System Performance Analysis and Estimation of Degradation Rates Based on 500 Years of Monitoring Data

Nils H. Reich, Alexander Goebel, Daniela Dirnberger, Klaus Kiefer

Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, D-79110 Freiburg, Germany

***Abstract* —Fraunhofer ISE has been involved in monitoring of PV systems since the "1000-roofs-program" in the 1990s. In a few of these "old systems" equipment is still in place, metering PV electricity output and plane-of-array irradiation. The majority of ~300 PV power plants in our monitoring campaign today, however, is large-scale and built in the past 10 years. In this paper, we briefly review the historical development of the Performance Ratio (PR) and how average PR for newly built systems increased to almost 90%. This rather high PR of 90% only holds, however, if calculated by on-site irradiation acquired with c-Si reference cells and for climates comparable with those in Germany. Next, we use about 500 years of monitoring data on aggregate to perform an analysis of variations of the PR over time. To this end, data points at similar environmental conditions are extracted from long-term time series as to calculate so-called "rates-of-change" of the PR. Highly scattered "rates-of-change" are obtained, however, not allowing for the estimation of specific degradation rates on the system level yet. To this end, we finally revisit uncertainties of irradiance sensors and in particular revisit our irradiance sensor re-calibration data.**

Index Terms — degradation, monitoring, system performance, long-term stability, PV system.

I. Introduction

Fraunhofer ISE has gained experience in monitoring PV systems since the 1000-roofs-program in the early 1990s. In a few of these systems we continue monitoring operations. But the vast majority of ~300 PV systems currently monitored by Fraunhofer ISE are commercial PV power plants. This is reflected in the average system size of power plants monitored, which rose from as little as 3 kWp in 2000 to 790 kWp in 2010; today's monitored capacity exceeds 1 MWp on average and total installed capacity exceeds 200 MWp by far. A notable portion of the systems is small-scale, however, attributed to the research setting at Fraunhofer ISE, distorting specific trends one may be tempted to derive from these figures here [1].

The performance of PV power plants is evaluated by determination and analysis of the Performance Ratio (PR). As reported in previous studies, typical ranges of the PR rose from 50%...75% in the late 1980s [2] and 70%...80% in the 1990s to >80% nowadays [3]. We therefore investigated a potential limit of the PR and outlined typical heights of individual loss mechanisms of state-of-the-art top-plants [1].

The PR of today's systems is usually much higher as compared with the 1990s. This is illustrated in Figs. 1 and 2, where the PR of today's systems is contrasted to the PR monitored within the 1000-roofs-program in 1994/1997. Note both Fig. 1 and 2 are discussed in greater detail elsewhere [1].

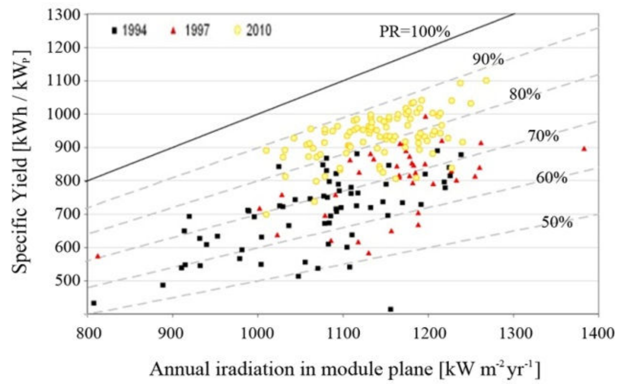

Figure 1: Monitored specific yield as a function of total plane-of-array irradiation of PV systems installed and monitored in years 1994 and 1997 (data plotted in black and red) and systems built between 2000 and 2009 with PR monitored in 2010, see [5] for more details.

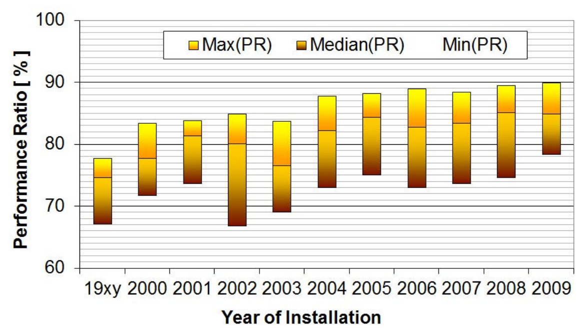

Figure 2: The PR of 94 systems monitored by Fraunhofer ISE as a function of installation year per system. The shown PR range was calculated based on annual PR data of each system since it started operation in the respective year, see [5] for more details.

