MEASURING DEGRADATION OF PHOTOVOLTAIC MODULE PERFORMANCE IN THE FIELD

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ABSTRACT

Accurate economic analysis of photovoltaic (PV) systems performance over the system lifetime requires knowledge of the performance of the PV system as the module and balance of system components age. Accelerated testing and experience with systems install 20 to 30 years ago show that PV modules will work over long periods. Nine years of PV data at Ashland, Oregon are used to determine the degradation in performance at the Ashland site. Three systems at the AEC PV Test Facility are used to study the degradation in performance over a two year period. All the systems have a degradation rate between 0.6 and 1.5% per year. It is determined that with good measurements a degradation rate of one percent can be observed over a two year period. It is unlikely that small rates of degradation can be determined accurately over one year. The accuracy of the rate determined can be improved with high precision irradiance and meteorological measurements.

1. INTRODUCTION

As the solar industry matures, more and more emphasis is being placed on the performance of the photovoltaic (PV) system over the lifetime of the system. Many communities in the United States are considering feed-in tariffs that have been successful in Europe. The benefits, costs, and design of the feed-in tariffs require knowledge of system output over time. Second party ownership arrangements, where system developers own the system and sell the electricity to building owners at a fixed rate, benefit from better knowledge of the system performance over time. The economic evaluation is dependent on system production, and uncertainty over the long-term production increases the risks and hence the cost of financing.

One concern to those financing or purchasing the system is the degradation of system performance over time. Questions are beginning to be asked about the long-term performance of the PV system. After 5, 10, 20, or 30 years ,how well will the system components perform. Many small systems have been working in the national forests since the 60s. In addition, larger systems installed in the mid 90s are also working. However, it is hard to get precise information of how performance has changed over time because high quality solar resource information is not typically available for photovoltaic systems, and maintaining a high quality solar monitoring site requires considerable effort and expense.

In 2000, the University of Oregon Solar Radiation Monitoring Laboratory (UO SRML) started monitoring two new photovoltaic systems installed in Ashland, Oregon. The systems' AC outputs were measured along with incident solar radiation, ambient temperature and wind speed. A rotating shadow band pyranometer (RSP) was also used in the monitoring project. Monitoring for this system is typical of many monitored photovoltaic systems and will be used to learn what data from such a system can provide and to illustrate the limitations associated with minimal data and maintenance.

In 2006, the UO SRML started working with the Alternative Energy Consortium (AEC) in monitoring a PV test facility located near campus. The UO SRML also operates a reference solar radiation monitoring site on campus using instruments with calibrations traceable to the National Renewable Energy Laboratory (NREL) and, hence, international standards.

With new module and inverter technologies continually coming on the market, characterization of their long-term performance is important to their acceptance and success. Performance information is especially important if the best technologies are to be utilized. Preliminary indications indicate that both long-term and shorter-term evaluations are complementary. However, can judicious use of high quality short-term data provide initial answers to the long-term performance of systems?

This article compares and contrasts long-term degradation studies using low maintenance solar radiation data with shorter-term studies using higher quality solar radiation data. To what accuracy and confidence levels can PV system degradation be measured with only two years of data but with high quality solar radiation measurements? Can limits on the rate of degradation can be set? The findings will be compared and contrasted with longer-term data when high quality solar radiation measurements are unavailable.

The paper is organized as follows. First, the PV systems are described along with the data monitoring equipment. The accuracy of the measurements is discussed. Next, the long-term degradation of system performance is evaluated. Then a method to evaluate the degradation is proposed and the systems' performance in 2006 and 2008 is examined. The results of the two methods are compared and contrasted. Finally, options for improved degradation evaluation are presented.

2. PV SYSTEM, MONITORING, AND IRRADIANCE DATA

A 15-kW_{AC} and a 5-kW_{AC} photovoltaic system are located on the Ashland police station and the Ashland courthouse that is next door. A Rotation Shadowband Pyranometer (RSP) is located on the East side of the police station array. Also, a pyranometer is installed on the frame of one of the modules in line with the tilt of the arrays. Both PV systems are tilted at 18º facing south and a LiCor pyranometer is located in the plane of the array of the 15 kW system. Both systems use ASE 300 DG-50 panels. The 15 kW array uses a Trace PV 15208 inverter and the 5 kW array uses a Trace PV 10208 inverter.

The PV arrays are washed about once a year but some years the arrays do not get washed. The pyranometers are occasionally cleaned. At best, the frequency of cleaning the pyranometers is about once a week. The RSP is calibrated every few years and the tilted pyranometer was calibrated in 2006. The tilted pyranometer is LiCor Li-200.

