Failure assessments of PV systems demonstrate the importance of elective quality assurance

Quality | In a four-year project sponsored by the German Federal Ministry of Economics and Energy, a consortium of German experts assessed the quality of actual PV power installations. The researchers now report on how the effects of several common module failures on module and string performance highlight the importance of consistent quality assurance to prevent risks to financial success

Credit: TÜV Rheinland

The number of photovoltaic installations worldwide has increased exponentially over the last 10 years. The PV market has evolved from one of small-scale applications to a mainstream electricity source with a trend towards increasingly utility-scale PV systems, with investments totalling tens to hundreds of millions of dollars.

Whereas in 2017 PV power plants worldwide made up only approximately 2% of the total electricity mix, their role continues to increase, and as this trend continues, the reliability and predictability of power supply as well as yield optimisation will also become increasingly more important. Depending on the design and projected results, the potential for improvement may be as high as a two-digit percentage.

Especially when it comes to large-scale utility power plants, a seemingly small 1% optimisation will yield an improvement potential totaling approximately US$1 million for a 50MWdc power plant.

In the interest of reducing risks and optimising the technology and therefore financial performance, this paper discusses a two-level approach, namely a solid supply chain and operational quality assurance throughout the plant's service life, including novel procedures for related statistical quality control, especially on-site analyses, EL image analysis and real-time monitoring, from inception to decommissioning after 25+ years, and considers insurance options for countering financial risks as well.

Extensive testing of PV systems in Germany has revealed serious failures with potentially large cost implications

In this spirit, the German government sponsored a long-term study called "PVScan", the major goal of which was to analyse and carefully evaluate selected photovoltaic systems, in order to assist the assessment of technical defects and faults occurring in practice, their influence on actual energy yields under actual operating conditions and, more importantly, their potential for significant future incidents of damage and defects leading to performance losses relevant for operators and investors.

Quality scanning of large PV systems

A closer look at the general quality levels of large PV plants newly built or already in operation for several years reveals some widespread problems whose implications for future performance are unclear in part, but also some serious failures with enormous consequential costs and even relevance in part to safety have been found.

For example, just over the last two years various problems with the stability of backsheets have been recorded that affect PV modules commonly installed in PV power plants – an issue concerning the overall gigawatt range. So-called "whitening" or "yellowing" refers to embrittlement or crumbling of the affected backsheets. It is undoubtedly a serious safety issue and affects performance during continued operation. Current laboratory stress tests of the combined effects of UV radiation, temperature changes and high humidity reveals that the increased penetration of moisture related to failures leads to massive energy yield loss in the modules ranging to 30%.

For some years now, potential-induced degradation (PID) has been responsible for occasionally massive energy losses in large PV installations. Severely affected modules perform 50% or even 60% below their rated power on the nameplate. Even if only some parts of the module strings are affected, the overall performance loss can be dramatic. The light-induced degradation (LID) of newly built PV systems has been another source of concern for investors and operators of PV systems. LID can cause a massive power loss in the first few days of a module's service life.

A major issue is critically overheated cable connections or junction boxes. For example, temperatures of 100°C and above were measured in a large-scale, eight-year-old reference PV installation investigated in the PVScan project. Complete strings had already failed due to thermally destroyed connectors of the junction boxes. A complete infrared (IR) inspection showed that around 6% of the installed modules were affected by overheated junction boxes in the affected plant with the connection failure, resulting, in the worst case, in electric arc ignitions. The affected module types are installed not only in open-space systems but also on residential houses and public building roofs, where the defects cannot be detected during operation, so that prompt module replacement becomes necessary.

All the aforementioned issues were found at PV plants that had been in operation for one to eight years, so that the PV modules in these plants still had to perform for the greater part of their expected service life.

These examples indicate the enormous financial impact poor component or construction quality can have. New ways to ensure a consistently high quality over the service life of PV modules are therefore urgently needed.

In short, poor quality of installed components tremendously jeopardises the attainable energy yield and consequently the financial success of investment.

An internal TÜV Rheinland study conducted in 2014 and 2015 and involving the inspection of over 100 large-scale PV systems mainly installed in Germany and other European countries showed that:

"30% of all investigated plants had suffered failures with a need of immediate action to prevent a plant breakdown!"

"50% of all identified serious component failures were PV module issues accompanied by wiring and connection problems."

A closer look at the issues in these PV modules reveals a slew of known abnormalities that have already been dealt with in recent years and which are classified according to different criteria and are therefore not discussed here in more detail.

A comprehensive collection and analysis of the available statistical data on component failures in approximately 800 PV installations totaling around 0.5GWp in different market segments in several European countries can be found in the reports by the EU-funded "Solar Bankability" project [1].

The results of the "Solar Bankability" project and a TÜV Rheinland analysis of more than 400 inspected PV plants conducted between 2010 and 2016 show the most commonly found abnormalities including issues of planning, installation and operation, all resulting in significant plant yield losses.

Here, too, considerable yield potential usually remains untapped, resulting in sub-optimal financial returns in the PV projects in real terms at the end of the operating period of 25 years.

Table 1 below lists the top 10 deficiencies and their frequencies of occurrence in large PV systems.

