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Frank Vignola, Josh Peterson, and Rich Kessler
University of Oregon

Fotis Mavromatakis
Technological Educational Institute of Crete

Mike Dooraghi and Manajit Sengupta
National Renewable Energy Laboratory

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Use of Pyranometers to Estimate PV Module Degradation Rates in the Field

Frank Vignola[1] Josh Peterson[1], Rich Kessler[1],
Fotis Mavromatakis[2], Mike Dooraghi[3], and Manajit Sengupta[3]

[1]University of Oregon, Eugene, Oregon, 97403, USA
[2]Technological Educational Institute of Crete, Heraklion, Crete, 71004, Greece
[3]National Renewable Energy Laboratory, Golden, Colorado, 80301, USA

***Abstract* – Methodology is described that uses relative measurements to estimate the degradation rates of PV modules in the field. The importance of calibration and cleaning is discussed. The number of years of field measurements needed to measure degradation rates with data from the field is cut in half using relative comparisons.**

***Index Terms* – PV, degradation, uncertainty, pyranometer**

I. INTRODUCTION

Many papers have been published reporting degradation rates of PV module performance in the field. There is a wide variance in the estimated rates of degradation. The reasons for these differences range from the methodology used to make these measurements to uncertainties in the measurement instruments and the accumulation soiling of the modules or pyranometers. Characteristics of the problems faced when measuring the incident irradiance are illustrated and a methodology is proposed to reduce some of the uncertainties in the measurements. Recommendations are:

1. Use relative measurements comparing year to year values under cloudless skies.
2. Calibration of the pyranometers should be made before, during, and at the end of the test period at the site where the instruments are used.
3. Instruments and PV modules should be cleaned regularly in order to see the effects of degradation and separate this information from the effects of soiling.
4. Maintenance should be documented and logs maintained.
5. Module temperature should be monitored.
6. Meteorological measurements should be made alongside irradiance measurements.

The goal of this study is to determine the time period necessary to obtain a reliable estimate of the degradation rate of photovoltaic (PV) modules using measurements in the field. The effects of module degradation are separate from the effects of soiling that reduce the irradiance reaching the module and raise the temperature of the module. The effects of module soiling are likely to be several times larger than the module degradation rate and can vary considerable depending on location, module glazing, and technology used in the module. While this study's presents a methodology to evaluate the degradation rate of a PV module, the methodology can also be used to the study of the effects of soiling on PV module performance.

A standard estimate of the degradation rate of a photovoltaic module is on the order of 0.5% per year. The absolute accuracy of a good pyranometer is approximately ±2.5% at 95% level of confidence for a well maintained instrument [1]. Therefore if one was just comparing incident radiation measured by a pyranometer to module output it would seem to take at least 5 years to see any change in PV module performance with any degree of confidence. The way to overcome this problem is to use relative measurements instead of absolute measurements because the relative uncertainties of the irradiance measured using a pyranometer are less than the uncertainties of absolute irradiance measurements. This study is separated into component parts. First the uncertainties associated with measuring irradiance with a pyranometer are illustrated. Next the steps needed to perform an accurate comparison methodology are described. The limits and accuracy of these comparisons are formulated and the implementation of this methodology is discussed.

II. CHARACTERISTICS OF PYRANOMETERS

The responsivity of a pyranometer to incident solar radiation changes from year to year, varies with the cosine of the incident angle, the ambient and sky temperature, the spectral distribution of the incident radiation, and the intensity of the incident radiation [1, 2]. Often the uncertainties in the measurements systematically deviate from the ideal or true cosine response. An example is given in Fig. 1. The deviation from a true cosine response may be 1.5% high at 30°, normalized to 1 at 45° and be 2.5% low at 60°. The uncertainty of the measurement at each angle is actually much smaller, approximately ±0.5%. The "BORCAL" calibration database at NREL [3] contains examples for a wide variety of irradiance sensors. In addition, a paper on the performance of 51 radiometers at NREL has been accepted for publication [4].