The AC output of the 5-kW array is measured with an Ohio Semitronic AC watt transducer, and a pulse counter is attached to the output meter for the 15 kW array.

2.1 AEC PV Test Facility

The AEC PV Test Facility is located about a mile west of the UO SRML reference solar monitoring station. Three of the PV systems at the test facility with long-term high quality data will be examined. All three systems (PV Sys-6, PV Sys-7, and PV Sys-8) utilize PV Powered 2800 inverters. PV sys-6 has 3.675 kW_{DC} of Sharp 175 mono crystalline modules, PV sys-7 has 3.6 kW_{DC} of BP #3150 multi crystalline modules, and PV sys-8 has 3.6 kW_{DC} of Isofoton #1-150 mono crystalline modules. The inverters for PV Sys-6 and PV Sys-8 were switched in 2007 with no apparent change in system performance. All systems face south and are tilted 30 degree from a flat roof.

The DC voltage and current, and the AC power are measured using Ohio Semitronic (OSI) transducers. Incident solar radiation on the tilted arrays and on the horizontal surface are measured using Kipp & Zonen Sp Lite pyranometers. Ambient temperature, module temperature, and wind speed are also monitored at the station.

The UO SRML reference station monitors direct normal irradiance with an Eppley Normal Incident Pyranometer (NIP) that has an absolute uncertainty of ±2% and relative uncertainty on the order of ±1%. The diffuse irradiance is measured with a Schenk pyranometer with an absolute uncertainty of about ±5%. The Sp Lite pyranometers have an absolute uncertainty of about ±5%.

The pyranometers at the site are cleaned weekly and the PV arrays are washed once a year.

Studies have shown that NIP calibrations are relative stable over the years [1, 2]. Little or no change in NIP responsivity has been observed over a 20 year period. This makes NIPs ideal for monitoring the degradation of performance. The Schenk pyranometer used in the diffuse measurements has also been stable, so calculating the incident radiation with those two instruments is useful for studying the change is PV system performance as long as solar instrumentation degradation is less than that of the photovoltaic system.

3. METHOD TO OBSERVE DEGRADATION

The performance of the 15-kW_{AC} PV system installed on the roof of the Ashland, Oregon police station and the 5

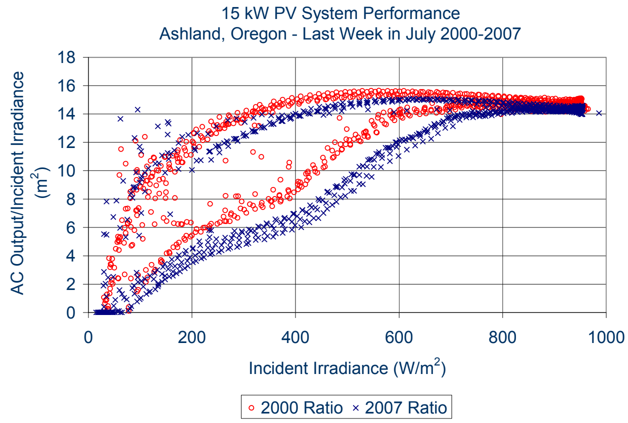

Fig. 1: AC output of 15-kW PV system/incident radiation plotted against incident radiation. Red circles are 2000 and blue x's are 2007 data. Data are from the last week of July.

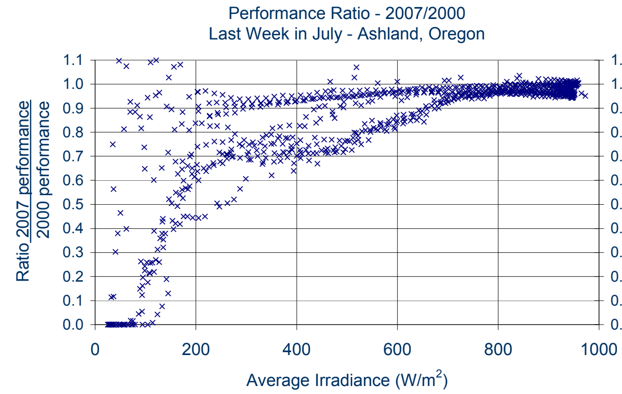

Fig. 2: AC output of 15-kW PV system/incident radiation divided by corresponding data in 2007 plotted against incident radiation. Data are from the last week of July. Both time periods are clear days.

kW_{AC} array on the court house have been monitored since July, 2000. The parameters measured are the incident irradiance and ambient temperature along with system AC output. Wind speed, and global, beam, and diffuse irradiance are also measured, but will not be used in this comparison.