II. Monitoring Systems

Measured data from our monitoring systems is collected on a daily basis. Therefore, not only retrospective assessments of PV performance are possible, but also the timely detection of malfunctions. For a significant number of systems, these checks are performed regularly, be it on a weekly or even daily basis, in case of suspected malfunctions using expert assessments.

Monitoring systems commissioned by Fraunhofer ISE usually record the plane-of-array (POA) irradiance as well as AC yields of the entire plant. Also module temperatures on the module back sheet and ambient temperatures are recorded.

978-1-4673-0066-7/12/$26.00 ©2011 IEEE

Also DC-currents and -voltages as well as AC power output of at least one reference subsystem, within e.g. a string or array of modules, are included in typical configurations. Reference subsystems supposedly allow for representative determination of PV generator efficiency and inverter efficiency. Therefore, AC energy for reference subsystems is monitored too, with measurement uncertainty of AC counters being 1%, in most cases. Measurement uncertainties of DC currents and voltages are 0.2% and 0.5%, respectively.

The AC energy output of the entire plant is of course measured as well, usually by tapping into the measurement data of the so-called "Feed-in-Tariff meters". These FiT-meters have small measurement uncertainty, usually between 0.2% and 0.5%. Finally, the measurement of POA irradiance is performed with usually at least one c-Si sensor, with an uncertainty of ± 2% in the calibration.

All monitoring data are stored as 5-minute averaged values. Availability of the data was greater than 99% on average, over the entire period and all systems considered in this study. The overall duration of all data combined roughly equaled 500 years. So, more than 50 million datasets on aggregate were processed. This excessively large dataset implied we needed to rely upon so-called monitoring "base-data". In comparison to the measurement data stored as-measured by the data loggers, "base-data" already went through some plausibility checks and few, basic system malfunction detection routines. For a significant number of cases, the base-data is used for daily or weekly expert assessments during the process of detection of malfunctions. However, system outages are still included in the data, which therefore needed to be filtered out for the purpose of this study.

II. Additional Filtering to Derive "rates-of-change"

Data points at comparable and failure-free conditions have to be selected, as to guarantee that derived long-term changes of the PR are at all meaningful. It was decided on a data-binning approach [4], considering only irradiation between 800-1000 W/m² and temperatures of either the 35-40 °C or the 40-45 °C temperature bin. This binning and subsequent filtering supposedly avoids shading and angle-of-incidence effects to be included when determining "rates-of-change" later on: This is based on the quite reasonable assumption that direct-normal irradiance predominates for POA irradiation of 800 W/m² and higher. Also, irradiance intensity dependent efficiency of crystalline silicon modules varies not too much between 800 W/m² and 1000 W/m².

Following this first round of binning and subsequent filtering, also remaining "outliers" were removed. Here, it was decided to discard all data points with a deviation of more than ±5% from the median of the annual PR that was calculated for each individual system using the binning-approach. This range was selected because there *"is no physical reason apart from malfunctions or measurement uncertainty, why PR or η_{SG} at the selected irradiance and temperature conditions should differ that much"* [4]. The filtering steps themselves and how the 5%-threshold affects already pre-filtered data are illustrated in Fig. 3. The "rate-of-change" is finally derived by a least RMS error fit to the remaining data (orange data points in Fig. 3).

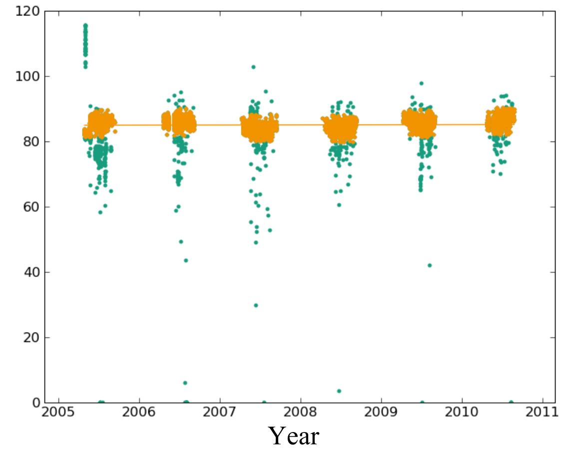

Figure 3: Rate of change of the PR of -0.14%/yr for an entire plant.

