This paper first appeared in the tenth print edition of *Photovoltaics International* journal, published in November 2010.

Comprehensive and advanced quality assurance measures for optimal yields from PV power plants

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ABSTRACT

As it makes its way towards a non-subsidised market, the photovoltaic sector has to deal with decreasing margins. To ensure investment goals are met in spite of this, it is imperative that PV power plants generate optimal yields. Comprehensive quality assurance for PV power plants covers all phases of the completion process from the planning to system operation. This article explains the extent of standard quality assurance measures that include yield assessments, module measurements, system testing and yield monitoring. It outlines the potential of linking these quality assurance measures and stresses the importance of the measures themselves being of high quality. Up-to-date scientific findings from Fraunhofer ISE are presented in order to further optimise quality assurance measures.

Introduction

Comprehensive quality assurance covers all phases of the PV system completion process from the planning to system operation. The required measures of yield assessments, module measurements, system testing and yield monitoring are, in most cases, linked to the phases of planning, construction, handover of ownership and operation, respectively. These four measures form the PV Quality Assurance cycle developed at Fraunhofer ISE (see Fig. 1) where experts for all of these measures work closely together. Since 1990, Fraunhofer ISE has made important contributions to quality assurance of PV power plants [1] and has continuously improved quality assurance measures according to the latest scientific findings with its accredited laboratory for module measurements, CalLab PV Modules.

Yield assessments

Proper quality assurance begins in the planning phase, and an independent yield assessment is the mandatory first step along the route toward optimal yields. Once a site and a basic layout for a PV system have been chosen, yield assessments provide information on the site's expected performance. Two essential criteria to assess the PV system are provided: the specific yield and the performance ratio. The specific yield in units of kWh/kWp indicates the expected AC energy produced relative to the installed module peak power for a given site. The higher the expected site-specific sum of irradiance, the higher the specific yield. In contrast, the performance ratio is the parameter used to evaluate the technology used, and indicates how much of the energy that would be produced under ideal conditions is actually produced. The nameplate module peak power refers to ideal conditions that are described as Standard Testing Conditions (STC; 25°C, 1000W/m^2 and spectral distribution as in IEC60904-3 [2]). Furthermore, the result of a yield assessment includes exact information on the absolute yield as well as all contributing parameters affecting the yield, plus their uncertainty.

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The necessary input data for yield assessments are site-specific meteorological data, characteristics of the PV modules and inverters and details of the system configuration. High-quality yield assessments can only be performed with high-quality long-term meteorological data for the site in question. Fraunhofer ISE has extensive experience with evaluating data and compares different reliable data sources wherever possible.

The next step is the calculation of irradiance in the module plane with respect to module inclination and orientation as well as row shading and external shading. Modelling the influence of shading is a difficult task, as one shaded cell of one module can affect a whole string of modules. Fraunhofer ISE is currently developing a model to describe the electrical occurrences in a shaded solar generator at the cell level (see Fig. 2), for which initial results were presented at the 25th EU PVSEC in Valencia [3].

The second step is the simulation of the module's power at real conditions. Naturally, temperatures and irradiances under real conditions differ from STC, and as a result, the modules normally operate

Figure 1. A fully closed circle of quality assurance measures as provided by Fraunhofer ISE includes yield assessments, module measurements, system testing and yield monitoring.