Monitoring of the system began at the end of July, and the performance of the system in July 2000 will be compared with system performance each July through 2008. To normalize the performance, the AC output will be divided by the incident solar radiation. A plot of the normalized data is given in Fig. 1.

Note that the afternoon performance is down considerably from the morning. That difference results from the shading of trees in the afternoon. Shading and the change in shading over time are conditions that significantly affect many comparisons. During the middle of the day, the performance change is minimal as shading is not a much of a consideration. This is especially true during the middle of clear days where the diffuse contribution is small (10-15%). Trees will block part of the diffuse irradiance, but the overall effect is minimal.

To get an idea of the change in performance over time, the AC to incident irradiance ratios in 2007 were divided by the similar ratios in 2000 (see Fig. 2). The change in performance over the middle of the day is around 5% while that in the morning hours decreases up to 10%. In the afternoon, the performance decreases by 20 to 30% as the trees have grown and shade more and more of the array.

Therefore to evaluate how the performance degrades over time, it is easier to look at the middle of the day. In addition, it is better to look at only clear periods to reduce the variability of the data and minimize the effects of shading by trees on the diffuse irradiance. In addition, the performance will be divided by the system kW_{DC} rating (kW_{AC} rating for Ashland) and multiplied by 1 kW/m^2. This is called the Performance Ratio (PR) in [3].

The Performance Ratio for the 5-kW system and the 15-kW system from 2000 through 2008 are plotted in Fig. 3. Only clear day July data from 11:00 to 13:00 are used in the plot. When working properly, the 5-kW system has consistently performed 5 to 10% better than the 15-kW system. The 5-kW system had problems in 2006 and those data are not included.

For each year there is a scatter between 5 and 10%. To

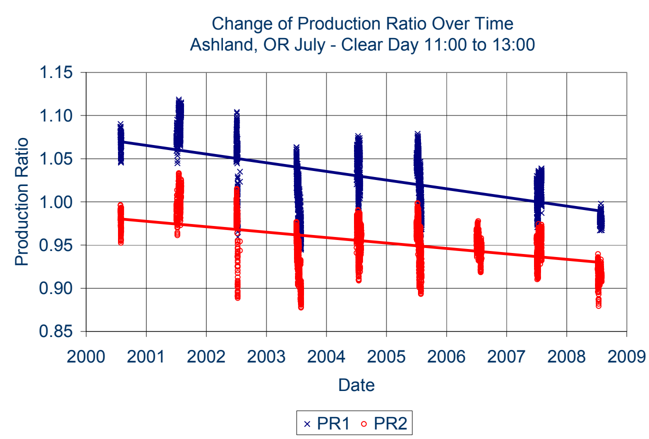

Fig. 3. Degradation of performance over time. Five-minute data from 11:00 to 13:00 on clear days in July are plotted against time. The data from the 5 kW array are plotted in blue x's and the 15-kW array are red circles. The 2006 data from the 5-kW array are not shown because of system problems.

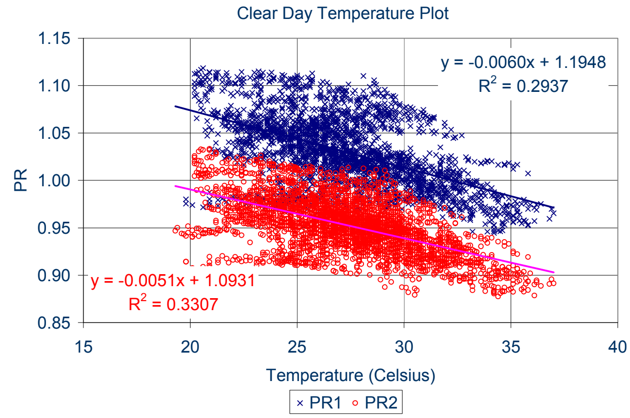

Fig. 4: Effect of ambient temperature on system performance ratio. The 5-kW array data are the blue x's and the 15-kW array data are the red circles. The 15-kW array decreases by about 0.5% per degree Celsius and the 5-kW array performance decreases by 0.6% per degree Celsius.

