All about PV power plants: Challenges for technical bankability

Quality assurance | More than ever, the global PV market provides attractive new investment opportunities, but the elements driving such rapid expansion also increase the risk of solar financial assets failing to meet long-term fiscal and performance goals. Boris Farnung, Björn Müller and Klaus Kiefer of Fraunhofer ISE, and Peter Bostock and John Sedgwick of VDE Americas explore major quality-assurance measures and the challenges today for achieving bankability of utility-scale PV plants

The PV market is growing rapidly and globally. Ongoing R&D coupled with economies of scale drives cost reduction and efficiency. Competitive price levels of PV power plants have led to solar energy being less dependent on government support to provide attractive levels of investor returns. In order to achieve bankability and differentiation, a first-rate level of certification and quality assurance at the system level is essential.

Importantly, it is necessary to go beyond the existing standards and implement new and customised quality-assurance products that address quality on a system-wide level. Such an approach leads to lower technical risk and increased trust and confidence for a PV system as a secure investment. Real-world experience highlights the importance of system design, proper planning, engineering, component selection and construction work for the success of a PV system. Thus, comprehensive quality assurance for PV power plants needs to cover all phases of the completion process, from planning to system operation and maintenance [1].

Quality assurance for PV plants

In general, technical risks arise from the components, construction and operation of PV power plants. Over the past few years, the modules have been the key component for bankability. However, because the investment share for modules is now decreasing, the inverters and other balance of system (BOS) components, as well as the system as a whole, are gaining more focus. The inverter, as the interface between generator and grid, is an essential component with regard to reliability and technical bankability. Today, the quality of large-scale PV plants is also differentiated by their design and construction.

On the other hand, components such as modules are produced under enormous cost pressure, at different locations worldwide, with frequently changing bill of materials (BOM), but indicated as the same module type. These trends are additionally challenging the quality assurance for the manufacturers as well as for the customer. Furthermore, recently observed failure mechanisms – such as potential-induced degradation, micro-cracks, snail trails and discolorations – may lead to a declining investor trust in the reliability of PV power plants.

Performance ratio (PR) and levelised cost of energy (LCOE) are the key figures for evaluating the quality of large-scale PV power plants. Recently developed approaches allow an independent assessment of both component and design quality in order to maintain the best values of PR and LCOE over the system's lifetime.

Evaluating performance

Today's utility-scale PV installations are multi-MW plants ranging from 10MWp to 500MWp. The quality assurance must therefore cover millions of modules, installed on several miles of metal rails, connected with bunches of cables to hundreds of inverters over an area of thousands of acres. This makes it clear why the quality of large-scale PV plants is also differentiated by design and manufacturing. State-of-the-art system engineering requires standardised plant units with sophisticated designs for efficient and flawless construction, since 100% testing is not possible, neither at the component level nor at the system level.

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One key figure in assessing a PV plant as a whole is the PR – an internationally introduced measure for the level of utilisation of an entire PV system [2]. The PR is defined in IEC 61724 and can be derived directly from global plane-of-array (GPOA) irradiance and AC energy produced. Thus, it indicates the efficiency of system operation by taking into account losses on the PV system's rated output due to temperature, incomplete use of the irradiation (soiling, spectral or reflection losses), and component efficiencies or failures.

Another key figure is the LCOE – the ratio of the sum of all the costs of energy production (from construction to operation and maintenance) and the total energy produced:

$$\text{LCOE} = \frac{\text{Cost of produced electric energy}}{\text{Produced electric energy}} \quad (1)$$

From a detailed analysis of this equation, several quality-sensitive parameters (circled in Equation 2) can be distinguished:

$$\mathrm{LCOE} = \frac{I_0 + C_0 \sum_{t=1}^{n} \frac{(1+i)^t}{(1+r)^t}}{R_P \cdot \eta_{STC} \cdot E_y \sum_{t=1}^{n} \frac{(1+d)^t}{(1+r)^t}} \qquad (2)$$

where (quality-sensitive parameters are highlighted in bold):

