Understanding module degradation in utility-scale PV plants

Power loss | The highly accurate module efficiency certified by accredited laboratories right after module production is at odds with the very rough estimate of the module´s long-term efficiency stated by the manufacturer for its expected lifetime, through a commonly accepted and industry-standard power warranty. Agustin Carretero of skytron energy presents an innovative method for calculating module degradation by using string-monitoring systems, and compares the results obtained for a case study with the module manufacturer´s power warranty statement

The potential for photovoltaic energy to be a major contributor to the world´s future energy mix is heavily dependent on the improvements being made in the energy conversion efficiency of the photovoltaic cells and modules. Manufacturers are constantly researching and applying new materials, always seeking to improve on the market-leading efficiencies, so that they can capture the attention of investors and decision makers. However from an investment perspective, just focussing on a module's efficiency directly after production could be misleading. The long-term stability of module performance is often not given the consideration it deserves. The high accuracy module efficiency figures cited by module manufacturers, taken directly after production and certified by accredited laboratories, contrast strongly with the very rough estimates quoted for their long-term efficiencies, usually through an industry-standard power warranty that is common across makes. Accurate and reliable long-term efficiency figures are still lacking in today´s module datasheets. In this article, following a description of the procedures commonly used to quantify long-term module degradation, an innovative method for calculating degradation using string-monitoring systems is presented. This can serve as a means of comparing actual results from a plant against the module manufacturer's power warranty statement.

The state of the art

Accurate prediction of long-term module performance under real environmental conditions is a topic that still involves certified laboratories and research institutions. For such an analysis, two main procedures are commonly used; however each has its advantages and drawbacks.

Module flashing under standard test conditions (STC)

The usual procedure for determining the rate of degradation of installed PV modules is to dismount a number of them periodically and then re-measure them in an accredited laboratory. By comparing the module power with that declared by the module manufacturer in its datasheet, the long-term module degradation can be determined. The main advantages of this method are that it is module-specific and that it is always done under exactly the same, ideal conditions. However, only a small number of modules are used, which may not be significant enough. This is especially true of utility-scale PV plants, where the exposure conditions and design parameters can vary across over the entire field. Besides this, the dismounting and remounting of individual modules of the PV array causes not only temporary energy losses, but also requires the intervention of the maintenance team. So the already expensive cost for producing flashing reports is inflated by contingencies for technical risks and other maintenance charges.

Plant performance analysis under real conditions

The second procedure for determining module degradation is to take advantage of the monitoring equipment that is often installed in large PV plants. Here, remotely monitored system data and measurements of the weather conditions can be used to systematically analyse and evaluate the systems and their components. In contrast to the module flashing approach, the results here are based on real operational conditions, and are statistically significant since all the modules in the plant are considered. However, a source of error comes from inaccuracies in the plant monitoring equipment being used. For analysing plant performance, energy measurement data from the utility energy meter or the inverters have commonly been used; the accuracy of these is typically ±5%. Further, this equipment is not always connected directly to the target modules, thus bringing in additional factors that have nothing to do with module degradation (inverter efficiency, balance-of-system losses, etc.). For the detection of such low, long-term module degradation, high-accuracy monitoring equipment is required with a low time resolution and which is mounted as close to the modules as possible. In contrast to the flashing procedure, no additional intervention is required from the maintenance team, so making it much more cost effective.

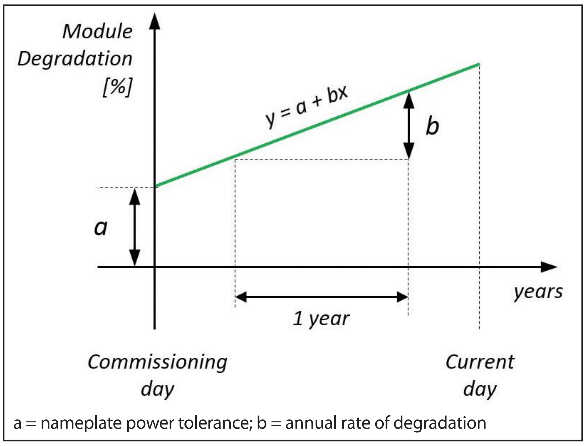
Proposed solution

By merging the main advantages of both previous procedures and taking advantage of high-accuracy string monitoring, a new methodology for detecting long-term module degradation has been developed: Simulating Module Flashing under Real Conditions. It is based on string power measurements to a minute's resolution, based on current and voltage samples every 100 milliseconds (then averaged over a minute), but only those where the weather conditions are close to STC. Next, this real measured power is compared with the string STC power, normalised to the selected STC-like conditions. By applying this analytical procedure based on historically monitored data to a utility-scale PV plant, module degradation can be obtained to string level in a cheaper, faster and more practical way [1].