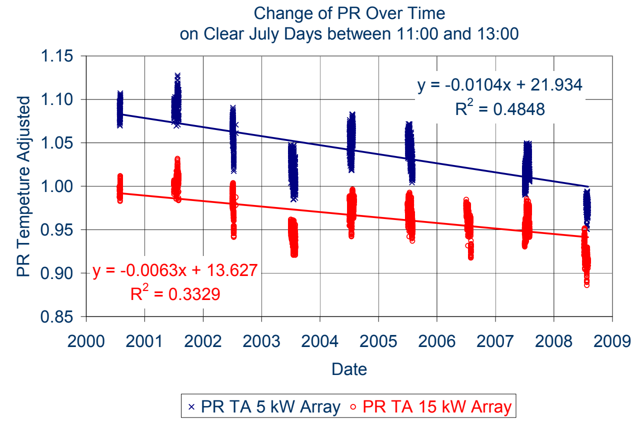

Fig. 5. Degradation of performance over time. Five-minute data from 11:00 to 13:00 on clear days in July are plotted against time. The data from the 5 kW array are plotted in blue x's and the 15-kW array are red circles. Performance Ratio change by 0.5% per degree Celsius for ambient temperatures deviating from 25 ºC.

reduce the scatter in the data, the affect of temperature on system performance was examined. Fig. 4 plots the Performance Ratio against temperature. As can be seen in the fits to the plots, the temperature decreases about 0.5% for each degree Celsius that the ambient temperature increases. No module temperature measurements were made at this site.

The performance ratios were adjusted by 0.5% for each degree Celsius away from the 25 ºC standard ambient temperature. This reduced the variance in performance by about 50% (see Fig. 5).

Notice that performance for some years tended to decrease more than in other years. For example, the systems weren't washed in 2008 and the performance appears to have dropped more rapidly than other years. The performance in 2004 also appears to be abnormally low.

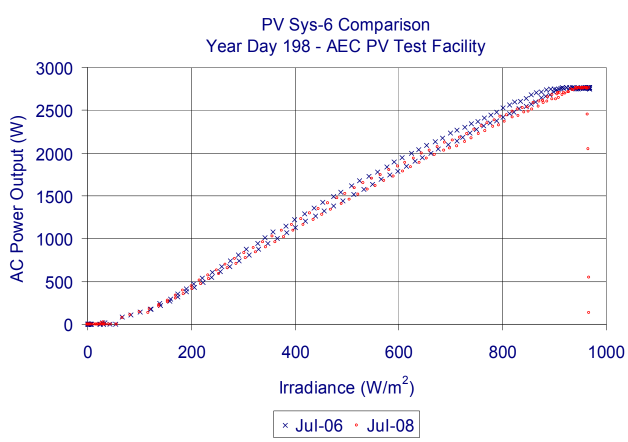

Fig. 6: Performance of PV Sys-6 on year day 198 in 2006 and July 2008.

On average, system performance for the 5 kW arrays appears to drop about 1% per year while the 15 kW system performance appears to drop at about 0.6% per year. In each case there is considerable uncertainty in the value.

One systematic error that is left out of this estimate is the decrease in the responsivity of the pyranometer over this time period. The responsivity is likely to have decreased several percent, but the absolute accuracy of the measurement is also several percent, so it is hard to precisely include the effect of the decrease in responsivity. Therefore the 0.6% degradation per year should be considered a minimum degradation rate.

Dirt build up on the array is certainly a significant reason for decreased performance. If the data from 2004 and 2008 are indicative, a year's worth of dirt can decrease the system performance by around 3%. A thorough cleaning appears to restore much of the performance, so it is really hard to pin down the exact rate of performance decrease without knowing when an array is cleaned and the thoroughness of the cleaning.

3.1 Comparison at AEC PV Test Facility

This section of the study examines how accurately the degradation rate of PV system performance can be estimated after only two years of data collection. The AEC PV Test Facility is located about a mile west from the reference solar monitoring site of the UO SRML. On clear days, the high quality solar monitoring site at the UO SRML station can provide reference measurements for the irradiance being measured at the AEC PV Test Facility.

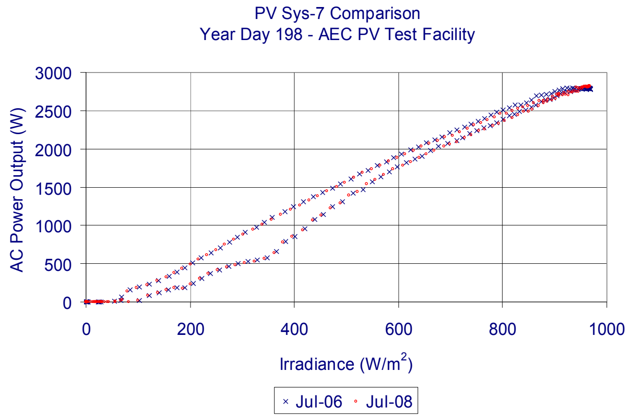

Fig. 7: Performance of PV sys-7 on a clear day in July, 2006 and July 2008. Note, that shading from trees affects the system about the same amount in 2006 and 2008.