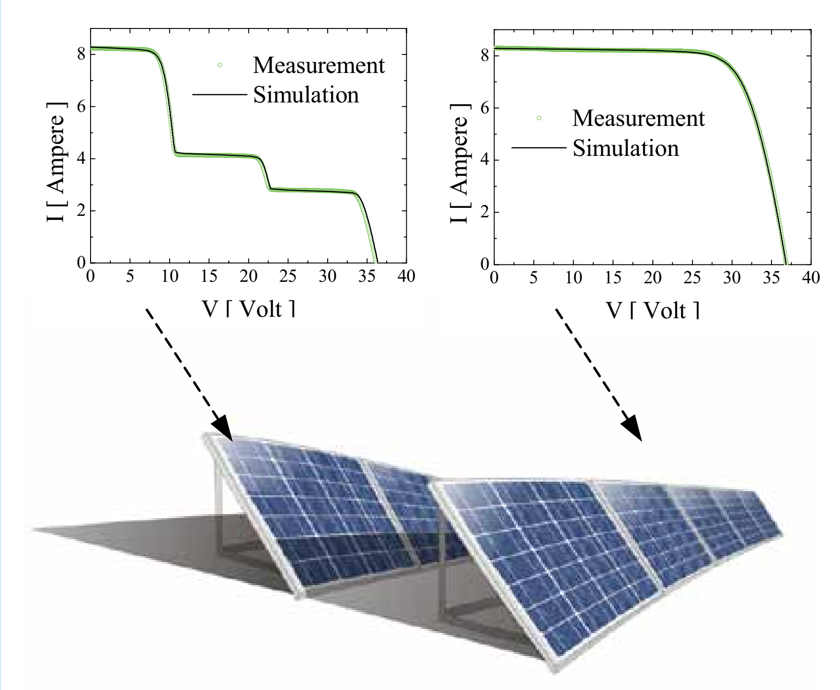

Figure 2. The first steps towards a comprehensive electrical model for the simulation of row-shading showed good results. The I-V curve of a shaded module (left) can be simulated just as accurately as thate of an unshaded module (right).

below nameplate power. The module characteristics needed for the simulation are temperature coefficient for module power and information on low light behaviour. Typical polycrystalline modules lose 0.45% of their STC power per degree and have about 95% of their STC efficiency at 200W/m^2 (20% of STC irradiance). Manufacturers' specifications are usually relied upon in the simulation of the components used, and judging and evaluating these specifications requires no small amount of background knowledge. Although there are several software solutions for PV system modelling commercially available where specifications are readily included, e. g. PVSYST or PVSOL, the most accurate results are to be expected from software which is continuously improved with new scientific findings.

A comparison of data sheet indications and measurements of CalLab PV Modules conducted in 2010 revealed considerable deviations. Deviating temperature coefficients do not have as large an effect on the estimated yield as deviations in low light behaviour, but from a scientific point of view, measurements are to be preferred compared to data sheet indications [4]. Fig. 3 shows the difference observed in calculated yield for two different sites when using measured data versus data sheet indications.

Module measurements

Once the planning of a PV system is finished and the module purchasing stage is approached, it must be assured that the modules meet their specifications. A reduction of 1% in the module's power over an operating period of 20 years represents a financial loss of around €60,000 in Germany for a plant 1MWp in size. In order to ensure that potential irregularities can be identified before system installation, measurements of module power in an accredited

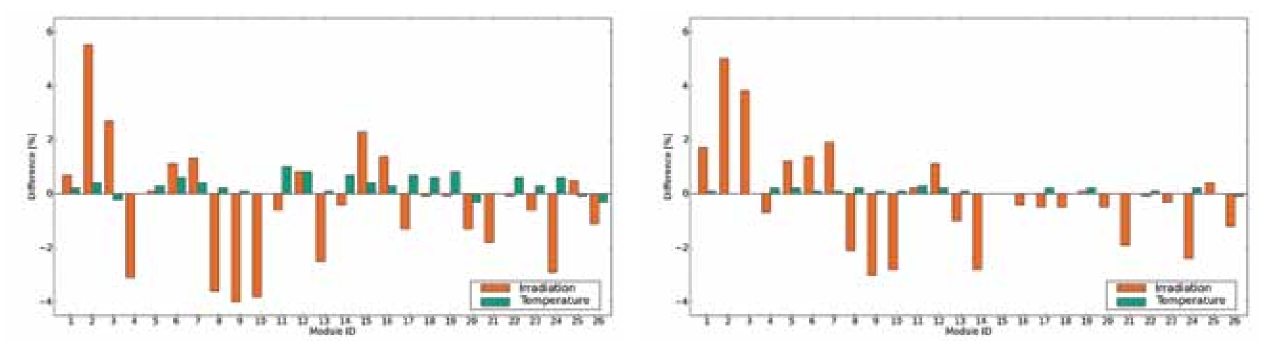

Figure 3. The predicted yearly energy yield differs for calculations based on measured and data-sheet-derived module parameters for a location in southern Spain (left) and northern Germany (right).