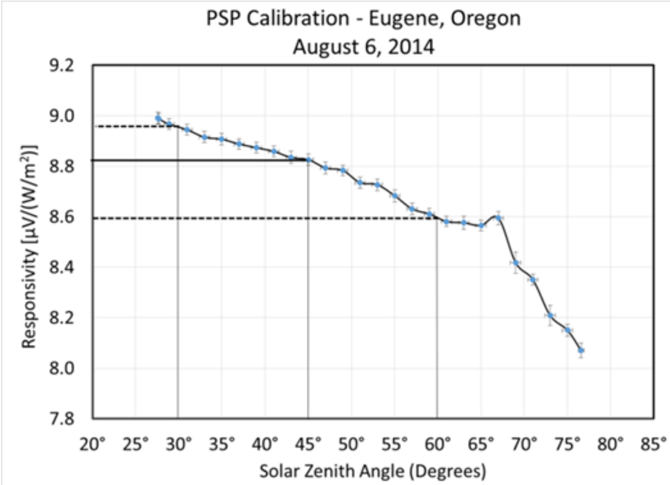

Fig. 1. Calibration of an Eppley PSP plotted against solar zenith angle. At 45°, the uncertainty of the responsivity is approximately ±0.5%. However, if one looks at the uncertainty from 30° to 60° it is +1.5% and -2.5% respectively.

Theoretically, if one does the same experiment under identical conditions a year apart, the uncertainty under those conditions would only be ±0.5%. The major fallacy with this statement is that the pyranometer's performance also changes over the year as its responsivity has degraded due to the exposure to the sun and elements and this needs to be taken into account.

It is important to track the change in pyranometer responsivity from year to year. Fortunately, pyranometers of a given model tend to behave similarly and undergo similar changes. Some of these changes relate to the exposure of the paint on the pyranometer disk to UV radiation [5, 6] so one can determine this rate of change with just a few years of data. If one is using a pyranometer for which there is a history on the rate of change, this time period is greatly reduced. However, calibrations of the instrument should be maintained at the beginning, during and end of the experiments. The decrease in responsivity of an Eppley PSP is shown in Fig. 2.

Each calibration and the trend have an uncertainty between 2 and 2.5%. These calibrations were done in the field with a side by side comparison between two similar pyranometer and are not as accurate as one done using an absolute cavity for Direct Normal Irradiance (DNI) and a shaded pyranometer for Diffuse Horizontal Irradiance (DHI) at a calibration facility. However, if the instrument is calibrated at a calibration facility and not in the field, it is important to place the same instrument back in the field. Otherwise a methodology using a relative relationship is not valid. Installing a new instrument at the site means that the procedure has to start anew to obtain a reliable degradation rate for the PV module.

Other factors also influence the performance of the pyranometer. Thermopile-based pyranometers measure irradiance from the temperature different between the central black disk and the body of the pyranometer.

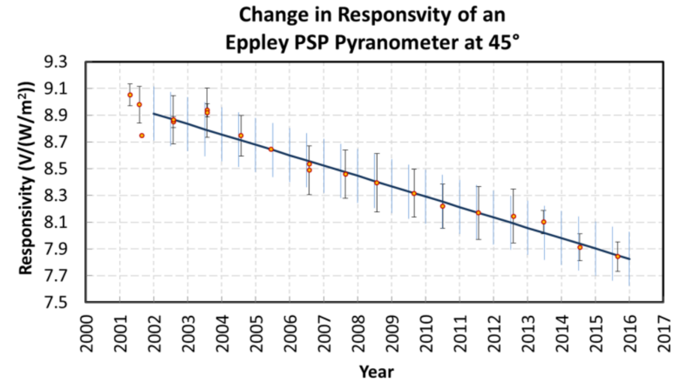

Fig. 2. Change in responsivity of an Eppley PSP pyranometer from 2000 to 2015. The pyranometer was seldom used from 2000 to 2005 hence the responsivity did not change significantly. From the middle of 2005 to 2016, the instrument has been used in outdoors and the responsivity change by about 0.8% per year.

When there is a significant difference between the ambient temperature and the sky temperature, there will be a net radiative loss between the pyranometer and the sky. Under clear sky conditions, this can be up to 15 or 20 W/m^2 as shown in Fig. 3. Black and white style pyranometers do not have this thermal offset because the incident irradiance is measured between the black and wedges that have similar thermal offset in the infrared. The amount of variation depends on the design of the pyranometer, the tilt of the pyranometer, wind speed, and capacity of the air to cool the pyranometer [1, 6]. If the thermal offset is not taken into account, a pyranometer can yield a different responsivity from one location to another because the thermal offset is different from one site to another. For example, the thermal offset in Eugene, Oregon is about 1/3 the thermal offset obtained in Golden, Colorado [6]. The thermal offset effects vary with tilt of the pyranometer [6] and therefore when comparisons are done, the pyranometer has to be tilted at the same angle or the thermal offset values will be different.