Sample performance of three systems with data taken over similar clear days in July two years apart is shown in Figs. 6-8. As expected, all three systems show a slight degradation in performance.

The PV systems 7 and 8 are slightly oversized for their inverters. Therefore the system performance maxes out at around 2800 Watts, the inverter's nameplate power. In 2008, PV sys-7 does increase slightly above the maximum on this day.

The system in Fig. 7 is also affected by shading of trees in the morning, although the amount of shading is about the same in 2006 and 2008.

To get a more accurate comparison, it is important to adjust for temperature. A sample of system performance

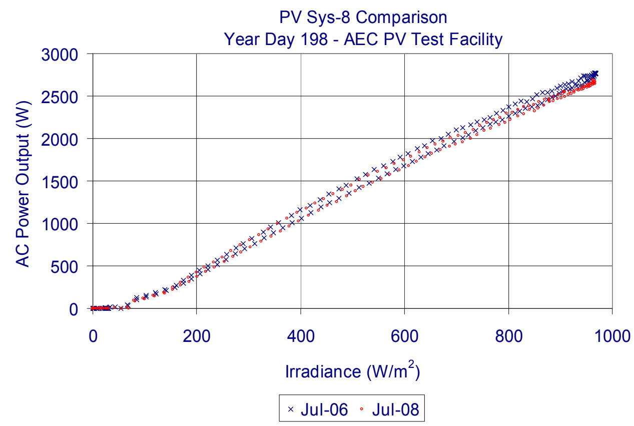

Fig. 8: Performance of PV sys-8 on a clear day in July, 2006 and July 2008. Note limit of PV performance at 2800 Watts is the same in both years.

degradation with temperature is shown in Fig. 9. The slopes for all three systems show a degradation in performance of about 0.4%/°C. For comparison, the system performance is plotted against module temperature in Fig. 10.

A selection of clear periods with significant irradiance was used to filter the data. Also, times when the inverter was not working were eliminated. The affect of temperature on system performance is also dependent on wind speed, relative humidity and other factors. The performance ratio was adjusted by a factor 0.5%/°C with zero affect at 25°C.

The day to be examined was a clear day when the beam radiation was close to the beam irradiance two years earlier. Year-day 198 was chosen for the comparison. The beam irradiance was used to set the match.

The percent difference between irradiance on July 16,

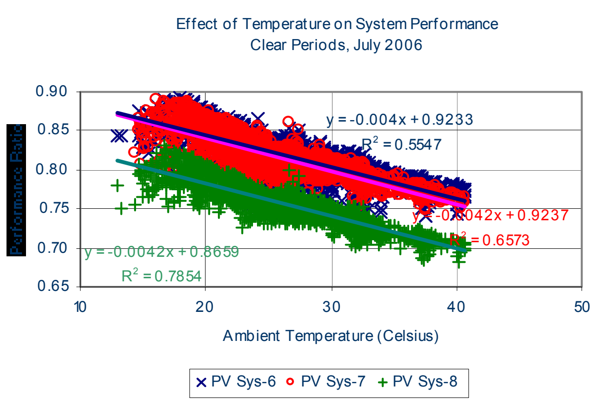

Fig. 9: System performance degradation with ambient temperature. For all three systems, the performance decreases about 0.4%/°C.

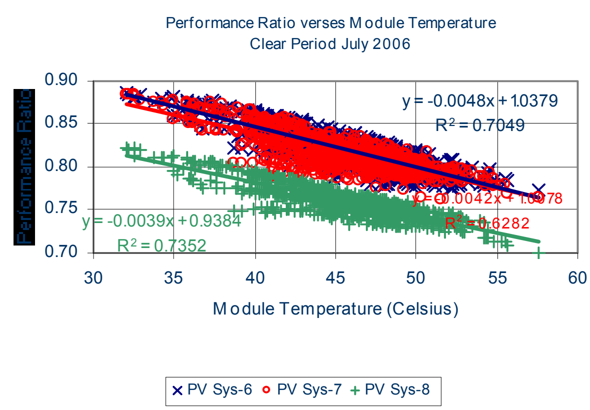

Fig. 10: System performance degradation with module temperature. For all three systems, the performance decreases between 0.4% to 0.5%/°C.