The plot shown in Fig. 3 illustrates our extraction routine of PR values from long-term time series. However, the plot also shows some more details. Notably some values of the PR around 60% and even lower, during summer, are still included after the *initial* filtering. A PR that low must stem from system outage of some sort, showing failure-conditions did remain after the first round of filtering by data-binning. Also information on the quality of data acquisition can be gained from Fig. 3. The PR during start-up of plant monitoring is too high, suggesting some measurement parameters were not appropriately defined during this start-up phase or perhaps calibration problems existed. Furthermore, in year 2007 one *single* data point of the PR reaches a value above 100%, suggesting the irradiance sensor was shaded only for as short as 5 minutes. However, it is obviously next to impossible and very cumbersome to analyze and discuss data of almost 200 systems on that level of detail. Here, the rather straightforward removal of "outliers" from annual means actually proved very effective. The "rates-of-change" that have been found so far and the way described here are presented in the next section.

III. Obtained Rates-of-Change

All calculated "rates-of-change" of the PR, for each individual PV power plant included in this analysis, are depicted in Fig. 4. In the upper panel of Fig. 4, the "rates-of-change" of the PR of mono- and poly as well as both EFG (edge-defined film growth) and string-ribbon silicon systems are shown. In the lower panel, "rates-of-change" for 8 systems that use a-Si thin film modules are shown. For mono/poly c-Si, data of 89 systems with 370 years on aggregate, for

EFG/string-ribbon technology 14 systems with 70 years and for a-Si 8 systems with 40 years on aggregate were used. This totals ~500 years on aggregate.

The obtained distribution is broadly scattered, with deviations towards actually *positive* “rate-of-change” as high as 3%/year (see highest data point in upper panel of Fig. 45). However, about the same can be observed for *negative* “rate-of-change” of individual systems: -3.5%/year for EFG/string-ribbon and -3%/year for c-Si systems. The average of “rates-of-change” for only the mono/poly c-Si systems depicted in the upper panel of Fig. 5 is -0.25%/year. In the lower panel of Fig. 4 also a linear function is plotted. The linear plot represents initial degradation of 7% in only the first year (in year one, 7% result for the “rate-of-change”, in year two 3.5%/year and after 7 years 1%/year). Initial degradation does of course not need to correlate with long-term stability, however, the graph shows initial degradation needs to be carefully considered.

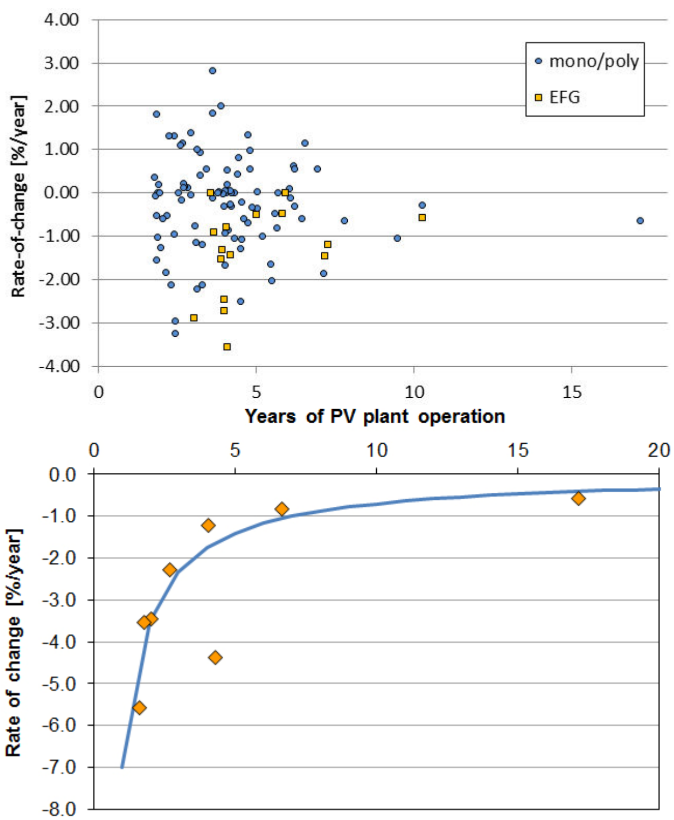

Figure 4: Derived “rates-of-change” of in total about 100 c-Si systems (upper panel) and 8 a-Si systems (lower panel).