Natural degradation and faulty degradation

PV modules are designed to convert incident sunlight to electricity. This conversion requires the occurrence of complex physical and chemical processes in the multilayered modules. Components are exposed to transport stress on the way to the final construction site, and are subsequently subject to long-term adverse environmental conditions such as frequent changes of ambient temperature, humidity, wind and snow loads, UV radiation and moisture during operational life.

All these stress factors lead to several

Failures	FR Total	FR Plant	Yield Loss	Potential
Soiled modules	8.1%	38%	10%	● (significant)
Improperly installed modules	7.7%	23%	5%	● (moderate)
Shading	6.2%	50%	10%	● (moderate)
EVA discoloration	4.1%	30%	0%	● (moderate)
Glass breakage	2.5%	44%	10%	● (moderate)
PID	1.9%	5%	10%	● (significant)
Defective backsheet	1.1%	42%	1%	● (significant)
Delamination	0.9%	17%	1%	● (moderate)
Hotspots	0.8%	28%	2%	● (moderate)
Failure bypass diode in JB	0.4%	20%	33%	● (not expected)

Increase in losses is not expected (grey dot)
Moderate increase in losses is expected (light red dot)
Significant increase in losses is expected (red dot)

Source: TÜV Rheinland

Table 1. Identified failure rates in terms of inspected modules (FR Total) along with rates of plants with this failure (FR Plant), the average detected power loss at inspection time and the estimated potential of further power loss.

degradation processes that influence the materials and their connections both within the module and in the exterior components of a PV system. Long-term irreversible decreases in PV module performance are therefore not preventable. Some of the known mechanisms responsible for performance loss are:

Degradation mechanisms

- Semi-conductor degradation
- Photo-degradation of polymeric materials
- Various thermal degradation mechanisms
- Diffusion processes, in particular water vapour ingress into the encapsulation
- Static and dynamical mechanical or thermo-mechanical stress
- Material interactions (selection of suitable materials)

The "natural" degradation rate depends on the specific module technology and the operating conditions of the PV system. For standard crystalline modules in moderate climates we may generally assume an average annual performance loss between 0.3% and 0.5%.

As already noted above, various types of failure can lead to a faulty, accelerated ageing process resulting in a higher degradation rate and in performance loss. The magnitude of this effect is still under discussion for many types of failure and was investigated as an important issue for investors and financial institutions in the PVScan project.

Detection of module failures in the field

The evaluation of a photovoltaic system requires expert knowledge as well as objective, data-based analyses. Concerning the latter, system-wide real data of a system under operating conditions is important, as is module-based data such as precise performance measurement data (STC) and electroluminescence images, which allow assessments of the occurrence of physical defects and damage.

Electroluminescence imaging is an established tool in the evaluation of modules in photovoltaic systems, but their analysis still relies mainly on personal expertise and experience, owing to the lack of automated assessment procedures. The PVScan project team developed novel statistical procedures to assess the significance of findings from electroluminescence imaging, including lower-quality images obtained under outdoor conditions.

The installation of data loggers to monitor performance and energy yield may be regarded as state of the art. The analysis of such data streams is challenging, however, given the large number of variables influencing actual energy production and its development over time, such as module characteristics, plant design, geographic location with its environment, ambient temperature, solar irradiance and angle of incidence as well as module soiling and temporary shading. For large-scale PV systems the number and positions of measuring devices will also influence results.

Novel statistical string-based monitoring schemes have therefore been developed and studied with the aim of monitoring the internal performance of a system in real time and reducing the probability of a false alarm.

This approach takes a reference string as a sort of gold standard and can therefore be applied without access to additional data sources. It also enables the detection of differences between strings of systems, which can be highly informative when identifying technical issues.

Methods for on-site data analyses

Sampling design for multi-site comparisons and analyses

To scan the quality of a large PV system, a sample of modules must be selected for on-site inspection and characterisation. Since application of the gold standard of randomly sampled modules is not feasible in practice, a cluster sampling approach was developed. Anchor modules are randomly selected and characterised together with their nearest neighbours from the same rack. The anchor modules may also form the core of a panel for a longitudinal study, in order to analyse medium and long-term degradation effects by re-measuring the panel (and its neighbours) at future time points.

For the statistical analysis of such a panel-based cluster sampling of PV measurements over time, an innovative comprehensive methodology has been developed. Quantitative data derived from EL imaging and IV curves, such as the mean EL intensity, number of detected abnormal cell areas, sizes of the inactive cell areas, fill factor and Pmax, as well as qualitative data, such as the presence of snail trails or damaged connectors, can be utilised. The new method can also take site-specific effects into account, such as the module type, the solar inverter and exposure to severe weather conditions. The source in [2] provides a comprehensive exposition of the method as well as Monte Carlo simulations investigating statistical quality in terms of real significance levels and the statistical effectiveness of effect detection.

The PVScan study began with the selection of a large cluster-based sample of modules among five PV systems located in different regions in Germany and the characterisation of these modules on site – without disassembly – through EL imaging as well as visual inspection and auditing, in order to obtain a comprehensive record summarising the technical quality of each system.

Automated EL image analysis

EL imaging is a challenging form of analysis usually performed in view of additional module characteristics, in particular, performance, fill factor and open-circuit voltage. Consequently, novel methods in automatic preprocessing and the analysis of lab and outdoor EL images have been developed. The first step involves specialised preprocessing in order to correct for optical distortions, especially pertaining to module orientation and perspective, and to enable automatic extraction of the cell areas from an image of the module; see [3] for some details.