- $\boldsymbol{I_0}$ = initial investment for the power plant
- $\boldsymbol{C_0}$ = annual operation and maintenance (O&M) cost
- n = service life
- i = annual inflation rate
- r = annual discount rate
- $\boldsymbol{R_P}$ = initial PR of the power plant
- $\boldsymbol{\eta_{STC}}$ = initial module efficiency in standard test conditions (STC)
- $\boldsymbol{E_Y}$ = energy irradiated on the module plane (i.e. POA)
- $\boldsymbol{d}$ = annual degradation rate

To ensure the levelised costs of energy, and thus the return on investment (ROI), the quality-sensitive parameters have to be predicted as accurately as possible (e.g. E_Y) or guaranteed to be stable (e.g. η_{STC} or R_P). For the quality of PV plants, the appropriate quality measure can be derived from the LCOE. An example for quality-assurance testing in different project phases is shown in Fig. 1.

In the following section, major quality-assurance measures will be introduced, and related challenges for assessing utility-scale PV plants will be addressed.

▲**Figure 1. Quality assurance for different phases of a project.**

▼**Figure 2. Input parameters for yield predictions and typical uncertainties.**

The basis – accurate yield assessment

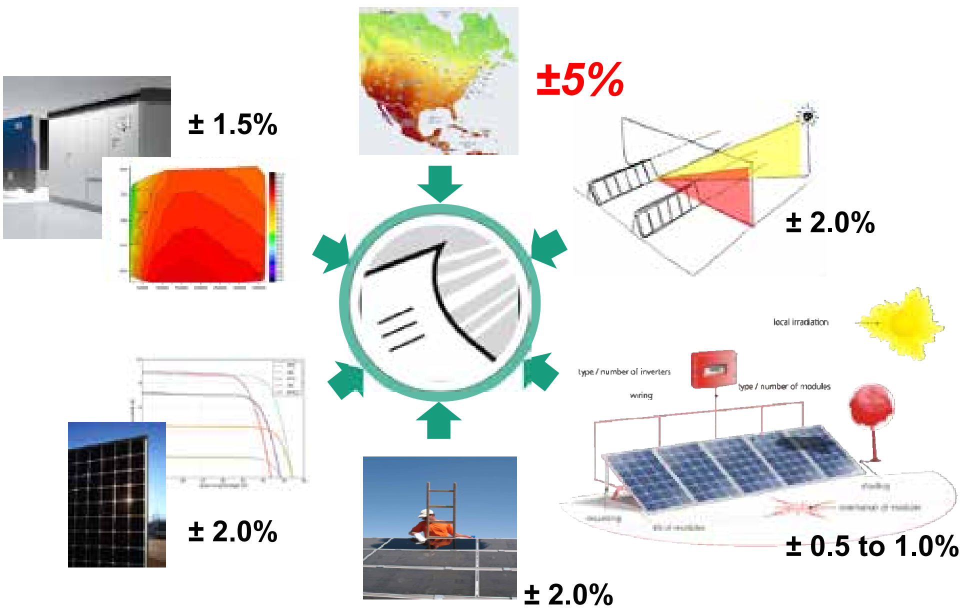
A primary practical challenge is that of a PV system realising its assumed yield prediction. Experience shows that this does not necessarily hold true if no acceptance tests are performed [3]. At first glance it may not appear that any deviations from the design will have an influence on the expected energy yield, but they could well be significant (e.g. a decrease in installed power may result from reducing inter-row distances and hence increasing shading losses). A yield prediction without any checks that the system has been built as expected is more or less worthless.

The main types of input data and their uncertainties are shown in Fig. 2. It is obvious that the weather data has the highest contribution to the uncertainty budget for yield prediction. State-of-the-art yield predictions generally use satellite-derived irradiance time series as a basis for system modelling. The quality of these time series has considerably improved over the last 10 years: this applies to the overall mean bias deviation as well as to the irradiance distribution compared with ground measurements. The mean of the bias deviations computed over multiple locations varies around zero, while deviations of about 3% can be expected for single locations. For a detailed analysis, the reader is referred to Ineichen [4].

A recent topic regarding the quality of yield predictions, which possibly has not gained due attention up to now, is the existence of long-term trends in solar irradiance, which could influence expected energy yields. These multi-decadal trends, known as *global dimming and brightening* [5–7], are observed in most parts of the world (to varying extents). In general, after a dimming phase from the 1950s to the 1980s, a brightening phase began in the mid 1980s.