IV. Measurement Uncertainties

The scattering of obtained “rates-of-change” is addressed in the following by looking more closely at involved measurement uncertainties. Module temperature and POA irradiation accuracy is of particular relevance, with the data filtering approach to calculate “rates-of change” relying on only these two measurement values. In this paper, however, we will focus on uncertainties related to irradiation measurement. It is nonetheless important to note that PT100 sensors used for temperature measurement are attached to the back side of modules usually by adhesive and that *“in a number of monitoring installations installed a long time ago, however, problems with slowly detaching temperature sensors occurred”* [4]. For these cases, an appropriate correction was noted to be advisable, because not correcting for these sensor drift may lead to dramatically wrong conclusions: “*Applying a data-filter for temperatures measured with constantly detaching sensors (…) would link high temperatures with increasingly lower, measured temperatures, which then appeared as negative rate-of-change in the analysis”* [4].

Regarding the uncertainties of irradiation measurement, we only consider data acquisition by c-Si reference cells in this study. Some of the *distinct* differences between pyranometer and reference cells are discussed in another paper presented at this conference [5] and in [1] and many more publications.

Also the long-term stability of c-Si reference cell sensor-signals has been addressed previously [4]. Here, data from 85 sensor recalibrations showed 70% of sensors were within the measurement uncertainty of the initial calibration. The largest deviations were smaller ± 4% and average deviation was only 0.2%. No correlation between initial calibration data and sensor periods of operation were found.

In our sensor recalibration data it is meticulously detailed which sensor was installed where at what given duration. In addition, it is known how much each sensor has drifted during the entire measurement period and also it is known what soiling level had accumulated until the moment of sensor-replacement. Sensor soiling levels are determined by two measurements taken at Fraunhofer ISE CalLab PV modules during recalibration measurements: A first measurement is conducted with the sensor still being soiled (as de-mounted from the site of measurement) and a second measurement directly thereafter with the sensor having been cleaned. Data available for analysis so far regarding found soiling levels of c-Si reference cells, installed for about 2 years at least on various sites, with various tilts, is depicted in Fig. 5.

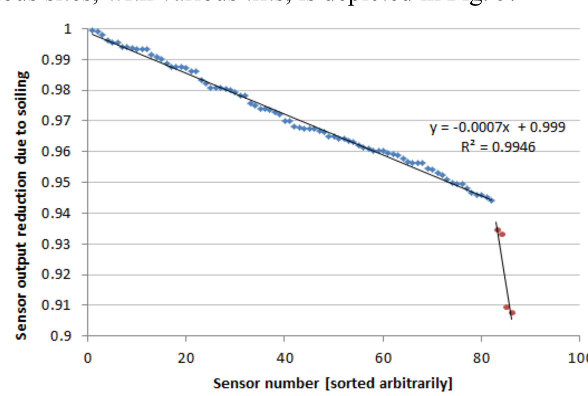

Figure 5: Sensor soiling levels: Deviation of measurement values with and without the sensors having been cleaned in the recalibration.

The systems considered in this analysis were commissioned between large time intervals. As a result, differing equipment was deployed at various sites. Facing various measurement uncertainties is therefore inevitable. To this end, we listed a preliminary estimate of overall uncertainties of stated "rates-of-change" in Table I, distinguished into best- and worst-case scenarios, considering both varying equipment and potential sensor soiling and sensor drift.

TABLE I
ESTIMATED BEST- AND WORST-CASE UNCERTAINTIES

	Best Case	Worst Case
Measured Irradiance at 45 °C	±2.3%	±3%
Sensor drift due to reference cell, encapsulant or incorporated electronics or the like	0%	±3.5%*
Sensor drift due to soiling	0%	-5.5%
AC Energy, FiT-meter	±0.2%	±1%
AC Energy, subsystem	±1%	±3%
DC Voltage	±0.3%	±1%
DC Current	±0.6%	±1.5%
Module temperature	±1.2%	not considered
Estimate for the Performance Ratio	±3.2%*	-10%...+17%.