Whereas recent work on infrared imaging as in [4] relies on segmentation procedures, improved and specialised procedures were employed to detect the boundaries of the module and to estimate the grid lines separating the cells and the grid fingers by means of nonparametric edge detectors and line estimations. This approach utilises known module parameters to improve stability and accuracy. This step results in standardised images of the cells with exactly the same pixel resolution to make valid statistical comparisons possible. In practice, a critical question is whether the focus areas of a cell are darker than properly working cell areas. A valid statistical image test has been developed in this regard. In addition, a fully automatic detector has been designed that scans the entire cell to determine the most suspicious (dark) areas and simultaneously conducts significance tests. In this way, the developed procedures deliver a statistically valid answer that can be reported as a p-value. Figure 1 illustrates the automatic detection applied to the extracted cell areas of a module. Suspicious lower-than-expected dark areas (in red) are frequently accompanied by nearby higher-than-expected bright areas (green),

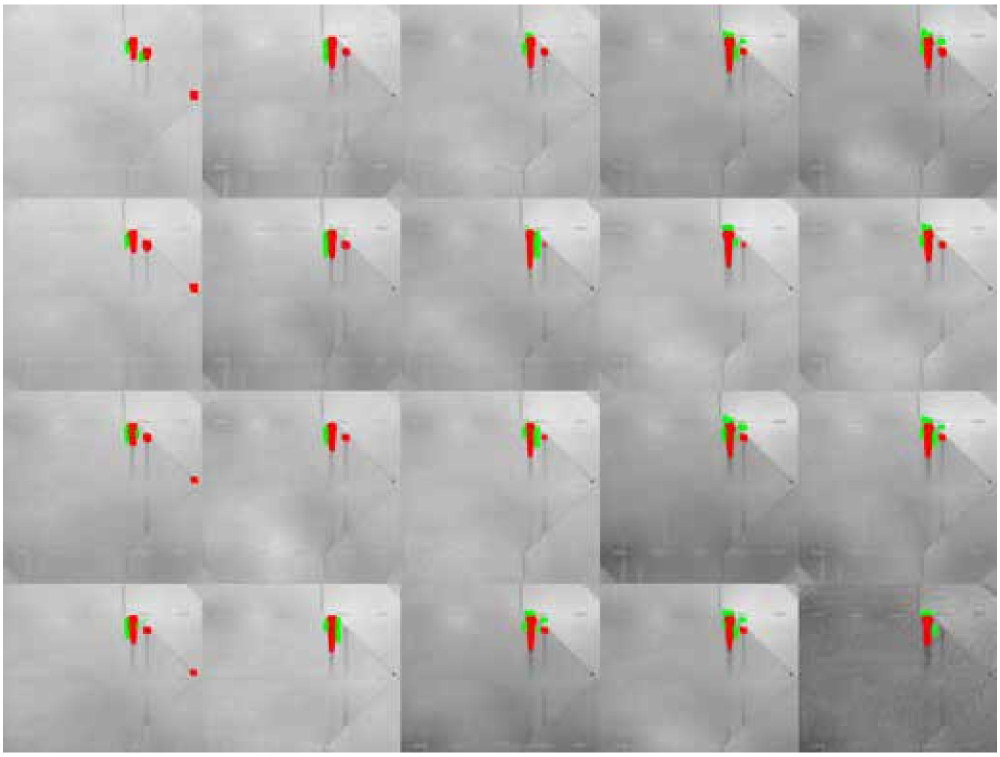


Figure 1. The automatic EL image detector can detect suspicious low-performing areas

where the electron-whole pairs bypass areas of increased resistance. The method controls the overall significance level α, i.e. an EL image of a properly operating cell or module shows any spuriously marked areas with probability α.

Monitoring for significant changes

Large-scale defects in and damage to modules, connectors, cables or other components typically lead to power losses. Weather data and variables such as current and voltage and of selected strings and solar inverters must be monitored. By noting differences from a reference string, underperforming strings or inverters can be detected.

To improve sensitivity and ensure that monitoring takes place at a controlled significance level, detectors were developed and optimised that are based on signal processing estimators and which substantially improve the sensitivity to critical events compared with existing methods. The results must still be evaluated with additional actual PV systems having specific failure characteristics.

Figure 2 shows differences of string currents to the reference string recorded in five-minute intervals. One can observe a notable degree of between-string variation at this high sampling rate. The first part (until the green vertical line) is used for learning and yields the control limit for 5% significance. The control statistic (black line) summarises the difference data and reduces the noise component. A signal indicating evidence for a change is raised if the control statistic exceeds the control limit. For the monitoring period shown in Figure 2 it does not cross the control limit meaning that there is no evidence for a significant change.

The substantial degree of noise in such high-frequency measurements can be reduced by considering the aggregated energy yield on a monthly or quarterly basis. To evaluate the differences in string performance relative to the reference string RWTH developed simulation-based confidence intervals taking into account serial correlations, which are shown in Figure 3 for the first quarter. This analysis reveals several statistically underperforming strings. These underperforming strings should be evaluated by experts to identify or exclude technical causes such as shading, dust, degradation, PID or other defects.