To understand module degradation, the model shown in Figure 1 can be used, where (a) is the nameplate power tolerance and (b) is the annual rate of degradation. The solution outlined here:

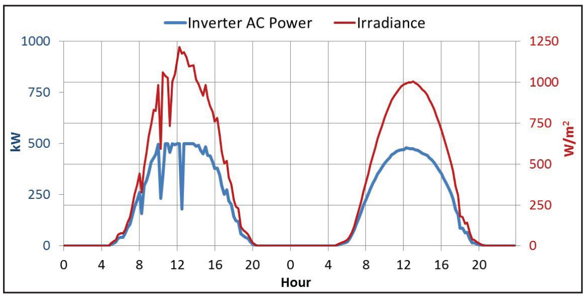
- Uses a precise time-filtering algorithm to search for clear-sky conditions. The calculation is then performed only under these conditions.
- Analyses the annual deviation of the radiation sensor due to ageing and compensates the measurement data accordingly.
- Simulates the string power by normalising its STC power to the measured weather conditions after compensation.
- Calculates a measurement for string power by multiplying current and voltage measurements from the combiner boxes, taking advantage of both its ±0.5% measurement accuracy over full temperature range and its one-minute time resolution.
- Obtains a figure for string power deviation by comparing the measured power of each string to its simulated version.

More about each of these aspects is explained in the following paragraphs.

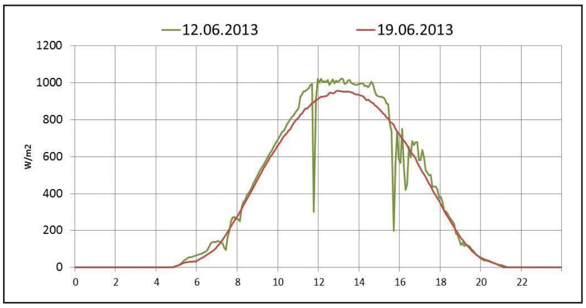


a = nameplate power tolerance; b = annual rate of degradation

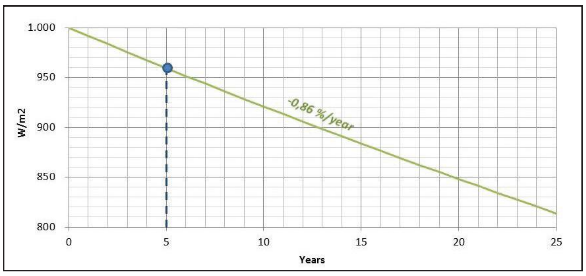
▲ **Figure 1. Modelling module degradation.**



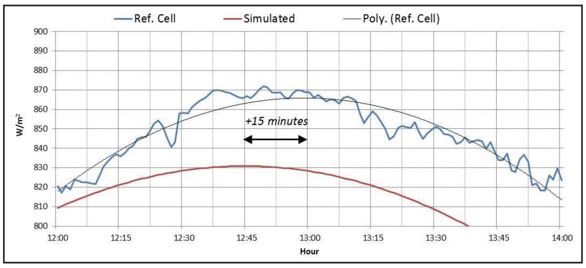
▲ **Figure 2. Effect of inverter power clipping.**



▲ **Figure 3. Intensity and stability of irradiance.**



▲ **Figure 4. Sensor ageing deviation.**



▲ **Figure 5: Misalignment of sensor orientation.**

Time filtering

In order to obtain a trend-line such as that in Figure 1, each day of the whole monitored history of the plant is assessed consecutively, so as to find those with clear-sky conditions. A time window of one hour, centred on the solar noon, is chosen for each day, according to the change of the solar azimuth angle over the year. Next, the power output of the inverters is checked over the selected time window to ensure that none has reached its nominal power (inverter clipping, Figure 2). Notice how the inverters will clip on days with intermittent sunshine, because on such days the modules are cooler and perform better.

Thirdly, the thermal stability of the modules is evaluated by checking that the irradiance level remains high and stable over the selected time window. The irradiance measurements for two almost clear days have been plotted in Figure 3.

From the figure, it can be see that the selected clear-sky day is not the one with the highest irradiance at noon, but that with the most stable irradiance.