Muller et al. [8] analysed the influences of these trends on solar resource assessments for Germany: resulting uncertainties of approximately 4–5% were estimated for irradiance in south-facing planes with 30-degree tilt angles. For recent solar resource assessments, an increase of up to 5% is expected when only the last 10 years of irradiance data are used for the estimation. An elaboration of these findings for other parts of the world is still lacking.

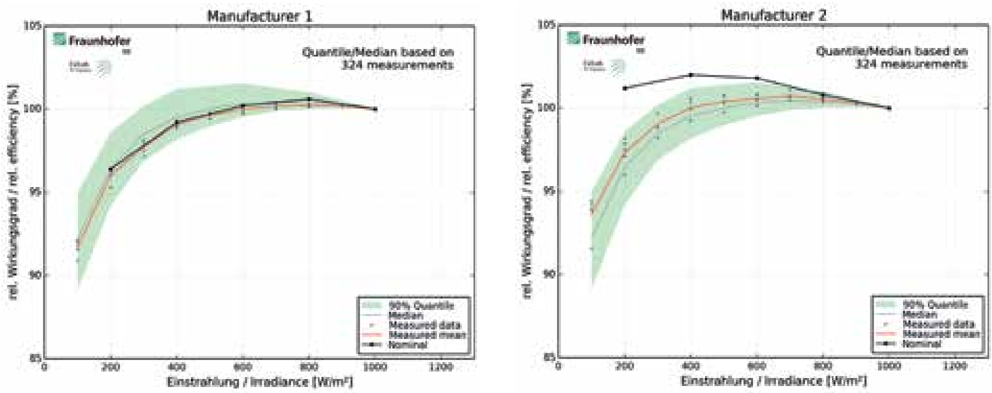
PV system modelling itself seems to introduce relatively low overall uncertainties (at any rate for time periods of



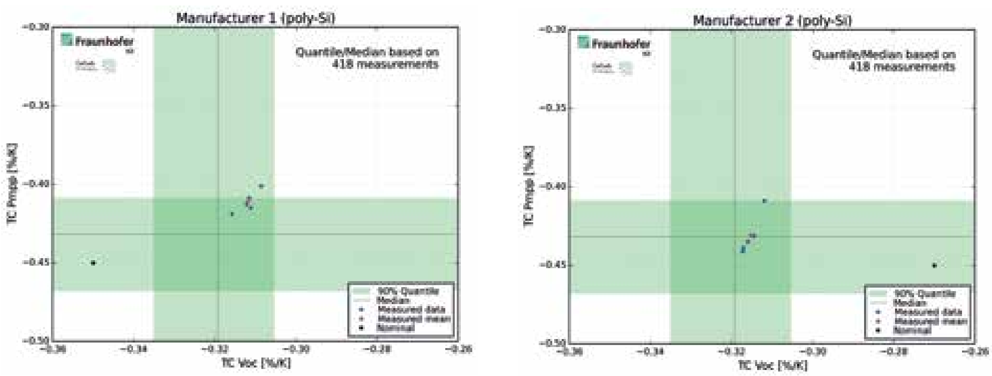
a year or more) [2,9]. Other modelling steps that may introduce higher uncertainties under particular conditions are shading and soiling losses. In addition, the calculation of the effective irradiance received by the module (angle of incidence effects, spectrum) is so far not fully understood. However, at least for silicon modules, it seems that the overall effect can be estimated by using relatively simple models, and the deviations are within measurement uncertainties [9].

Big challenges concerning the input parameters exist for PV modules with regard to the behaviour of PV modules in conditions different from STC. It has been shown that datasheet information about the low-light behaviour of PV modules is usually not adequate for reliably assessing yield [10]: therefore the parameters used for yield prediction should be determined independently by the application of the power-rating standard IEC 61853-1, or by the measurements of temperature coefficients at 1000W/m^2 irradiance and low-light behaviour at 25°C. Usually, the characteristics are measured for several modules. Fig. 3 shows an example of an evaluation of the measured low-light behaviour for two different manufacturers. In the case of manufacturer 1, the nominal values are in excellent agreement with the mean value (average of five modules) measured in the laboratory. For manufacturer 2, there are strong deviations between the nominal and measured values; such deviations can lead to significant overestimation of the yield [3,10].