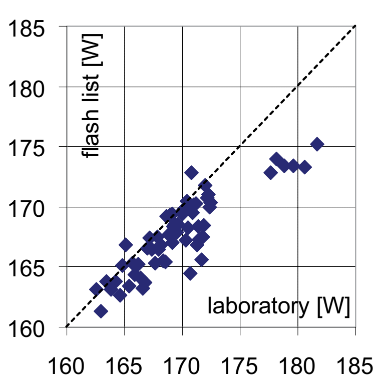

Figure 4. Module power according to flash list versus laboratory results. In this case, the manufacturer flash list underestimates the power of the modules, especially for modules with above-average power.

laboratory of a statistically representative number of modules are recommended. Since a purely number-related definition of "statistically representative" will result in an amount of measurements too high to be feasible, Fraunhofer ISE developed a special distribution-related procedure to select representative modules from the manufacturer's so-called flash list. This flash list indicates the manufacturer-measured power of each module. For the selected sample of modules, which usually comes to about 0.1% to 1.0% of the total of modules, actual laboratory measurement results are compared to the flash list. This uncovers deviations between actual and manufacturer-indicated module power and thus enables reliable information on the power of all modules (Fig. 4).

Of course, it is crucial that the responsible laboratory works according to state-of-the-art standards [5–9] and can reliably provide small uncertainties. Prerequisites for the latter are traceable calibrations of all parts of the measurement equipment, an uncertainty calculation according to international standards [10, 11] and a thorough quality management including regular international round-robin tests. CalLab PV Modules provides measurement uncertainties of 2% to 3% for crystalline silicon modules and 3.5% to 5% for most thin-film modules, depending on the technology and measurement procedure chosen. Fig. 5 shows the results of a round-robin test conducted during the European Commission-funded integrated Project Performance (see also [12]).

Apart from module power, module characteristics as temperature coefficients and low light behaviour can also be verified in the laboratory. In 2009, CalLab PV Modules performed almost 4000 I-V curve measurements at STC, as well as more than 100 measurements of temperature-dependent module behaviour and around 80 measurements of low light behaviour.

Additional benefits of interlocking measures

Anonymously analyzed, this measurement database enables a detailed statistical overview on the state-of-the-art module behaviour which can be used for improvements of other quality assurance measures. The study in [4] for example would not have been possible without close collaboration of the responsible experts. For customers, this doubles the advantages: the close link boosts improvements which lead to smaller uncertainties for the standard quality assurance measures, and it also enhances the development of new services and flexibility with respect to special requirements. For example, smaller uncertainties of a yield assessment could be provided by basing it on measurements instead of data sheet indications. By performing laboratory measurements