Reliable and low false alarm rate monitoring of real-time high-frequency string difference data can detect underperforming strings and thus reveal faults instantly, but suffers somewhat from the noise present in such data, such that small effects are dominated by noise and are hard to detect. The learning sample needs to be carefully selected, as such difference data may still show a slight seasonal pattern. Aggregated performance measures operating on a coarse timescale allow assessment of the medium and long-term energy yield and can detect underperforming systems by calculating proper confidence intervals to evaluate these performance measures. Both statistical tools allow for systematic and cost-effective monitoring and evaluation in a targeted manner, avoiding unnecessary on-site inspections, and therefore provide an effective framework for objective data-driven quality control of PV systems.

Impact of module failures on performance

Quality assessment of reference systems

From the cluster-sampled on-site investigations, two common types of module errors were identified by the EL imaging method:

1. Micro cracks in different types and accumulations, from individual cracks up to 30% of affected cells in one module;
2. Discontinuities in grid fingers in the cell, resulting in interruptions of current flow in the affected cells. Occurrences ranged from individual production-related interruptions to half of affected areas in the cells and to two-thirds of the affected cells in one module.

The detected average failure rate for micro cracks was 4.9% and for grid finger breaks 3.3%. Other EL-visible abnormalities that were found were mainly darker cell

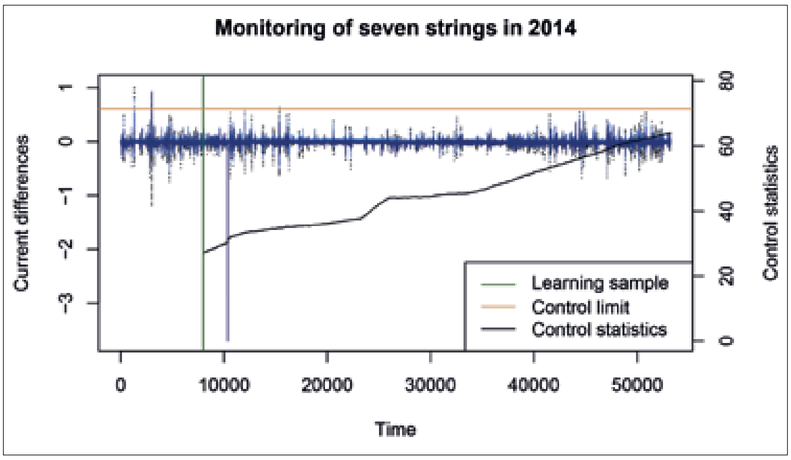
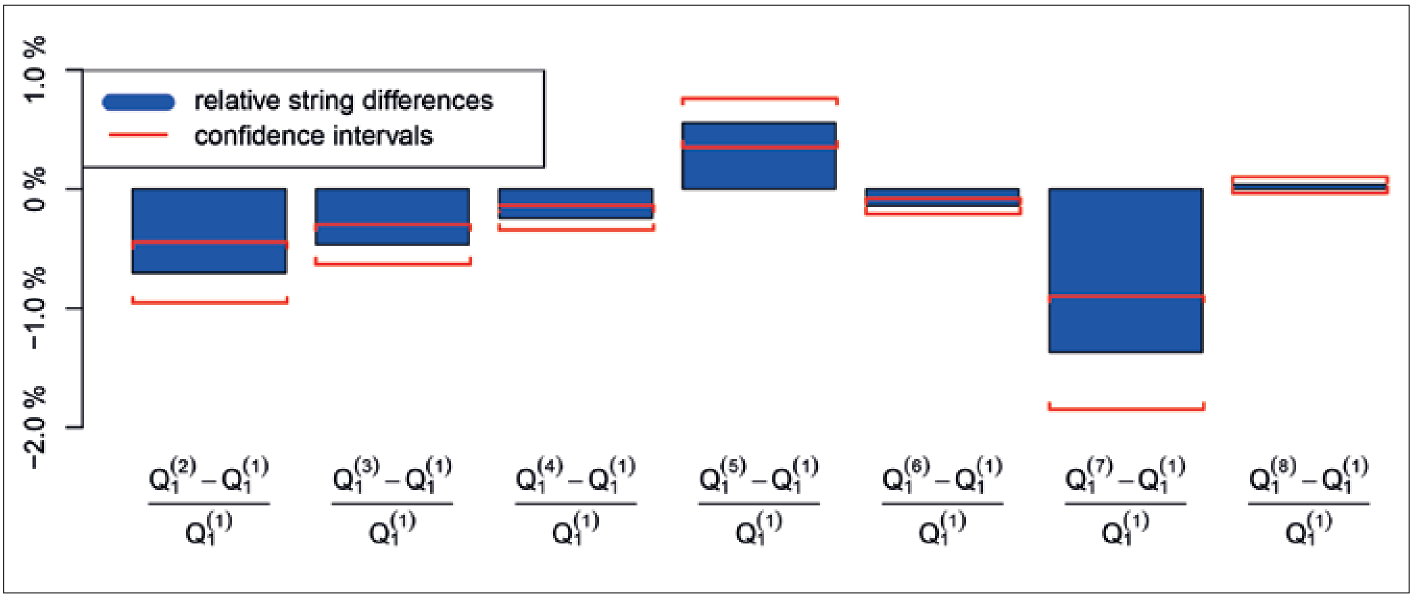


Figure 2. Detection of critical events with real monitoring data



areas, particularly on the edges, with a lower productivity, as well as mismatched cells and very uneven cell areas. Other types of failure were only occasionally found.