The same evaluation was done for the temperature coefficients, as shown in Fig. 4. In particular the temperature coefficients given for the open-circuit voltage (V_{oc}) demonstrated large deviations from the expected range (90% quantile). The 90% quantile, shown as the green area in Figs. 3 and 4, represents more than 100 measurements performed at Fraunhofer ISE in the last two years. These evaluations allow an initial validation of datasheet and manufacturer data before being used as input data for yield predictions. Besides a validation of the input data by laboratory measurements, confidence in a yield prediction can be increased by on-site testing and performance evaluation as described later, in the system testing section.



▼Figure 3 (top). Measured irradiance dependency (average of five modules) compared with nominal and typical values for two manufacturers (typical = range covered by 90% of all modules measured at Fraunhofer ISE during the last year).



▼Figure 4 (bottom). Measured temperature dependency compared with nominal and typical values for two manufacturers (typical = range covered by 90% of all modules measured at Fraunhofer ISE during the last year).

Laboratory testing

Laboratory testing is valuable at different stages of the project, starting at the planning and design phase, as shown in the previous section. But the planning and design phase is also when the cornerstone is laid for confidence in the product. A quality benchmarking process, with predefined quality criteria, will help to:

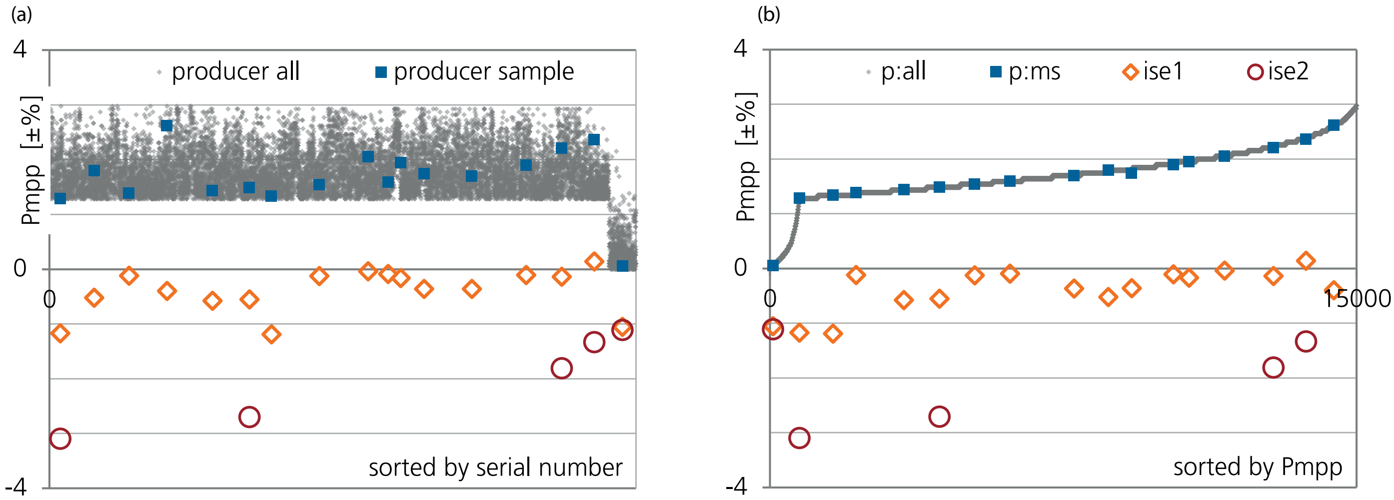
- prevent systematic underperformance;
- provide independent parameters for yield assessments;
- detect sensitivity of modules to known failure mechanisms (e.g. snail trails, yellowing, potential-induced degradation, etc.);
- compare the products with state-of-the-art results.