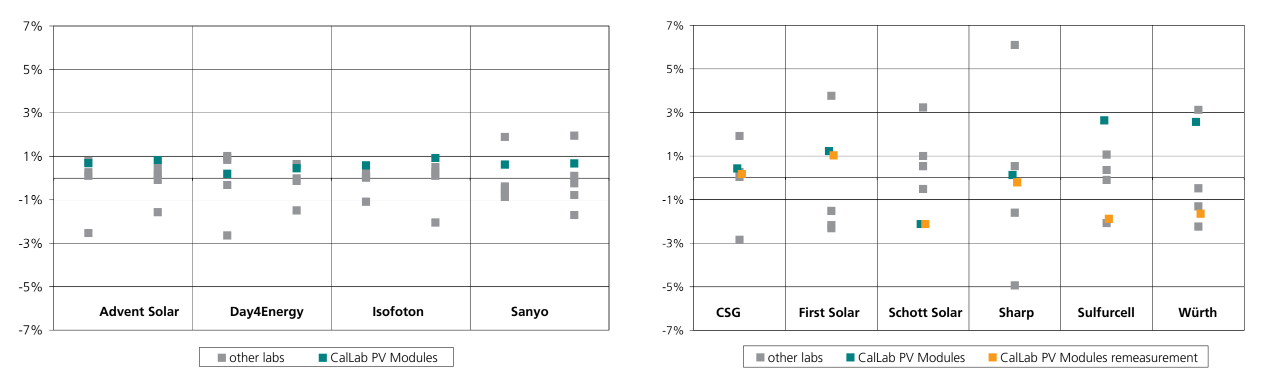

Figure 5. Left: Results of the final 'Performance' round-robin test for crystalline modules. CalLab PV Modules' results barely differ from the average of all participating laboratories. Right: Results of the final 'Performance' round-robin test for thin-film modules. CalLab PV Modules performed measurements at the beginning and at the end of the test in order to state the stability of the modules. The deviations in case of Sulfurcell and Würth modules are due to instability.

Figure 6. Fraunhofer ISE experts perform field I-V curve measurements.

Power Generation

of the modules, the actual power and the module characteristics can be determined and used as input for the yield assessment. In the case of modules performing slightly better than their nameplate power, which is no longer a rarity, the yield can be calculated more accurately. Using measured module characteristics further increases accuracy. As a result, the comparison of calculated Performance Ratio with results from PV system monitoring is more significant. Deviations can be relied upon as results of actual faults rather than uncertainties, and thus faults or non-optimal circumstances can be eliminated more comprehensively.

System testing

After the modules have been checked for their correct power, the focus turns to the installed system. Determining whether the PV system actually conforms to the specifications and delivers the predicted power requires comprehensive testing of the entire installed system. The test includes both general identification of defects and the documentation of deviations from the system specifications in the yield assessment, the latter being a not infrequent task. Specifications that strongly affect the yield, such as installed module power or system inclination and orientation, can also differ, leading to problems when the original yield assessment is taken as a reference for the altered system, for example in advertisements for closed funds.

In the event that doubts arise regarding to which aspect of a PV plant the yield assessment is referring, investors should always request an independent system test with a report comprising a comparison between the as-built and as-planned system. Getting yield assessments and system testing from one source can ensure that no significant false assumptions have been made about the plant. Concerning general defects or faults, stating and documenting them in an independent system test report facilitates taking timely measures and the lodging of possible claims against system suppliers or manufacturers. An independent test report confirming that a PV system is both in operation and free from errors is often a prerequisite for final payments.

> "The extrapolation requires module parameters such as temperature coefficients that have to be carefully determined for the module type in question."

System testing usually also necessitates a closer examination of the modules, which is carried out using an infrared camera in order to identify damaged modules or those that are not working optimally. Damaged modules register faults thermally by showing so-called hot spot effects, and can often be exchanged on a warranty basis.

Furthermore, system testing can involve an alternative to verifying the module power before installation. This might be necessary when no prior tests of module power were performed or when re-verification of module power is requested after a period of operation to check for degradation. In installed systems, module power is checked by measuring I-V curves of sub-arrays or individual strings of the solar generator (Fig. 6), which can reveal not only weak module power, but also faulty cabling.

The drawback of this approach compared to laboratory measurements is weather dependency: field I-V curve measurements can only be performed under clear blue skies with fairly high irradiance (> 800W/m^2), a result of the necessary extrapolation from actual operating conditions to STC [13]. The extrapolation requires module parameters such as temperature coefficients that have to be carefully determined for the module type in question. Close cooperation with CalLab PV Modules enabled a study on the variation of these parameters [14], benefitting the customer by providing both outdoor measurements with an indoor module characterization for minimal uncertainties of the outdoor measurements.