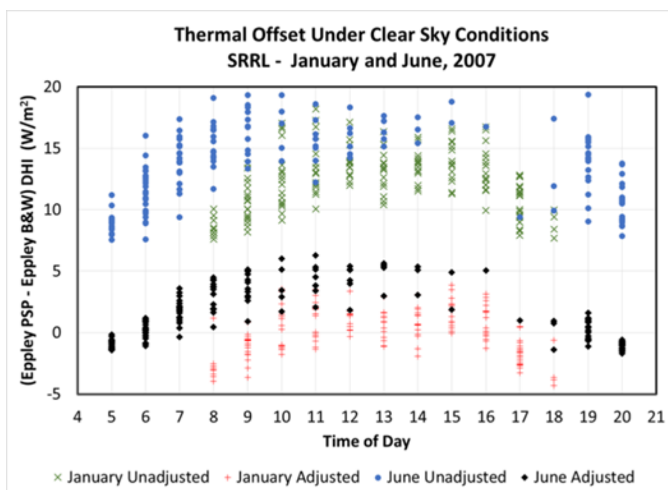

Fig. 3. Example of thermal offset at SRRL in Golden, Colorado. The magnitude of the thermal offset can vary from location to location depending on water vapor and aerosol content of the atmosphere.

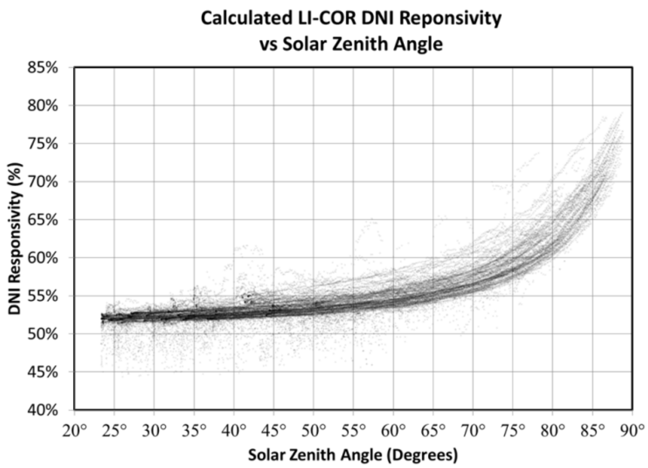

Fig. 4. Change in a DNI responsivity of a LI-COR pyranometer as a function of solar zenith angle for Payerne, Switzerland in 2012. As SZA increases, the sunlight's path through the atmosphere increase and differences in the atmospheric constituents result in a wider variation in the responsivity of the pyranometer.

This makes absolute measurements of the solar resource difficult and this is an advantage of relative comparisons because the thermal offset should be about the same if comparisons are made during similar circumstances.

The spectral distribution of the incident radiation also affects the output of the pyranometer (Fig.4). This is particularly true for photodiode-based pyranometers and instruments that use photodiode-based pyranometers [7, 8]. While the effects of changing spectral distributions can be modeled using the air mass parameter, the algorithm is likely to be relevant only to the location where it is derived and may not be appropriate for another location. PV modules react to changes in spectral distributions much in the same manner that photodiode-based react. Again, making comparisons under identical air mass conditions significantly reduces a large portion of the uncertainty associated with the different spectral distributions in the incident irradiance.

III. Significance

For most large PV systems the incident irradiance is monitored to check on the performance of the system. Because solar irradiance varies from year to year as well as day to day, it is of particular importance separate changes in system performance from changes in incident irradiance. In addition to overall system performance, there is considerable interest in PV module degradation rate. While performance degradation can be studied in the laboratory, it is performance degradation in the field that is of prime concern for developers and financers. Many groups have attempted to use the irradiance data obtained alongside system performance data to estimate module performance degradation.

A crucial part of every PV performance study is a precise knowledge of the incident irradiance. The uncertainty in the irradiance data typically is many times greater than other measurements. In addition, the quality of the incident irradiance data varies greatly and there is very little information from well calibrated instruments that are maintained on a regular basis. This can lead to conflicting results with large uncertainties, often many times greater than the actual change in PV module performance.

As a result of large uncertainties in degradation results manufacturers, developers, and financers use conservative estimates of PV module performance, often affecting the financing of the system. More reliable results lead to greater confidence in the performance predictions and less risk for developers and financers.