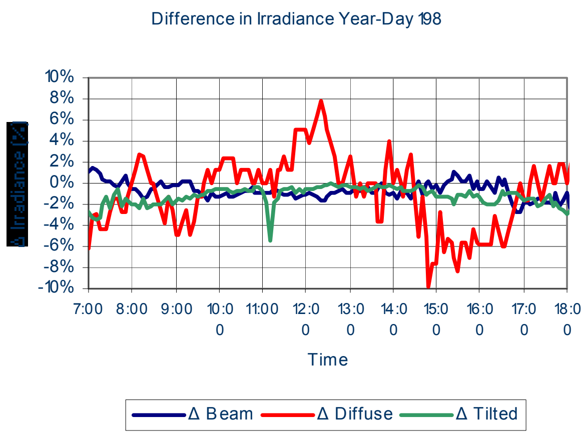

Fig. 11: Comparison of irradiance on year-day 198 for 2008 - 2006. The value are percent differences with 2006 data subtracted from 2008 values and divided by 2006 values.

2008 and irradiance data on July 17, 2006 is plotted in Fig. 11. The tilted irradiance is from a pyranometer tilted in the plane of array at the AEC PV test facility. There was a brief cloud, possibly a vapor trail, around 11:15 in 2008. The direct normal beam irradiance was from measurements at the reference solar monitoring station. The reference station did not see the cloud (or vapor trail) pass in front of the sun, but the diffuse irradiance did pick up some enhancement at that time.

The beam irradiance in 2008 is within 1% of the beam irradiance in 2006. The 2008 tilted irradiance is also within 2% of the 2006 value. Between 13:00 and 14:30 the values are within 1%. This difference is taken into account by dividing the AC output by the incident solar

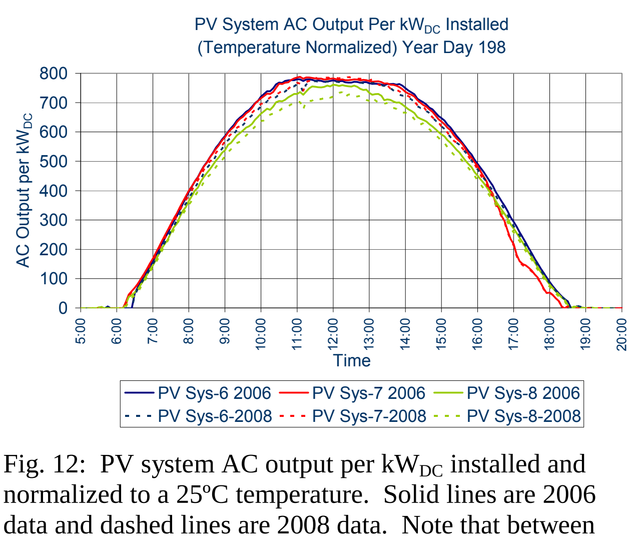

Fig. 12: PV system AC output per kW_{DC} installed and normalized to a 25ºC temperature. Solid lines are 2006 data and dashed lines are 2008 data. Note that between 11:00 and 13:45 the AC output reached inverter maximum limit for PV Sys-6 and PV Sys-7.

radiation. Since there is a linear relationship between AC Output and incident solar radiation, this makes the two periods equivalent if the instruments themselves did not degrade.

Two studies [1,2] have shown that the NIP does not degrade measurably, at least at the 2% level of accuracy, although there is some minor temperature dependence. Since the days are similar, the relative accuracy of the beam measurements should better than 2%.

Plots of the data are shown as AC output divided by system kW_{DC} size in Fig. 12 and as Performance Ratios in Fig 13. In Fig. 12, the AC Output, normalized to a temperature of 25 °C is plotted against time of day. Note that from about 11:00 to nearly 14:00, the maximum AC output of the inverter is reached for PV sys-6 and PV Sys-7. This is not the case for PV Sys-8.

Fig. 13 is a plot of the performance ratio over the day for 2006. A similar plot would be produced for 2008. Note that the Performance Ratio takes a dip that corresponds to the time when the maximum AC output is reached and the inverter moves the array off the max power point.

Degradation in system performance becomes more evident when dividing the Performance Ratio in 2008 by the Performance Ratio in 2006 (see Fig. 14). The ratio shows a loss in performance of 1 to 4%, except during the middle of the day for PV Sys-6 and PV Sys-7. These are the two systems that reach the maximum power production during this time period

If the inverter and transducer measurements were completely accurate, the ratio during max power output should be 1 because the power output should be the same. How-