When field I-V curve measurements are performed according to international standards using primary calibrated measurement equipment and using thoroughly determined parameters, as presented in [14], measurement uncertainties of roughly 2.5% to 5% – depending on the conditions – are possible. Additionally, external influences such as soiling of the modules or electrical losses

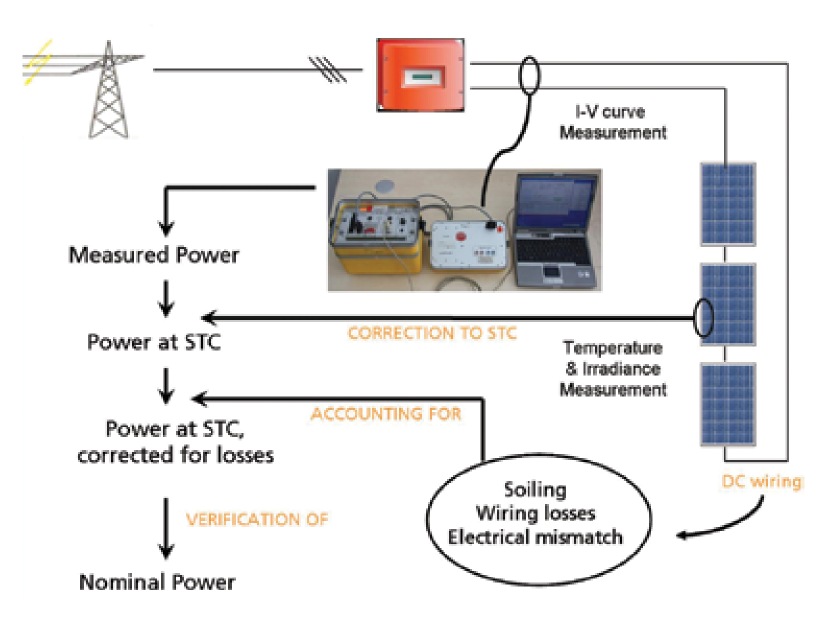

Figure 7. The three steps involved in verifying module power in the field I-V curves.

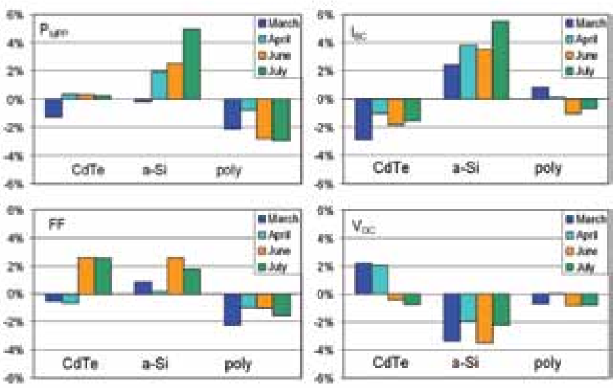

Figure 8. A good agreement of outdoor measurements performed on small PV strings during 2010 with CalLab PV Modules' measurements confirms the accuracy of thoroughly performed field measurements.

have to be considered (see Fig. 7). A comparison of outdoor and laboratory measurements performed at Fraunhofer ISE demonstrates that outdoor measurements are a reliable alternative for crystalline and thin-film technologies if properly performed (see Fig. 8). Outdoor measurements were conducted at a test field at Fraunhofer ISE; indoor measurements were carried out by CalLab PV Modules.

Yield monitoring

Assuming these quality assurance steps are carried out correctly, the PV system is likely to be in an optimal condition. But will this be reflected in the performance, and will things stay the same for the next 20 years? Independent long-term confirmation of the