Irradiation sensor ageing compensation

To calculate the ageing of the irradiation sensor, the variation in irradiance between a sensor measurement and a simulation of the clear-sky irradiance is analysed for each clear-sky day. To assess the impact of the sensor time resolution, four different resolutions have been analysed, and by sketching the progression of the variation over time, different sensor annual deviations due to ageing can be obtained:

Time resolution	Annual deviation
15min	–1.11%
10min	–1.15%
5min	–0.96%
1min	–0.86%

Impact of measurement time resolution.

For this case study, the manufacturer specified an annual deviation of <1% for the radiation sensor. It can be observed that a time resolution under five minutes is necessary to detect this. Taking the manufacturer´s initial sensor calibration, the deviation of the sensor's irradiance measurement due to aging can be plotted as in Figure 4.

After five years of monitoring, and without any recalibration over this period, the measured value under STC conditions was found to be 960W/m^2, i.e. 40W/m^2 less than the initial measurement. The resulting annual deviation is **8W/m2/year**. This annual deviation can be used to adjust the calculations for module degradation.

Besides the ageing of the sensors, any misalignment in the orientation between the reference cell and the modules can be

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> "Accurate time filtering is necessary in order to select both the optimum time window and the clear days for which the power deviation calculation should be performed"

determined and taken into consideration (Figure 5).

When the two curves are compared, a time shift can be seen between them. This has been used to further improve the accuracy of the final results.

String power deviation

The module degradation can be defined as the ratio of the measured power to the simulated one. For this to be valid, both must be related to the same environmental conditions. The procedure for normalising the STC string power to the Measured Weather Conditions (MWC) so as to calculate the final string power deviation is shown in Figure 6.

Once the string-measured power (Pstring) has been obtained as the product of the string current and the voltage, the string-simulated power can be obtained by:

$$P_{\mathrm{STC}}^{T_{\mathrm{mod}}} = P_{\mathrm{STC}} * \left[1 + \gamma * (T_{\mathrm{mod}} - 25°\mathrm{C})\right] \qquad (1)$$

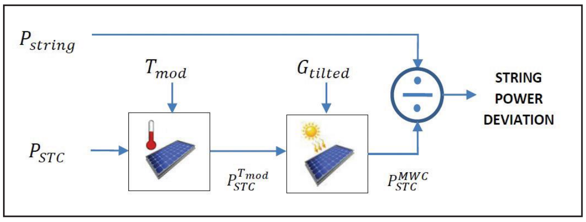
$$P_{\mathrm{STC}}^{\mathrm{MWC}} = P_{\mathrm{STC}}^{T_{\mathrm{mod}}} * \frac{G_{\mathrm{tilted}}}{1000\mathrm{W/m^2}} \qquad (2)$$

Here, γ is the module-power temperature coefficient (%/K) obtained from the manufacturer´s datasheet. The final string power deviation is then calculated as:

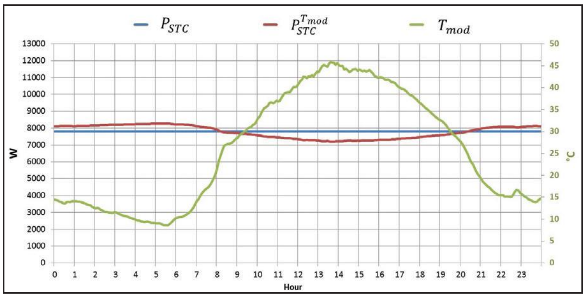
$$\mathrm{Deviation_{MWC}}[\%] = \left(1 - \frac{P_{\mathrm{string}}}{P_{\mathrm{STC}}^{\mathrm{MWC}}}\right) * 100 \qquad (3)$$

To illustrate these normalisation steps, a real string of 40 modules @ 195Wp has been taken as an example. Its STC power is 7,800Wp, and the power temperature coefficient (γ) of its modules is -0.37 %/K. Measurement data has been taken from a selected clear-sky day. Its simulated power under the measured module temperature has then been calculated by applying equation 1 (see Figure 7).

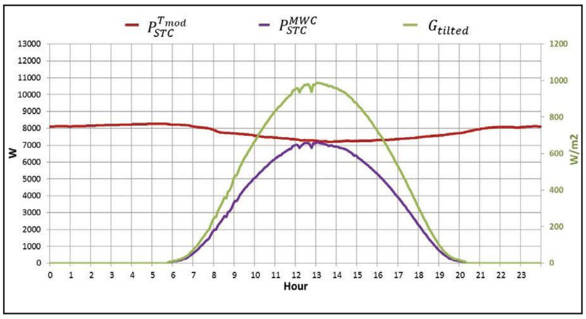
The temperature-normalised power, i.e. the result of normalising the STC power (blue) against the measured module temperature (green), has been shown in red. The next step is to normalise this against the measured irradiance, by applying equation 2 (see Figure 8).