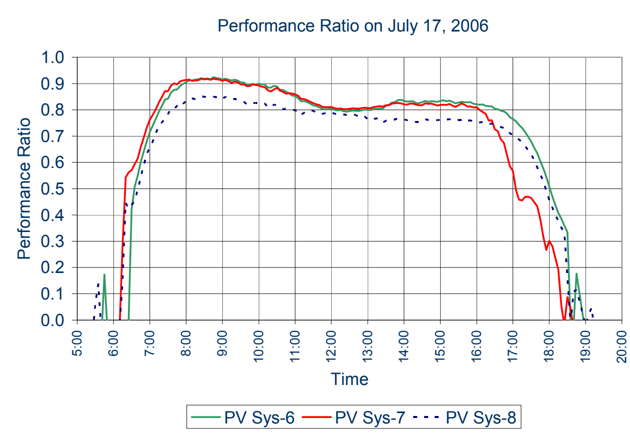

Fig. 13: Performance Ratio for PV systems on June 17, 2006. Even after temperature normalization the morning values are higher than the afternoon values.

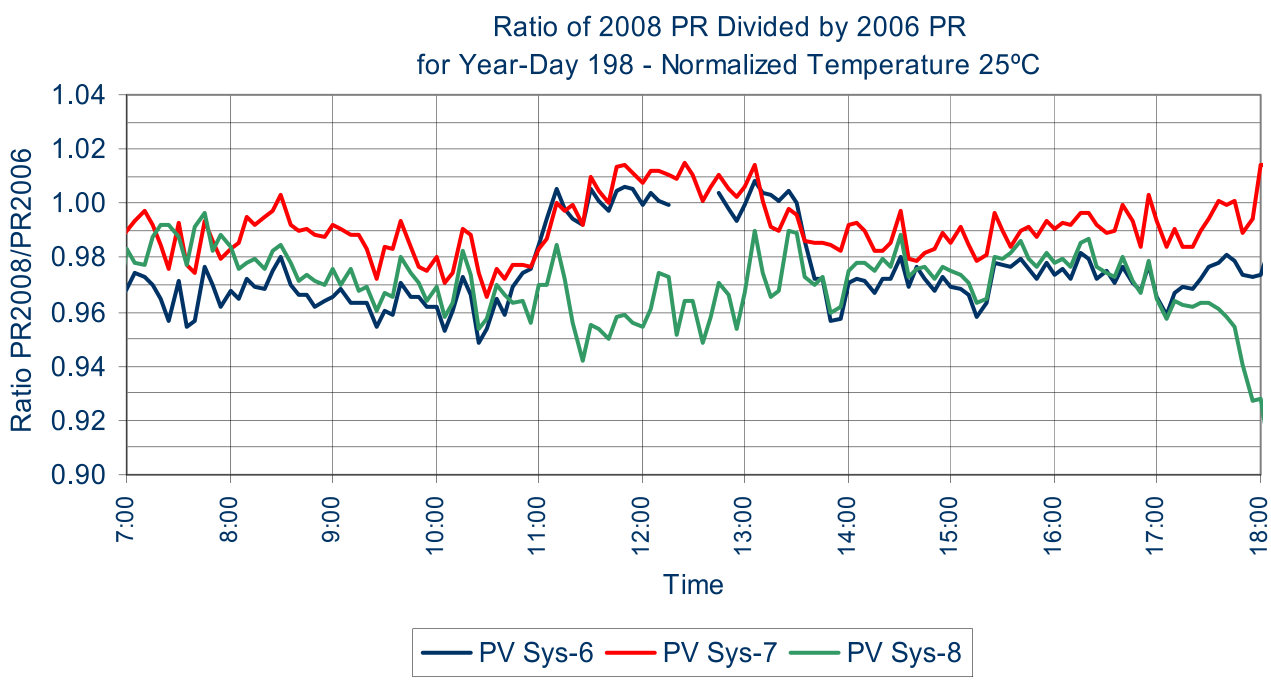

Fig. 14: Comparison of the Performance Ratio in 2008 to Performance Ratio in 2006. In each case, the Performance Ratio was normalized to 25ºC to remove the temperature dependence.

ever, there would be a slight difference because of the irradiance and temperature adjustments. For PV Sys-6, the average is 1.0013 ±0.0036 and for PV Sys-7, the average is 1.0085 ±0.0044. This indicates that there is minimum variation on the order of 1% for this technique. For the time period when the maximum AC output is not reached, the change in performance is:

PV Sys-6 96.85 ±0.0073%
PV Sys-7 98.59 ±0.0075%
PV Sys-8 97.35 ±0.0074%

Over the whole time period, PV Sys-8 had an average of 97.02 ±0.0100%.

This means that the system performance degraded by 1.5 to 3% over two years with an uncertainty of at least 1%.