PV modules have been in the field for a long time and have shown to be reliable. However, new module technologies are developed each year and these new technologies cannot be assumed to last like the original technologies. A great deal of effort goes into testing in the laboratory and in accelerated testing before the modules are deployed in the field. It is experience with the modules in the field that provides confidence in performance estimate and assurance that unforeseen failures cut short a module's useful lifetime.

To measure module degradation rates in the field requires knowledge of the incident irradiance. Measurements of irradiance in the field have large uncertainties compared with module degradation rates. Therefore with standard techniques, it takes many years to confidently quantify modules degradation rates in the field.

The ability to measure the degradation of PV modules in the field in the shortest timeframe has financial implications and requires well maintained irradiance measurements. Changes can be as low as a few tenths of a percent per year and are much smaller than the changes associated with soiling. The performance of the PV module is dependent on the incident radiation, the spectral distribution of the incident radiation, temperature of the module, and the soiling of the module. The magnitude of these changes can be determined by having a long-enough time so that the changes are significant or the uncertainty in the variables needed to estimate the performance must be minimized. The most direct way to minimize the uncertainties is to run comparisons under identical conditions from one year to the next [10]. This reduces the time needed to see the degradation of the module from 5 to 10 years down to 3 to 5 years.

IV. Methodology

To get reliable relative measurements it is recommended that one should:

1. Conduct measurement in the plane of array of the PV module. For tracking PV arrays, the pyranometer should be attached or mounted on the array that is moving. Models used to estimate irradiance on tilted or tracking surfaces from Global Horizontal Irradiance (GHI) measurement have large uncertainties and do not have the accuracy required to detect changes in module performance (see [11]).

TABLE I
IMPORTANT PYRANOMETER CHARACTERISTICS

1	Deviation from true cosine response
2	Linearity of response to irradiance
3	Dependence on spectral distribution of irradiance
4	Change in responsivity with time
5	Thermal offset and temperature effects
6	Repeatability – standard deviation when calibrated against an absolute cavity radiometer and diffuse measurements
7	Effect of tilt on the responsivity of the pyranometer

2. Document system maintenance and calibration information. Documentation helps identify any problems within the dataset and can assist in validating the quality of the data. It is also useful to monitor the data on a regular basis. This reduces the amount of problem data because problems can be spotted more quickly and addressed.
3. Make measurements under the same or very similar circumstances from one year to the next. Almost all pyranometers exhibit some systematic daily and seasonal effects. Comparing results about a year apart at the same time of day negates many of these daily and seasonal affects.
4. Short time intervals should be used (5-minute averages or shorter). It is much easier to identify clear periods with shorter time interval data. In addition, with five-minute or one-minute data, it is possible to see if cleaning the instruments has an effect on the data.
5. The same instrument needs to be used during the whole period of study. When an instrument is changed, its calibration uncertainty is typically on the order of ±2.5% and it becomes difficult to differentiate between changes in module performance and differences caused by the calibration of the pyranometers. In addition, even pyranometers of the same model have slightly different characteristics and these differences can obscure any PV module performance change.
6. The instrument should be calibrated at the start, during, and end of the experiment - ideally, once a year. The responsivity of a pyranometer changes over time. It is not unusual to see changes in responsivity on the order of 0.5% to 1.0% per year. By tracking the change over time, it is possible to model the degradation in responsivity. Because an instrument's responsivity is likely to be different at a particular location than at a test facility, the calibrations should be conducted at the location or at the test facility. If they are done at the test facility, the pyranometer originally used at the site should be returned after the calibration. Having the same instrument is necessary for a relative comparison to yield useful results. If the calibrations are performed in the field, an initial calibration should also be performed in the field to help ensure that the calibrations are performed under similar circumstances. Field calibration should be obtained using the same model instrument as used in the field. If calibrations are all performed at a given Solar Zenith Angle (SZA), say 45º, any reference pyranometer might work, however, subtle effects such as ambient temperature can affect pyranometers differently.
7. The performance of the pyranometer should be fully characterized so that one knows how the instrument reacts under a variety of conditions (see Table 1). This helps to identify the optimum ranges of conditions under which comparisons can be made.
8. While comparisons should be made during different times of year, it is the relative changes that are found during each period that should form the basis for any conclusions. It is useful to study changes over time during each season or under different cloudiness conditions. This can help separate differences related to seasonal changes from those that result from PV module degradation.
9. The measurements should be made after the pyranometer has been cleaned and the PV module has been washed. Otherwise, the effects of soiling can affect the results and obscure and/or mimic module degradation.