The final testing procedure, especially in the case of reliability testing, should be derived from the customer's quality criteria, the experiences gained in the field, and the environmental conditions (installation site, system layout, etc.). The goal of the laboratory testing is not to repeat the testing specified in the standards, without any possibility to extrapolate the data to an estimated lifetime: the goal must be to prevent known failure mechanisms occurring in the field (e.g. snail trails, yellowing, PID, etc.) and to gain confidence in the fact that this module type is not sensitive to these degradation mechanisms.

During implementation, an independent performance check of the modules is recommended to prevent a systematic underperformance of the purchased module lot. In this process, the values indicated in the manufacturer's flash list (list of electrical characteristics) should be evaluated on the basis of a selected sample set. It is particularly important to select modules from different time (serial number) and power ranges, as shown in Fig. 5.

The bank or investor often stipulates a specific number of modules for testing. To simplify matters, modules are randomly selected; in most cases this means that, if 50 modules are required, two boxes are sent for laboratory testing without specifically selecting the modules. In this case, most of the modules are from the same serial number range and thus represent the same time frame of production. An example shown in Fig. 6 clearly shows the small range. In actual fact, there is no practical value in measuring 25 modules from a single box with the aim of preventing a systematic under-

Figure 5. Flash list (15,000 modules) evaluation based on a small sample: (a) sorted by serial number; (b) sorted by Pmpp. (p:all = power value of all modules in this flash list; p:ms = selected modules for measurement; ise1 = power value of the selected module 'out of the box'; ise2 = power value of the selected module after light-induced degradation (LID) with 20kWh/m² sun exposure.)



"There is no practical value in measuring 25 modules from a single box with the aim of preventing a systematic underperformance of the total quantity of purchased modules"

performance of the total quantity of purchased modules.

To remove the risk of systematic underperformance of the modules, the sampling needs to be done carefully, and the evaluation of the results requires a high accuracy. At Fraunhofer ISE, measurements are carried out with an industry-leading uncertainty of 1.6% [11] for crystalline modules, or with a slightly greater uncertainty in the case of thin-film modules.

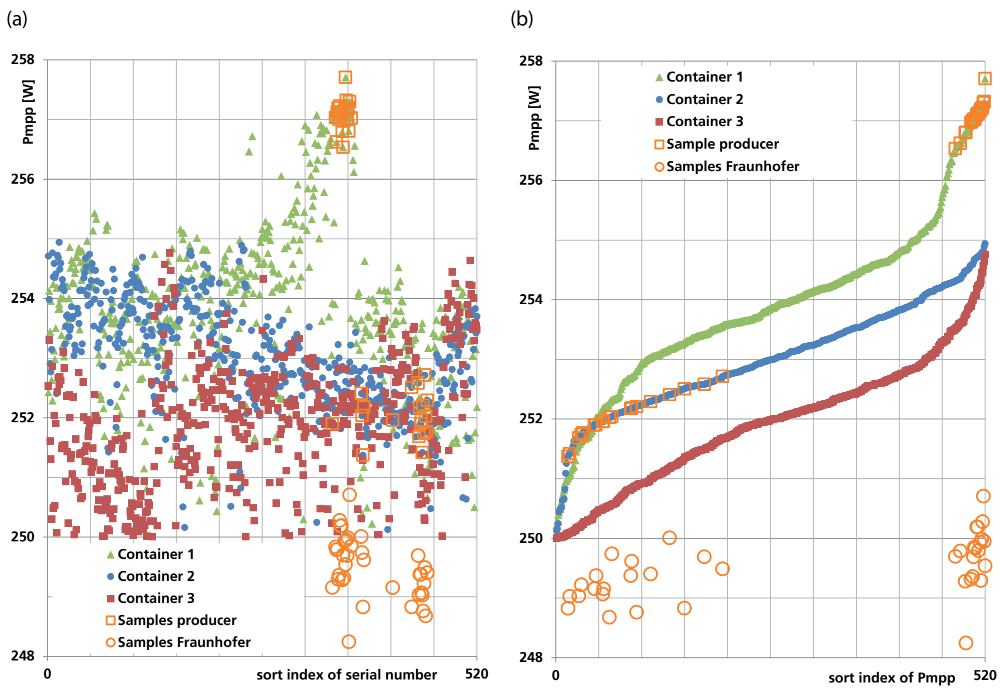
For the evaluation it is also essential to take into account initial effects with an impact on performance in the field. Crystalline modules lose up to 3% of their power in the first hours of operation [12]; this degradation is usually finished within 10 to 20kWh/m² of light exposure and the module will have stabilised. In accordance with the standard DIN EN 50380:2003-09 [13], the modules must comply with the rated power at STC specified on the nameplate and datasheet after preconditioning with a sun exposure of 20kWh/m² or more.