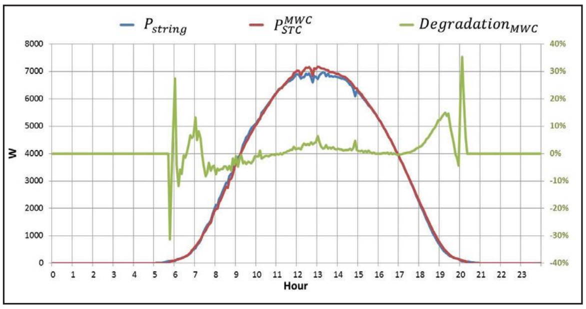
▲ Figure 6. Power normalisation.



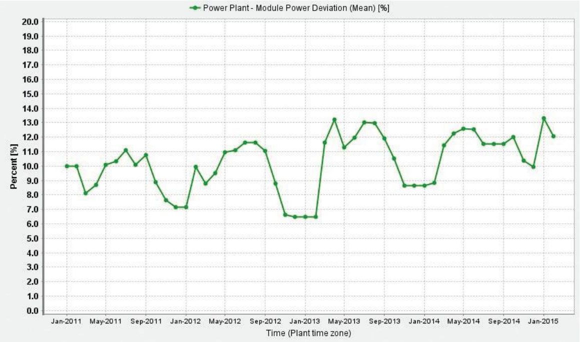
▲ Figure 7. Power temperature normalisation.



▲ Figure 8. Power irradiance normalisation.



▲ Figure 9. Power deviation calculation.



▲ Figure 10. Monthly plant power deviation (PVGuard).

The temperature-normalised power (red) is then normalised against the measured irradiance (green) to give the final normalised power, shown in violet. The next step is to calculate the string power deviation according to equation 3 (see Figure 9).

Examining Figure 9 shows that valid results can only be obtained within the central hours of the day. Therefore, accurate time filtering is necessary to select both the optimum time-window and the clear days for which the calculation should be performed.

Results

To assess the proposed solution, measurement data from a utility-scale PV plant has been analysed using the supervision platform PVGuard. Operational data at string level was available for the plant's entire life since commissioning.

Module annual degradation

After determining the power deviation for every string of the plant for every established clear-sky day, the plant power deviation was obtained by taking their average. By calculating the mean value for each month, the chart in Figure 10 was then obtained.

This shows considerable fluctuations, even between consecutive months. This could be caused by:

- Non-linear behaviour of the module power temperature coefficient (γ), in dependence on both the seasonal irradiance level and spectral variations. This study has assumed the constant values given in the datasheets.
- Variable amounts of module soiling either due to rain (that lower the deviation) or high amounts of dust and pollen (that increase it).

The next step in obtaining the module degradation is to determine the trend line across all the plant's power deviation values, as plotted in blue in the graph in Figure 11.

The trend line shows that there is a slight increase in the deviation over time. Dividing the absolute difference by the number of operational years of the plant results in a final figure for annual degradation of around 1%.

Module nameplate power tolerance

In order to obtain the module degradation line, a final step has to be made by taking the seasonal fluctuations derived from soiling and spectral issues into account. Therefore, the trend line shown in Figure 11 has to be shifted down by the amount found on the clear-sky day where the difference between the trend line and the plant power deviation is a maximum. The resulting module degradation line, shown in Figure 12, represents the module nameplate power tolerance and in this case results in the final figure of around +4.5%

> "Module degradation figures for single strings can be obtained and used to determine which strings are more affected by degradation than others"

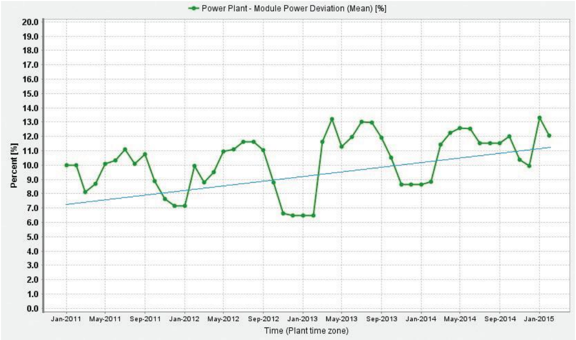
Module soiling

One last result, the module soiling, can be derived from the module degradation line, by calculating the difference between the plant power deviation and the module degradation line (Figure 13).