4. CONCLUSIONS

The PV system in Ashland showed a degradation in performance of 0.6 to 1% per year over the 9 years of data. The year to year degradation varied considerably and it is postulated that years when the arrays were not washed, the performance decreased considerably more. This long-term degradation in performance is consistent with the rate of degradation found at the AEC PV Test Facility of 0.75 to 1.5% per year. At the AEC PV Test Facility there is more confidence in the irradiance because the reference measurements at the nearby site show the same change that is being seen at the AEC PV Test Facility.

Trying to determine system performance degradation in the field is made more difficult due to the minimal cleaning of the pyranometer of the arrays. A record is needed showing when the array and the pyranometer were cleaned. In addition, a calibration record of the pyranometer needs to be maintained.

Pyranometers have an absolute uncertainty of ±3% or greater. The responsivity of the pyranometers is dependent on the incident angle, temperature, and other factors. The relative change in responsivity from year to year is smaller than the uncertainty in the responsivity. This means that monitoring sites that retain the same pyranometer have a better chance of more accurately determining the degradation rate. This is especially true if the pyranometers are calibrated regularly and cleaned often. Some sites switch out pyranometers and substitute recalibrated pyranometers. Switching out pyranometers complicates the comparisons because each pyranometer has unique behavior although pyranometers of the same model have similar behaviors. The uncertainty introduced by changing pyranometers is usually much greater than the decrease in performance of a photovoltaic system. For the best comparisons, if field calibrations are not done, a pyranometer sent to a reference lab for calibration should be returned to the site where it is being used. It also should be noted that responsivity values should not be changed every time a pyranometer is recalibrated. Once a degradation rate for the pyranometer has been determined over several calibration runs, then the responsivity numbers can be change accordingly. Responsivity values change from year to year and just using each calibration's responsivity value can add scatter to the data.

Trying to measure system degradation over a short time period is difficult because the degradation rate is on the order of 1% per year or less. The absolute uncertainty in the solar radiation measurements is on the order of at least 2%. The relative uncertainty in the solar radiation measurement is considerably less than the absolute uncertainty but is still on the order of 1%. Trying to improve on the accuracy of the measurements would require an accuracy on the order of 0.5% or better to see the degradation of a system over a one year period. This is probably possible with an Absolute Cavity Radiometer, but is rather difficult to obtain in the field.

Good temperature measurements are also important since the AC output decreases by about 0.5% per degree Celsius. This change in AC output is not always straightforward and depends on wind speed and, probably, relative humidity. Even module temperature measurements have an associated uncertainty.

Output also depends on the spectral characteristics of the irradiance. In Fig. 14, there is a large variation in the ratio of the Performance Ratio for PV Sys-8. This resulted from a small cloud that reflected some of the incident solar energy. This showed up in the change in the diffuse irradiance, but not in the direct beam. It is also the cause for the increase in standard deviation when these times were used.

Dirt buildup on the PV modules definitely affects the system performance and is likely the primary cause of system degradation. This was seen at the Ashland site where the system wasn't washed for at least one year. This means that if one wants to look for more than just the effect of dirt building up on a PV module, the system should be cleaned in the same manner when making comparisons over the years. It also means that the pyranometers measuring the system performance have to be calibrated regularly. Keeping the same pyranometer at the site is also important in that the absolute uncertainty of most pyranometers is at least +/-3%. It is the relative uncertainty that is much better. Work is currently underway to determine the accuracy of the relative year to year uncertainty of various pyranometers.

At the AEC PV Test Facility, the inverters and instruments measuring the power seem to indicate that the maximum power point is being reached at about the same power two years apart. This indicates that there is minimal change associated with the inverters and associated instruments.

Without taking the panels into the lab, it is difficult to say what is causing the degradation in performance. Many factors could be at play, especially build up of dirt on the glazing and other damage to the glazing.

This study is limited by the data available and is an attempt to see how well the degradation rate for PV systems can be determined with existing data. It does seem possible to uncover some degradation after only two years, but the accuracy of the degradation rate has many uncertainties. Many factors, such as spectral changes in irradiance and effects of wind speed, were not taken into account. Thorough calibrations of all instruments involved, included the data loggers, are needed to refine or reduce the uncertainty in the degradation rates. If all the uncertainties were combined, the overall uncertainty would be larger than the performance change over a two year period. By looking at the relative changes, some of this uncertainty is reduced and the degradation in performance begins to appear.

5. ACKNOWLEDGEMENTS

We would like to thank the Energy Trust of Oregon, the Bonneville Power Administration, the Eugene Water and Electric Board, Emerald People's Utility District, and the National Renewable Energy Laboratory for sponsoring the work of the UO Solar Radiation Monitoring Laboratory.

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