In one reference system, visual inspection showed "snail tracks" to be the failure type, an evident visual indication of micro cracks in the cells. The absence of this marker in the other systems is no indication of the absence of cell micro cracks, however.

Another, actually severe, type of failure was initially not identified. The module failure from overheated conductors is a typical self-reinforcing type of failure and can destroy contacts, interrupting current in the modules and thus in the string as a whole. Temperatures of up to 100°C have been measured in the large-scale reference PV installation (built in 2009) under medium irradiation conditions, as Figure 4 illustrates.

In the summer of 2017, complete strings had already failed due to several thermally destroyed junction box connectors. A complete IR inspection showed that about 6% of the installed modules were affected by overheated junction boxes. We may infer that hundreds of detected modules could have this progressive defect due to connection failure, which in the worst case can lead to the ignition of an electric arc. This type of failure can also lead to an increasing performance loss in the affected strings.

Performance measurements

The modules of the selected reference strings were characterised in the high-precision lab of TÜV Rheinland in Cologne, Germany. The results showed that beginning in 2014 most of the modules performed at a good level, given the operating period time of about five years. Only some modules of one installation performed less well than expected.

The EL imaging analysis showed that the underperforming modules in addition to single cell defects contained striking cell mismatches as shown in Figure 5.

The modules of the reference strings of the PVScan-investigated PV installations were precisely measured in the solar laboratory at a time interval of three years. The average annual degradation rate observed corresponds to the expected value of -0.3% (crystalline module type). However, individual modules showed a strong deviation up to more than -1%. Fluctuation varies between plants as shown in Figure 6.

There was no significant correlation found between accumulated cell defects such as micro cracks or finger interruptions and increased degradation. In conclusion these module failures had not led to significant performance losses over the observation time of three years.

Figure 3. 95% confidence intervals of plant-specific normal performance values

Development potential of failures

Degradation effects during project term

Various careful investigations of both brand new modules and modules removed from PV systems selected according to defined error types suggest that poor cell quality or cell mismatch can contribute to acceler-

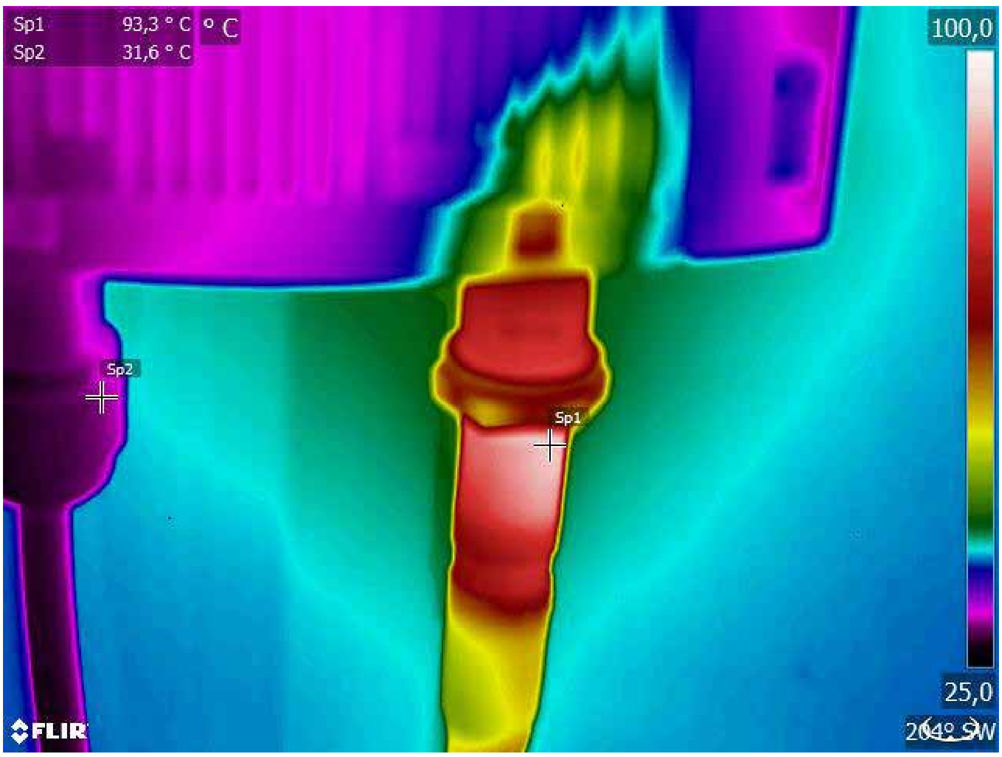


Figure 4. On-site IR inspection revealed a greatly overheated junction box connection