In a thirty year study [9] of the effects of soiling on a PV module, a 22% decrease of the module performance was determined. Of the total decrease in performance, 18% was found to be the result of soiling and 4% was the results of performance degradation. The effects of soiling can easily obscure the degradation rate of a PV module. Therefore to get reliable data about module degradation rates from field data, one has to clean the modules as well as maintain the pyranometers.

V. Example of Using Relative Comparison

The following is illustrates how to estimate the uncertainty with the relative comparison method. The actual uncertainty depends on the characteristics of the pyranometer used to make the measurements. The steps taken and the rationale for taking these steps are given. The pyranometer will be assumed to be in the plane of array (POA) of the PV module because there is a much larger uncertainty if models are used to estimate the POA irradiance from GHI measurements (see [11] for a comprehensive study of these transposition models).

A comparison of PV module performance from year to year yields the most consistent results if periods are used with clear skies with similar atmospheric and solar configurations. For instance, take a week and separate the SZA into two degree bins. Treat the morning and afternoon data independently to eliminate any azimuth dependence associated with the pyranometer. This also removes some of the temperature dependence as mornings are generally cooler than the afternoons. Next remove an periods when the irradiance isn't smoothly varying within an hour of the selected data. This means that one to five-minute averaged data should be used in the analysis. (One-minute data would show some variability that may not be visible in five-minute data.) Next remove any periods where the instrument was not cleaned with the previous five days. Thermopile-based pyranometers in ventilators exhibit less soiling than those without ventilators.

TABLE II
IDEAL MEASUREMENT UNCERTAINTIES

Source	% Uncertainty	Notes
Calibration	±0.5%	At a fixed angle
Change in responsivity per year	±0.2%	Field comparisons same pyranometer
Spectral Response	±0.02% - ±0.3%	Assume thermopile pyranometer
Thermal offset	±0.2% - ±0.4%	Treat in a consistent manner
Miscellaneous	±0.1%	Data logger

Photodiode pyranometers are reported to be less subject to soiling than pyranometers with crystalline domes, but this hasn't been quantified.

For this example it is assumed that three calibrations of the instrument have been performed in the field against a reference instrument that has a calibration traceable to the international standard. The calibration of the reference instrument is ±0.5% in the 35 to 37 degree range. The same reference instrument should be used in all three field calibrations. Assume that the results show the responsivity changes by about 0.7% per year with an uncertainty in the rate of change about 20%. This uncertainty should decrease with a longer record.

The uncertainty in the thermal offset from one year to the next under similar circumstances should be about 1 to 2 W/m^2. This estimate can be check by comparing the night-time thermal offsets. Given that the irradiance might be 500 W/m^2, this yields an uncertainty between 0.2% and 0.4%. Since the conditions are similar, there should not be much difference in the ambient temperature and that difference from year to year should be minimal. For some pyranometer, correction formula exist that can adjust for changes in ambient temperature.

Thermopile-based pyranometers measure a broad range of irradiance and have minimal dependence on the spectral distribution. Photodiode-based pyranometers have a distinct dependence on the spectral distribution of incident irradiance. Making comparisons at the same time of day can significantly reduce the effects of changing spectral distribution.

The combined uncertainty (u_c) is the square root of the sum of the square of the uncertainties. To get an idea of how long it might take to validate a change in PV module performance in the field, one can look at the u_c of the values used in Table 2.

$$u_c = \sqrt{(0.5)^2 + (0.2)^2 + (0.02)^2 + (0.2)^2 + (0.1)^2}$$

This yields a combined uncertainty of 0.59%. At the 95% level of confidence the expanded uncertainty is $1.96*u_c$ or 1.16%. This assumes that instrument has been cleaned within a few days of the measurements being used.

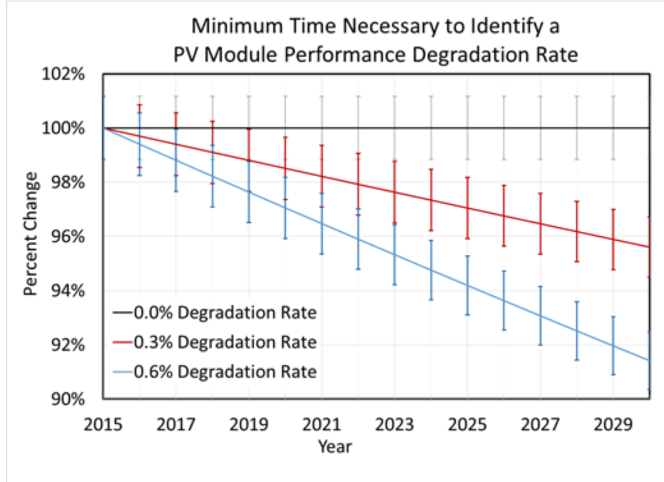

Fig. 5. Visualization of performance degradation rates and uncertainties associated with comparison measurements. Red line is a 0.3%/year decrease in performance and the blue line is a 0.6%/year decrease. The error bars illustrate a 1.16% uncertainty in the relative measurements.