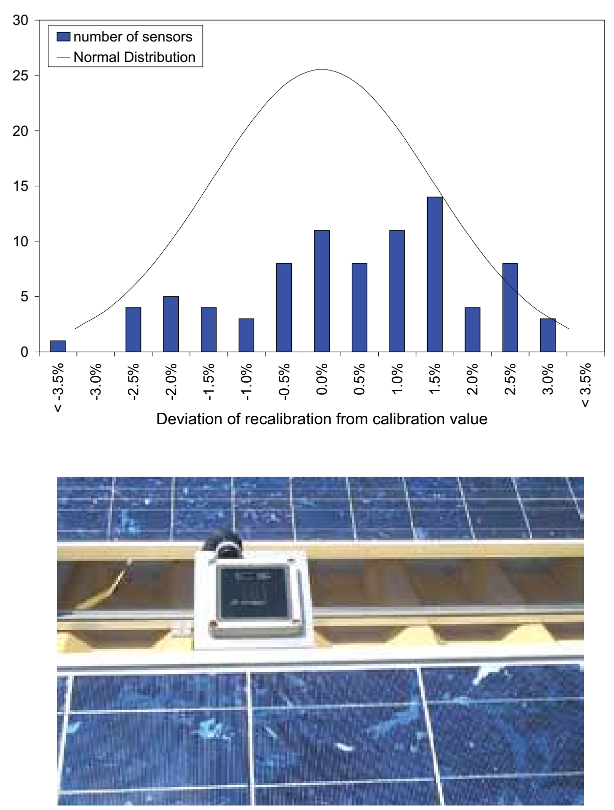

Figure 9. The recalibration value of the majority of recalibrated sensors lies within ±2%. The measurement uncertainty for cell calibrations is ±2% at a 95% significance level.
Below: A Fraunhofer ISE crystalline silicon reference sensor.

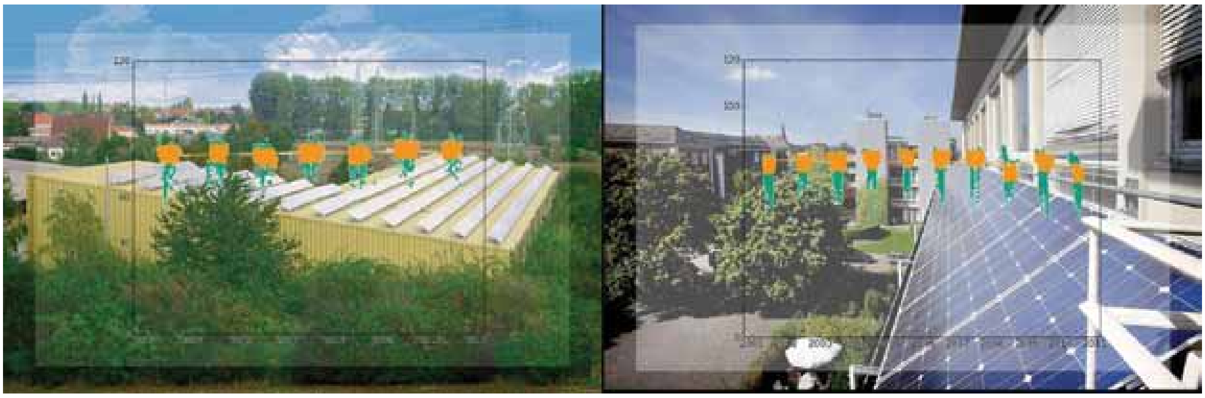

Figure 10. The Performance Ratio of the PV systems shown did not change significantly during several years of operation. Green dots are five-minute average values at high irradiance; orange dots are the reminders after outlier removal. The orange line is a regression line to the orange points and indicates the long-term change in Performance Ratio.

quality and performance of a PV system is provided by a state-of-the-art monitoring system. Such systems are comprised of at least one calibrated irradiance sensor – preferably a pyranometer installed to ensure coplanarity with the modules, measurement of AC system output and measurements of module and ambient temperature. Crystalline silicon cells can also serve as irradiance sensors in place of a pyranometer. Accurate DC measurements of one or several subsystems are recommended to enable a closer analysis of module and inverter operating behaviour.

The total electrical output is certainly the most important information provided by a monitoring system as the kWh level is the figure of most interest. However, optimal system performance cannot be judged from the yield because the yield is dependent on the available irradiance. An irradiance sensor with traceable calibration makes it possible to calculate the Performance Ratio, the value that indicates how close to the optimal level the system is running. The benchmark today is around 90%, based on a crystalline silicon sensor for systems in Germany. Needless to say, the reliability of the results depends fully on the irradiance measurement: if regular sensor recalibrations are not performed, or the calibration is not accurate, the results will be questionable. Fraunhofer ISE recommends recalibrations every two to three years as a state-of-the-art interval and applies sensors with a calibration uncertainty of ±2%. Fig. 9 shows the results of the recalibrations performed at a total of 85 irradiance crystalline silicon sensors.