For thin-film PV modules, determining the power representative of field operation demands technology-specific know-how [12,14]. Depending on the technology, the effects of initial degradation or dark storage change the power. Preconditioning procedures therefore have to be applied prior to the *I–V* curve measurement, in order to bring the module to a state that is representative of field operation (CIGS, CdTe).

System testing

Most of the acceptance testing, initial performance and safety evaluation or plant certification takes place in the commissioning phase of a project. As mentioned before, the PR is a key figure in assessing a PV plant as a whole – it indicates how well a PV system is performing.

▼Figure 6. Randomly selected modules – two boxes selected from three containers (520 modules each): (a) sorted by serial number; (b) sorted by Pmpp.



Besides a visual inspection and safety and component testing, the actual PR of the system should be validated. By comparing actual (measured) and expected (simulated) PRs, one can obtain valuable information about whether the system is performing as expected. Important input data for the PR calculation are the actual irradiance and the system output, which means that both values have to be measured accurately during operation. However, it has been observed that, in many cases, unreliable and inaccurate measurement equipment is used.

In this approach, therefore, available monitoring data is validated by comparison with calibrated and high-quality measurement equipment that has been installed for a defined time frame; if necessary, the measurements from the calibrated instruments are used to correct the monitoring data. Higher accuracy can be achieved if the actual power loss due to soiling is measured. The tests are conducted on selected strings with and without soiling, and cleaning procedures are reviewed to provide an estimate of the impact of soiling for a specific site.

After validation and correction, existing monitoring can be used to determine the actual performance ratio. For comparison with the expected performance ratio, the measured weather data (irradiance, temperature) are used to simulate the PR using an established procedure and the system model and parameters from the original yield prediction (Figs. 7 and 8).

This procedure has been developed over the last few years and corresponds to the current state of science and technology. Out of all the specific plant parameters (e.g. inverter efficiency, cable losses, etc.), the ones resulting from the power-rating measurements performed on modules selected in the plant are included in the model.

In recent years this procedure for performance verification has been successfully applied to utility-scale PV plants worldwide. It has been shown that performance can be accurately evaluated within just a few weeks, and, as a plant's monitoring system is validated, a third-party evaluation of existing and future yield data is possible.

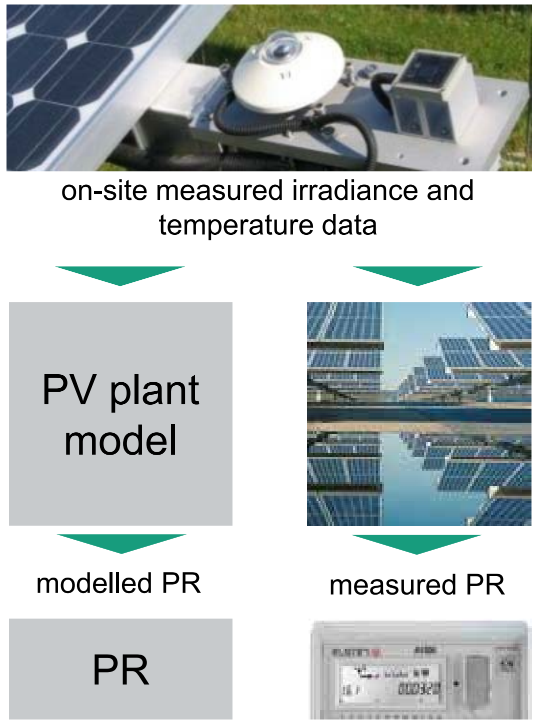
Another important aspect is that performance evaluation should cover all components of the PV system and their behaviour. The inverter in particular, as the interface between generator and grid, is an essential component with regard to reliability and technical bankability. On the basis of efficiency, availability and long-term repair or replacement cost, the inverter can decide between success and failure for an investment. Even if an inverter itself has passed tests in accordance with all current standards, the conditions at a specific location may cause noticeable yield losses. For instance, the operation of hundreds of inverters in parallel and the interaction with other inverters or a noisy grid can cause problems in the field. Thus, for the technical bankability of a system, looking not just at single components is of utmost importance.