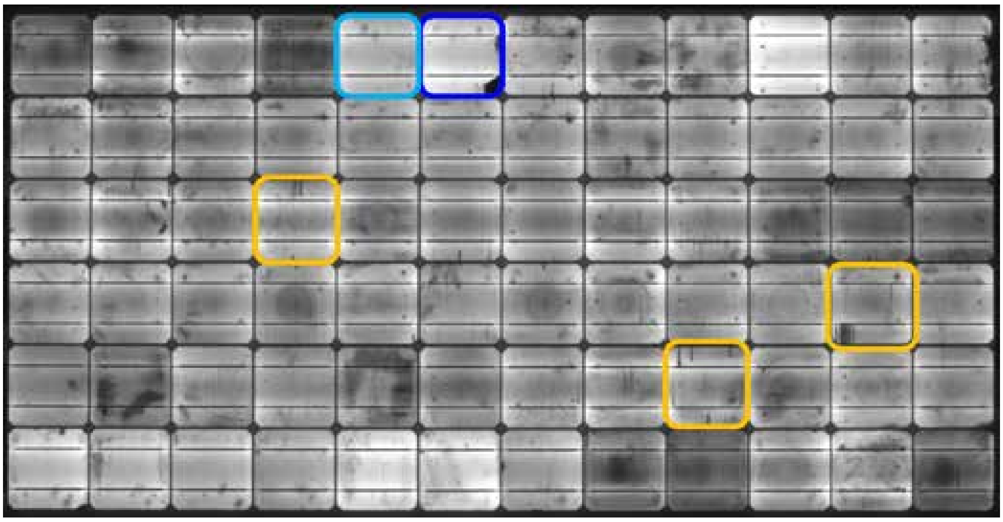


Figure 5. Sample of a poor module from the field after five years of operation: cell mismatch, micro cracks (light-blue), isolated cell area (blue) and finger interruptions (yellow), power loss: -5% in relation to data sheet (0 …+3%)

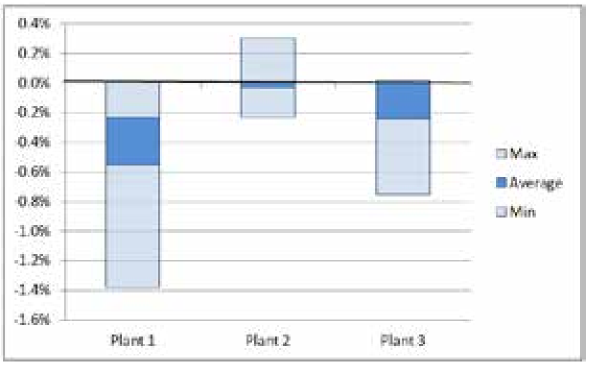


Figure 6. Annual module degradation rates of three reference strings

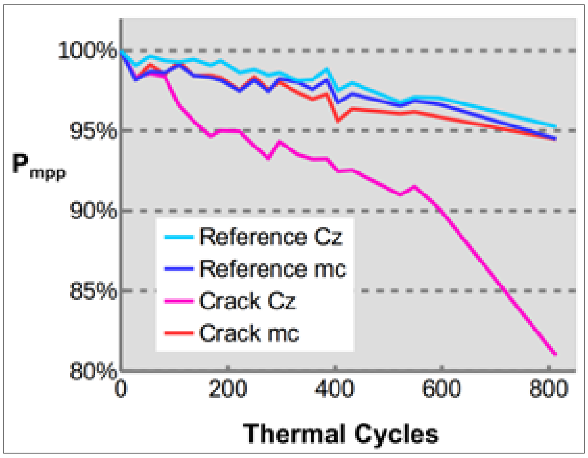


Figure 7. Degradation of test modules during extended thermal cycling testing. Reference samples without cell micro cracks (blue/cyan) show linear degradation of 0.5% per 100 TC. A mc module having a medium-sized cell micro crack (red) shows the same result, whereas a Cz module with a long micro crack (magenta) shows much stronger degradation

ated degradation while even significant micro cracks have a smaller impact on the performance loss discount in the observation period. It is assumed that contact resistances in the module connectors were increased by multiple opening (repeat measurements), which caused additional performance loss.

More detailed information will be published after completing the work on the PVScan project expected in the third quarter of 2018.

Development of micro cracks

The long-term degradation of solar panels is investigated in the lab by means of accelerated ageing testing.

The degradation of modules during thermal cycling testing (TC) according to EN 61215:2005 was investigated, but with the cycle count increased to >800.

Single-cell test modules from typically designed industrial solar panels served as samples. Figure 7 shows the results of power degradation for two reference modules and two modules affected by cell micro cracks. The reference modules exhibited a constant power degradation of -0.5% per 100 TC. The polycrystalline module affected by a medium-sized crack shows the same effect. The monocrystalline module having a long cell micro crack revealed increased degradation of -1.8% per 100 TC, however.

The good news is that the degradation rates in all cases did not increase over time. Degradation rates of standard 60-cell modules are expected to be slightly higher, since additional electrical degradation mechanisms exist compared with our samples. Further results can be found in [5].

In a second step, the degradation of some PV modules taken from the actual reference systems and exhibiting defects such as micro cracks, grid finger discontinuities or busbar failures have been investigated. These modules were stressed in thermal cycles and dynamic mechanical cycles simulating important natural stress factors for the purpose of accelerated aging. A stress intensity scheme based on data such as ambient temperatures and wind loads recorded over an entire year in Cologne was developed.

Module pairs with very similar failure characteristics were carefully chosen comparing the laboratory stressed modules with their outdoor counterparts. In terms of results, we often identified discontinuous developments in micro cracks, in particular in the case of large or branched cracks up to now isolated cell areas. New micro cracks were also observed.