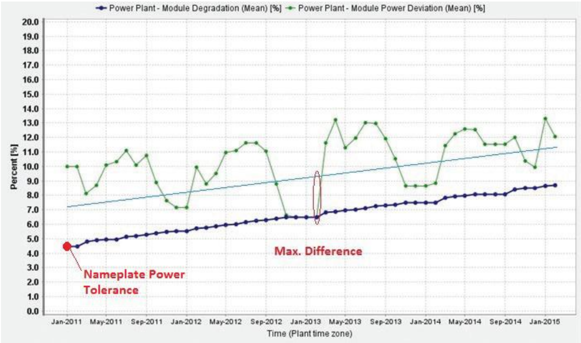
Module annual degradation versus industry standard

By converting the rising degradation trend line back into a falling power performance trend line and drawing it together with both the module manufacturer´s industry-standard power warranty and a typical yield report prediction, the chart shown in Figure 14 can be plotted.

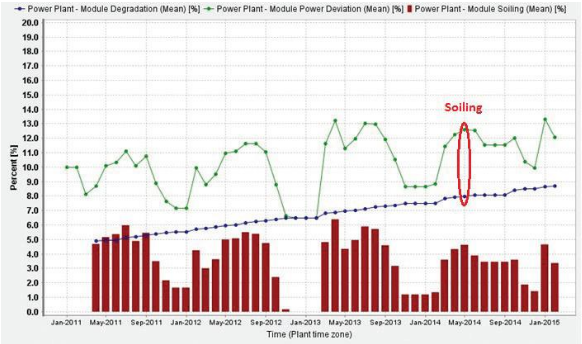
Neither nameplate power tolerance nor initial degradation has been considered here. However, the annual module degradation rate is still well adrift of that predicted in the yield forecasts. Obviously, if the initial degradation is taken into account, the industry–standard power warranty would not be achieved either at the tenth or after the twentieth operational year. So once the initial degradation is known, the characterisation of the module can be enhanced and yield predictions improved correspondingly.



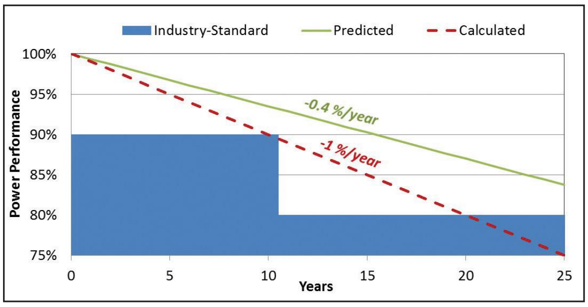
▲ **Figure 11. Trend line for the plant power deviation (PVGuard).**



▲ **Figure 12. Shifting down trend line (PVGuard®).**



▲ **Figure 13. Module soiling (PVGuard).**



▲ **Figure 14. Module performance over time**

Conclusions

An innovative method for a precise calculation of module degradation has been presented. Based on an assessment of string power measurements over a long duration under specific measured weather conditions, the results could satisfy the need of investors and decision makers for reliable information about the long-term performance of modules outside the laboratory.

In order to obtain accurate and reliable results, it is essential that power measurements are taken as closely to the modules as possible, so as to minimise the losses due to cabling or other intervening equipment. Ideally string monitoring should be used, so that the results are only affected by the DC cable losses. In addition, the ±0.5% measurement accuracy of the string monitoring system and a time resolution down to a minute are crucial. Measurement accuracy of inverters is commonly stated as being around ±5%. This can be shown to be inadequate for such a precise calculation.

The long-term deviation of the measurements from the irradiation sensor due to its ageing process has been calculated precisely by comparing them to simulation of clear-sky irradiance with a one-minute resolution. The result has been used to compensate the final degradation results and so to increase their accuracy.

Figures for module degradation in individual strings can be obtained and used to determine which strings have been more affected by degradation than others, consequently providing a valuable source of information for the maintenance team. ■

Author

While studying his MSc. on Global Production Engineering in Solar Technology at the Technical University Berlin, Agustin Carretero joined skytron energy GmbH in 2012 where he has developed algorithms for plant performance engineering. Module degradation and soiling detection together with energy loss calculations are some of his recent scientific contributions.

Reference

[1] A. Carretero / H. Hoffmann, "Where are my Watts gone? Five Years of Utility Scale Power Plant Monitoring", 28th EU PVSEC Proceedings (pp. 4045 – 4050), September 2013.