* Figures as published in [4]

Note the worst-case listed in Table I is quite unlikely, but physically it is possible. Actually, one can observe about the same height in the "rates-of-change" data shown in Fig. 4 when multiplying the depicted "rate-of-change" values with the duration of plant operation: The highest data point shown in the upper panel of Fig. 4 lists 2.9%/year as the "rate-of-change" after 3.6 years of plant operation. The least RMSE fit of filtered PR data thus suggested 10.4% in positive change. Let us assume, theoretically, that the reference cell calibration for the sensor used in this system the past ~2 years was at the lower end of measurement accuracy of -2%, quite heavily soiled by -5% rather quickly and then also drifted by -3.5%. This gives -10%, meaning -10% is measured for POA irradiation as compared with reality. Hence, a resulting "rate-of-change" of +10% of the PR is not unreasonable.

Sensor drift and soiling levels are the predominant cause of the tremendously high worst-case uncertainties. Whether or not a retrospective data-correction for presented "rates-of-change", factoring in these sensor-drifts, actually makes sense is difficult to say. Also here, uncertainty of the c-Si sensor calibration of about 2% needs consideration. Reproducibility was assumed as to be much better in terms of found deviations, but gathering more information on reproducibility of the responsibly laboratory has been demanded, too [4]. Especially for recalibrations with long durations between two measurements, this question was stated to be relevant [4].

Another aspect is that retrospective corrections of sensor drift are not necessarily beneficial for data quality: Drift-rate is neither known for "inherent drift", which might for example be caused by bleaching c-Si sensor encapsulants, nor for soiling-induced drift of each sensor. Whereas the former drift leads to higher irradiation being measured, the latter leads to lower irradiation being measured. One idea to gain more insight into sensor drift would be to correlate irradiation series measured by local sensors with independent data sources, for example irradiation series derived from satellite images. To ascertain the influence of "soiling-induced drift" also precipitation data could be factored in, together with mounting angles of sensors and times of sensor displacement. This way, sensor drift rates or at least drift-patterns might be unraveled. In turn, some systems or measurement periods could be excluded, reducing data quantity but improving data quality such that less scatter in "rates-of-change" could be obtained.

IV. SUMMARY AND CONCLUSIONS

We briefly reviewed the historical development of the Performance Ratio (PR), reaching almost 90% today. These results underscore how well nowadays PV systems perform, if appropriate quality assurance measures are included.

We then evaluated the long-term performance of PV power plants by an analysis of long-term monitoring data. We used a simple data binning and subsequent data filtering approach to reduce ~500 years of data on aggregate to data points at comparable and supposedly failure-free conditions. These filtered datasets for individual systems were then used to derive "rates-of-change" of the PR over time for each system. Resulting "rates-of-change" are broadly scattered. It therefore remains unclear, if found "rates-of-change" of -0.25%/year on average on the system level for PV power plants equipped with c-Si modules (both mono/poly) are representative. We are confident, however, that long-term stability of entire PV power plants equipped with c-Si modules are *much* more stable as one may infer from current, *worst-case* guarantees of c-Si module manufacturers, stating -1%/year so far. We also believe in having found quite encouraging results using this statistical approach on long-term stability, as in many ways improvement of the data and reductions in uncertainty seem possible. However, future research is obviously needed here. To this end, we close this paper with starting a first discussion on uncertainties of calculated "rates-of-change".

REFERENCES

[1] N.H. Reich et al., Performance Ratio revisited: Is PR>90% realistic, Progress in Photovoltaics: Research and Applications, published online (2012)

[2] A. Reinders et al., Technical and economic analysis of grid-connected PV systems by means of simulation, Progress in Photovoltaics: Research and Applications 1999; 7(1): 71–82

[3] Y. Ueda et al., Performance analysis of various system configurations on grid-connected residential PV systems, Solar Energy Materials & Solar Cells 2009; 93: 945–949.

[4] K. Kiefer et al., A degradation analysis of PV power plants, 25th EUPVSEC pp. 5032-5037

[5] A. Driesse et al., Spectrally Selective Sensors, this conference