The long-term further development of cracks is expected as in the aforementioned cell investigations. A quantitative statement on the further impact on module performance cannot be made at present. Overall, from our many investigations of micro cracks and bus finger discontinuities it was concluded that only massive failures in a large number of the cells will lead to measurable performance losses. It is a positive finding that the performance of the faulty modules under test proved to be unexpectedly stable.

Risk mitigation and hedging against the remaining risks

Manufacturing quality assurance gaps and proposals

The continued sharp decline in solar panel prices underscores the need to persuade manufacturers to performing a minimum of quality assurance (QA). Compared with other industrial sectors, solar panel production still presents the potential for advancement. Providing general QA recommendations can be tricky, since effective QA measures will always depend on the particular production situation. Production lines can vary from fully manual assembling to full automation.

As an industrial product, a solar panel has the peculiarity of a long service life with a manufacturer warranty of 20+ years. Feedback on customers' warranty claims can take between weeks (installation), months (medium-term defects, such as PID) and many years (long-term degradation). For the manufacturer it is helpful to be able to trace back a defective panel for even years and to have information about its production. Valuable information includes characterisation and testing results, process parameters, component lists, etc. Yet providing this information is far from easy. Challenges lie in collecting this data, correlating the data with the panel and making the data accessible for many years to come. A large potential for improvement lies here.

In the field of inline process control, characterisation tools now exist for most processes.

As an extract of a large number of factory inspections the following tools may be considered useful:

- IV testing: final inspection
- EL: before lamination and at final inspection
- Visual inspection: before and directly after lamination and at final inspection
- EVA cross-linking testing: during or after lamination
- Insulation/high potential testing: at final inspection
- Reverse voltage/diode testing: at final inspection.

Besides inline testing, accelerated ageing testing performed in parallel with production is recommended, since medium and long-term defects like PID, discoloration and poor soldering cannot be detected during production. Testing can be performed with samples from production or with small test modules. PID testing can be reliably performed over 24 hours; most ageing tests unfortunately take several days, weeks or even months, however.

Identification of high-quality products

The aim for differentiation in this commoditised market continues to be strong, and high quality can be an important differentiator. Therefore, building on the results of the PVScan project as well as on the expertise in the field, a rating initiative has been launched that is expected to become an international standard at IECRE.

The rating system is built on several pillars illustrated in Figure 8. While the overall concept of PV power plant rating is not completely new, current rating systems so far concentrate the valuation mostly on financial metrics that reflect on historical performance data and project this performance into the future.

Adding a technical performance rating is supposed to add significant value as the viability of performance projection into the future is expected to increase substantially. The technical rating design aims to allow a PV power plant investor to better estimate the risk exposure of his current and future assets.

EPC / O&M contracts

Besides quality assurance for components, installation as well as the operation and maintenance are important for good performance and a long service life of the plant. Quality assurance accordingly forms part of EPC and O&M contracts as well. The EPC contract should stipulate detailed quality assurance measures such as checking product qualities and commissioning procedures, including final acceptance inspections. The O&M contract should describe all measures (such as monitoring and off-line measurements) and service intervals for visual inspection, module cleaning and grass cutting, spare parts stockpiling and message chains and responsibilities in case of failures or interruptions.

Professional, economically optimised system design and expert installation form the basis of an early return on investment. It is therefore recommended to include the review of the component selection and system design according to local environmental conditions, contracting of qualified staff, supervision of the installation work and professional project coordination. Any quality deterioration may have negative effects on performance and energy yield over the operating period and therefore on the return of investment. Well-defined O&M measures will preserve the performance level over the service life. Without a proper O&M strategy and measures there is a high risk of performance loss due to failures and downtimes and hence loss of revenue. An enhanced plant monitoring system will help assess plant performance and identify problems. Short reaction times will become possible and performance losses or downtimes can be limited. The experience and professionalism of EPC and O&M partners significantly affect quality. Special care must therefore be taken in selecting these partners.

Hedging against the remaining risks – warranties and insurance

Regarding the performance warranty particularly of solar modules mentioned above, without going into detail on the possible variations of warranty and guarantee terms and on system interrelationships, it is to be pointed out that the viability of such warranties and guarantees significantly depends on the assessment of the manufacturer's financial strength. Many manufacturers (and EPC companies) find themselves in bleak financial situations that can be expressed in many different ways. Besides the fact that the risk of a manufacturer's insolvency will trigger a complete loss of value of the warranties and guarantees, the potential inclination to compromise on quality to reduce component manufacturing or construction costs may also prevail.

Quality defects deriving from possible deviations from the bill of materials or from standard operating procedures may be difficult to detect after component delivery and project completion, and may become evident only after several years of operation. As a consequence, a widely discussed solution to counteract (or mitigate) the risk of underperformance of PV power plants due to internal defects is performance warranty insurance.