"Quality is the key factor in achieving technical bankability"

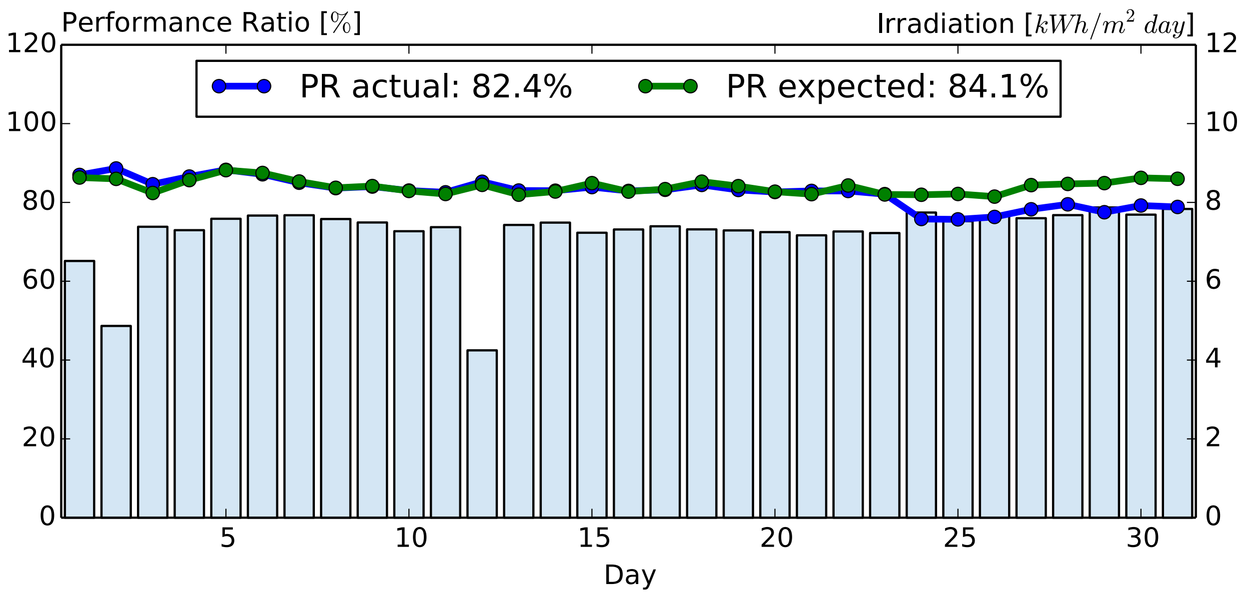
Experience of PV plants in operation

Appropriate monitoring and control of plant operation is mandatory for commercial- and utility-scale PV installations. Failures during operation must be detected using reliable methods in order to avoid major yield losses. Accurate monitoring, however, also shows whether the plant performance is stable, which will guarantee the ROI; moreover, the monitoring provides the basic data for logging the track records of the system layout, workmanship and components used. Therefore, independent third-party performance reports are required for the bankability of projects.

