverter are important. Just as important is the need to integrate the system into the structure of the building so that system enhances the quality of the building. Sometimes the design and siting of the system will conflict with the optimum performance of the system. Therefore it is important to know the tradeoffs between performance and attractiveness. It is very difficult to avoid all shading problems, but a good analysis of the site can help locate and orient the system to minimize the effects of shading and optimize performance. Solar systems that look good and perform as predicted are the best advertisements for the solar industry.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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