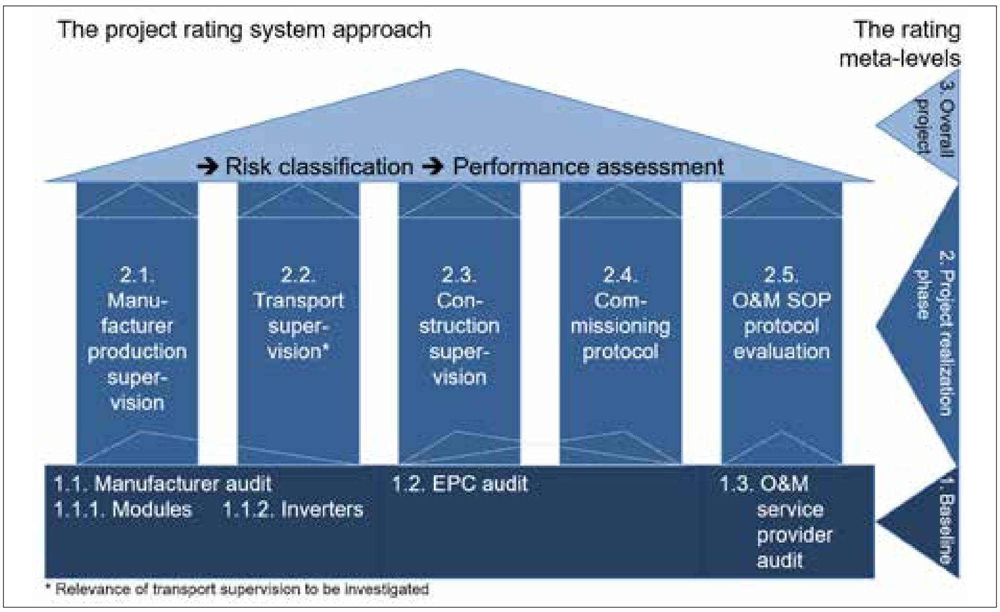


Figure 8. PV power plant rating pillar system

Topic	Examples
PWI process management	One-stop shopping? Many partners?
Auditing	One-stop shopping or many partners? Validity and reliability of audit (i.e. expertise and scope)?
Insured entity	Manufacturer? Project owner?
Scope of insurance	Period insured? Which components are insured?
Obligation	Revocable? Irrevocable?
Coverage	What default cases are covered? Which components are insured?
Start of coverage	From day 1? Only during financing period? Only after initial period of operation?
Coverage amount	Full purchase price for new PV power plant or time value? Cash flow for PPA term?
Method of determining premiums, premium range	Various models (per project, up front, flat fee, annually, …)?
Deductibles, limits and quota shares	Deductibles: percentage, min. fixed amount, …? Limits: time limits, max. coverage limits, …?
Time and budget required	Duration of audits, shipping time, construction period?

Table 2. Examples of questions related to performance warranty insurances

Overall, the market offers a wide range of insurance solutions covering a variety of risks associated with owning and operating a PV power plant. Special insurance solutions such as performance warranty insurance vary quite substantially from one risk carrier to another. Some insurance solutions aim at hedging against the risk of a manufacturer's insolvency and therefore seem to eliminate the risk of the manufacturer becoming unable to meet the warranty obligations. We ascertained two insurance principles: policy contracted directly between the PV power plant owner and the insurance company; and an indirect policy whereby the component manufacturer provides insurance essentially covering the manufacturer's inability to meet the terms of the warranty, e. g. due to the manufacturer's insolvency.

The quality of the actual coverage under real conditions will vary, since some insurance solutions include a number of exclusion clauses in their terms and conditions or include withholdings or other measures in an effort to keep insurance premiums at an acceptable level. The key question accordingly arises as to how tangible insurance coverage may be when the case is foreseeable or has already occurred.

Table 2 indicates the complexity of assessing the risk mitigation value of an insurance solution, given the significant inter-relationships between the relevant factors.

A study analysing the root causes of insurance claim cases is currently in its final phase. Initial findings of this analysis suggest that statistically internal defects of a PV power plant are a significant source of power plant failures. More detailed results can be shared as soon as the study is completed.

In conclusion, our overall findings suggest that the avoidance of internal defects requires serious attention especially during the inception phase of a project. Moreover, the insurance solutions offered on the market should be evaluated in detail in the context of the overall project lifetime in order to assess the value of this risk mitigation method.

Finally, investing in solid quality assurance from the inception of the project through its lifecycle is not only a very important risk mitigation measure – it typically results in surplus performance relative to the nameplate that may in turn contribute to additional financial returns – and all the aforementioned measures can yield preferential financing terms.

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References

[1] Consortium, Solar Bakability, *Report on technical risks in PV project development and PV plant operation*, 2016/2017.

[2] RWTH Achen, Pepelyshev, A., Sovetkin, E. & Steland, A., *Panel-Based Stratified Cluster Sampling and Analysis for Photovoltaic Outdoor Measurements [Open Access]. Applied Stochastic Models in Business and Industry, 33* (1), 35-53., 2017.

[3] RWTH Aachen, Sovetkin, Evgenii and Steland, Ansgar (2015a). On statistical preprocessing of PV field image data using robust regression. In: Nikos E. Mastorakis, Adam Ding & Marina V. Shitikova (Hrsg.), Advances in Mathematics and Statistical Sciences, Vo.

[4] S. D. P. Guerriero, *"Automatic edge identification for accurate analysis of thermographic images of solar panels", Clean Electrical Power (ICCEP) 2017 6th International Conference on, pp. 768-772, 2017, ISSN 2474-9664.*

[5] ISC, Schmauder et al., *Extended Thermal Cycling Lifetime Testing on Crystalline Silicon Solar Modules with Artifically Introduced Defects, 33rd EUPVSEC, 5CO13.3,* Munich, 2016.