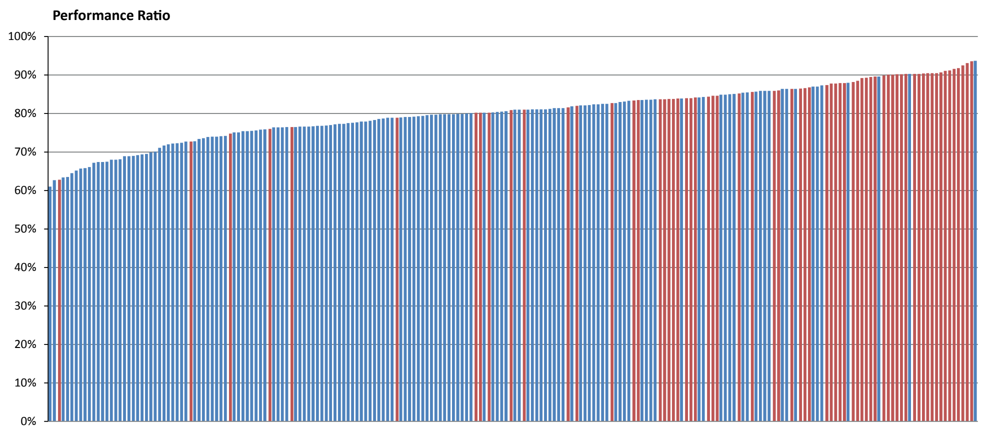
Benchmarking of the 300+ PV plants



▲Figure 7. Process for performance verification. On-site measured and validated irradiance and temperature data are used for: 1) the calculation of the expected (modelled) yield by using a plant model, and 2) the calculation of the actual (measured) plant PR based on the data from the energy meter.



▲Figure 8. Comparison of actual and nominal PR values for July 2013 for a utility-scale PV system in southern Spain. On 24 July, a failure in the system caused a drop in PR of almost 10%.



▲**Figure 9. PR measurements for 300 PV plants carried out by Fraunhofer ISE. Red bars represent plants with basic initial quality assurance and continuous O&M contracts.**

monitored by Fraunhofer ISE demonstrated annual PRs between 60 and ~90% for the year 2014 (Fig. 9). For most new PV plants with basic initial quality assurance and continuous O&M contracts, PRs greater than 80% were reported. In central Europe, initial PRs above 85% can be expected for today's high-quality PV plants.

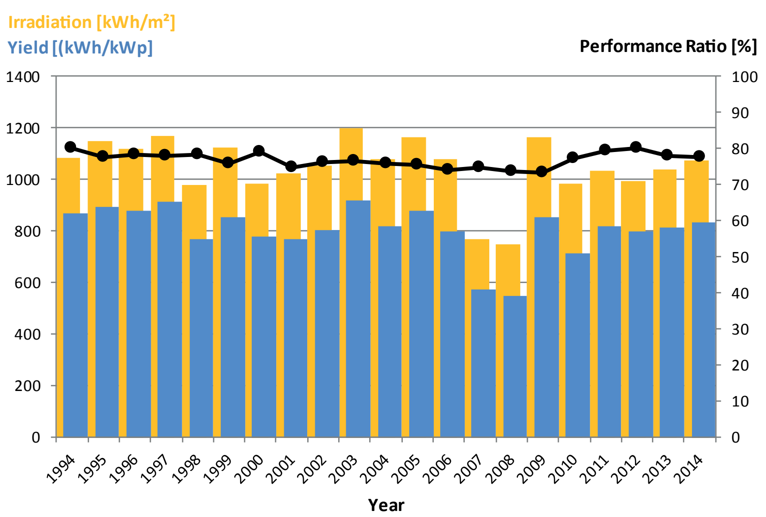
PRs of 75 to 80% were also found for plants that had been in operation for 15 to 20 years. The evolution of the performance of a 4.88kWp plant in operation since 1993 in the northern part of Germany is shown in Fig. 10. This system had an average PR of 77% for the last 20 years and very small variations from year to year of just ±2.7%. There are many other examples showing that solar energy today is a reliable source of energy if appropriate quality-assurance measures are adopted.

Conclusions

Quality is the key factor in achieving technical bankability; this implies state-of-the art system design and standardisation. Appropriate quality-assurance measures, such as plant certification, reduce the technical risk of component or system failure, as well as validating performance with a higher degree of certainty. Thus, quality provides a clearer picture of the financial returns of a system. For component suppliers and system integrators, quality can help to achieve differentiation in the competitive market, where the various stakeholders involved now have different criteria for evaluating investment in projects.

Finally, technical bankability is an indicator of the attractiveness of a project from the perspective of the financing institution. Whereas assessments of bankability in the past were often derived from the particular components selected, today the quality of the plant as a whole is becoming more and more important. ■

▼**Figure 10.**
PRs of a 4.88kWp system, which has been in operation for 20 years, installed in the northern part of Germany.



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