Most monitoring solutions include data analysis where experts analyse the operating ranges of system components and inform clients of faults and underperformance if they occur. As a result, the client recognizes sub-optimal operation quickly and counter-measures can be taken to avoid loss of valuable yields. Internet access to the operating data of the system is offered by many providers.

Nevertheless, monitoring PV systems is not enough. Major project developers have been able to improve the performance of their systems significantly by continuous co-operation with Fraunhofer ISE – as has been documented by comparisons of the Performance Ratio of systems with continuous, comprehensive quality assurance and those which are subjected only to monitoring. Fraunhofer ISE has 20 years of experience in monitoring PV systems, starting in 1990 with the German 1000-Roofs-Programme [1]. Today, the number of Fraunhofer ISE-monitored PV systems has risen to more than 200, which comes to a total installed power of more than 38MWp.

Benefits of monitoring

The vast font of knowledge that is formed by the monitoring data is not only valuable to customers, but also to the providers of quality assurance measures. The data allows for answering questions about long-term behaviour, provides the unique possibility of 'quality assurance' for yield assessments by comparing estimated and actual yield, and offers the opportunity to compare the output of different plant concepts.

The results of yield assessments are compared to real-life system performance on a regular basis; for example, deviations of Fraunhofer ISE-predicted and -observed Performance Ratio in a study from 2009 were less than 2% for systems with no technical problems [15,16].

In order to officially confirm the findings that crystalline silicon PV systems operate on a stable level over many years, Fraunhofer ISE conducted a degradation study in 2010 [17] that comprised a cumulative total of 125 years of operation from 17 PV systems that had been in operation for five to 15 years individually. The results were promising: on average, no systematic degradation for poly- and monocrystalline silicon modules could be detected (Fig. 10). Therefore, it is unnecessary to assume any degradation for this kind of module in yield reports. The study included sensor recalibrations, which is not the case for other studies that are in conflict with the Fraunhofer ISE result [18].

In a similar cross-section analysis, the output of PV systems with the central and distributed converter concept were analysed [19]. Systems with distributed inverters in practice did not seem to offer a clear advantage, although there may be instances where they deliver a higher potential.

Conclusions

Each measure described in this article applies mainly for one phase of implementation of a PV project. Nevertheless, comprehensive quality assurance accomplishes additional benefits by closely interlocking the different measures. This refers, in the first instance, to the fact that none of the measures covers the examination of all relevant components and specifications. The location and layout of a PV system being approved by a yield assessment does not guarantee profit – the predicted yield can only turn into actual profits in the event that the modules meet their specifications. Even 'flawless' modules will not be capable of working optimally if system installation is not performed thoroughly.

> "Only a fully closed quality assurance circle guarantees that the full potential of a PV system is tapped from the beginning."

Similarly, an impeccably installed system will underperform in the long run if output-decreasing effects such as inverter problems or increased shading remain undetected because of a lack of system monitoring. Closing the loop, the average performance of a system with the potential to perform at an above-average level might not be recognised as insufficient without comparing monitoring results to a yield assessment. It becomes obvious that, on omission of any step of the quality assurance process, it may become harder to detect the reason for any underperformance of the system as the investment fails to pay off as planned after some years of operation. Only a fully closed quality assurance circle guarantees that the full potential of a PV system is tapped from the beginning.

Naturally, comprehensiveness of quality assurance can only be one side of the coin that buys optimal yield. It is just as important that the quality assurance measures themselves are of high quality, otherwise the results are unlikely to take a real step forward. Quality assurance measures must be subject to continuous improvements based on both up-to-date scientific findings and long-term real-life experiences. This challenge can be best met if the different quality assurance measures are provided from one source, as Fraunhofer ISE's up-to-date scientific findings show. The additional knowledge that is built up by the close interconnection between the measures is a surplus for every customer.

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