VI. Discussion

Given an expanded uncertainty of about 1.16%, it would take at least 3 years to convincingly detect a PV module degradation rate of about 0.6% per year. For a degradation rate of 0.3%, it would take about 5 years to confirm the degradation rate (see Fig. 5). This assumes that the PV module is cleaned periodically before the data are used for the comparison. Otherwise, soiling could and likely would account for much of the observed degradation in performance.

The comparison works best under narrow circumstances that are repeated year after year. By narrowing the circumstances when the test data are compared, many of the uncertainties associated with irradiance measurements can be eliminated or greatly reduced. The deviation from true cosine response is not important in the comparison made at the same solar angles. This is also true for azimuthal variations. By choosing cloudless periods at the same time of year, the irradiance levels will be about the same and any uncertainty in linearity of the measurement is not important. The atmospheric aerosols and precipitable water vapor are roughly the same at the same time of year. There will be some increase in variability for photodiode-based pyranometers measurements resulting from differences in aerosol and water vapor content of the atmosphere. However, the production from photovoltaic modules is also sensitive to these differences and there may be some reduction in variation of the ratio of PV production to measured incident radiation if photodiode-based pyranometers are used. The thermal offsets should be similar at the same time of year under similar circumstances. As with spectral differences there may be some differences with the thermal offset depending on the meteorological conditions at the date from on year to the next. If water vapor or other relevant meteorological data are available they can be used to ensure the field conditions are the same for the comparison data. The effect of tilt on the responsivity of the pyranometer should be about the same for identical solar angles one year apart.

Two uncertainty factors are not reduced by this comparison methodology. The first is the uncertainty associated with the calibration of the pyranometer. This relates to the ability of the pyranometer to provide the same voltage output when the solar angles and irradiance are the same. The other important factor is the change in responsivity of the pyranometer over time. Several years of data are usually required to obtain a good estimate of the pyranometer's change in responsivity. Errors in the pyranometer's degradation estimate will affect the estimate of the decrease of the PV module's performance.

Other meteorological and site conditions can affect any comparison. Wind speed and direction and relative humidity are such factors. Growth of vegetation or changing vegetation from one year to the next can have small effect. When one is trying to identify small affects, these can become important.

This example is for comparisons each being made a year apart. When this process is used in practice, many different time periods should be used if they fit the criteria for clear skies. They all should produce a trend. There will be a difference between these trends and one can use this information to calculate an uncertainty in the module performance degradation rates observed.

The discussion in this article is applicable to any pyranometer. The less dependent the pyranometer is to the sources of uncertainty, the quicker one would be able to identify module degradation rate using field data. Using POA photodiode-based pyranometers or reference cells for baseline irradiance measures is often considered because these instruments have the same or similar spectral as the PV modules under examination.

If one is to look for small effects such as module degradation rates, it is important to have maintenance for the data being gathered and a good record of calibrations and maintenance schedules. Many questions can arise about the validity of the data without well maintained records.

VII. Summary

It is very difficult to determine any change in PV module performance that is less than 1 to 2%. Even the best pyranometers have uncertainties of ±2% to ±2.5% at a 95% confidence level for an absolute irradiance measurement. Therefore relative irradiance measurements are needed to track low degradation rates. Still even relative measurements have trouble confidently identifying changes on the order of 1% unless long-term records are available.

Small changes are best reviewed under laboratory conditions where all the variables can be measured and controlled. Changes on 1 to 2% should become apparent under field conditions if proper maintenance and cleaning is conducted. The relative method proposed here should be able to clear identify the large changes resulting from soiling within a two to three year period.

While the decrease PV module performance is difficult to measure even with relative measurements, the technique would be useful in reviewing overall system performance degradation such as soiling or more dramatic failures because many of the uncertainties associated with measurements of incident irradiance is significantly reduced by confining comparisons to identical solar conditions.

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