Quality assurance for PV modules: experience from type approval testing

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ABSTRACT

Photovoltaic modules and components, due to the nature of their employment, must be designed to withstand the most diverse of environments. The large spectrum of climatic conditions and mechanical stresses that these components must weather merit the application of some standards by which they can be tested for durability, reliability and safety. TÜV Rheinland operates several ISO 17025-accredited laboratories worldwide for type approval testing of flat plate as well as concentrating PV modules, PV components and solar thermal systems. Test data, collected over the past 20 years, shows that there is still a rather high failure rate when it comes to testing of PV modules, and also that there are different failure mechanisms for crystalline and thin-film PV modules. This paper presents data from these tests and draws some conclusions regarding the need for future standards development.

Introduction

Several international type approval standards have been released for PV modules, components, concentrating PV modules and assemblies, but this third party testing and certification is still not required by law in most cases. However, certificates document the adherence to a certain quality level and form the basis for PV project financing. Several test marks have been established to signal to the buyer the satisfactory completion of standards requirements, but a certificate or quality mark alone does not guarantee the high quality of a product. As testing is usually limited to a small amount of samples (typically <10 for a new module design), which in many cases are not even taken from a series production but prototypes of a new series, additional quality assurance measures are needed.

Important standards for PV modules and components

The product certification of crystalline PV modules for open-air climates is based on international standards from the IEC 60068 'Environmental Test Procedures' series. Considerable preliminary work on the definition of special test procedures for PV modules was carried out by the Research Centre of the European Commission in Ispra (Italy).

IEC 61215

Test specification no. 503, 'Terrestrial Photovoltaic (PV) Modules with Crystalline Solar Cells – Design qualification and Type Approval,' developed in Ispra, was adopted in 1993 as the standard IEC 1215 of the International Electrotechnical Commission (now IEC 61215) and in 1995 ratified as the European standard EN 61215. In April 2005, a second version of IEC 61215 was published and named 'Terrestrial crystalline silicon photovoltaic (PV) modules – Design qualification and type approval.' The newer edition of the standard contains some changes in testing conditions and pass criteria as well as additional, more comprehensive tests.

IEC 61215 comprises the examination of all parameters responsible for the ageing of PV modules. Radiation testing, thermal testing and mechanical testing in particular are used to simulate the ageing effects that can occur during the service life of a PV module (see Table 1).

IEC 61646

In 1996, a comparable standard was published for photovoltaic thin-film modules. This standard was revised in 2008 and a second edition was published, namely IEC 61646, or 'Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval.' This draft of the out standard addresses new developments in thin-film technologies and should reduce testing efforts – and in many ways is identical to IEC 61215. The main difference between the two standards lies in the test procedures added to adapt to the special properties of thin-film technologies, such as the degradation behaviour of thin-film modules on exposure to irradiance.

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However, the standard only took amorphous-Si thin-film technologies into account. As a result, the behaviour of CIS, CdTe and others after light exposure is not sufficiently covered in the standard

Code	Qualification Test	Test Conditions
10.9	Hot-Spot Endurance Test	5-hour exposure to >700W/m^2 irradiance in worst-case hot-spot condition
10.10	UV-preconditioning Test	15kWh/m^2 UV-radiation (280 - 385nm) with 5kWh/m^2 UV-radiation (280 - 320nm) at 60°C module temperature
10.11	Thermal Cycling	50 and 200 cycles -40°C to +85°C
10.12	Humidity Freeze Test	10 cycles -40°C to +85°C, 85% RH
10.13	Damp Heat	1,000 hours at +85°C, 85% RH
10.16	Mechanical Load Test	Three cycles of 2400Pa uniform load, applied for 1 hour to front and back surfaces in turn
10.17	Hail Test	25mm diameter ice ball at 23m/s, directed at 11 impact locations

Table 1. Overview of selected IEC 61215/IEC 61646 tests.

as there is a lack of information on these materials. Measurements under standard test conditions (STC) of modules of these technologies therefore require additional considerations.

IEC 61730

The long-term environmental tests of IEC 61215 and IEC 61646 do not adequately cover the aspects of electrical safety. In order to overcome these shortcomings, TÜV Rheinland developed test procedures for the qualification of PV modules as Safety Class II equipment (double or reinforced insulation), which accreditation had gained a reputation globally.

Most aspects of this TÜV Rheinland standard are present in the international standard IEC 61730 'Photovoltaic (PV) module safety qualification.' This standard derives some elements from U.S. safety standard UL 1703 'Flat Plate Photovoltaic Modules and Panels.' Following translation of the IEC 61730 standard into the European standard EN 61730:2007, it was listed under the low voltage directive of the EU, therefore forming the basis for the compulsory 'CE' (Consormité Européenne) standard in the member states of the European Union.

The IEC 61730 consists of two parts:

Part 1: Requirements for construction

Part 2: Requirements for testing

Part 1 of the EN IEC 61730 defines the mandatory design characteristics of the modules (such as minimum distances of conductive parts from the module edges, wall thickness of the junction boxes, etc.) as well as requirements of the materials used in the module (UV stability, temperature parameters of polymeric materials, protection class, etc.).

Since this safety standard insufficiently covers requirements for PV components, TÜV Rheinland aided in the development of a standard that addresses the main safety

Figure 1. Module testing at TÜV Rheinland's PV laboratory in Cologne, Germany.

IEC standards	European or national standards	Standard title
IEC 60904-1:2006	EN 60904-1:2006	Measurement of photovoltaic current-voltage characteristics
IEC 60904-9:2007	EN 60904-9:2007	Solar simulator performance requirements
IEC 61215:2005	EN 61215:2005	Crystalline silicon terrestrial photovoltaic (PV) modules – design qualification and type approval
IEC 61646:2008	EN 61646:2008	Thin-film terrestrial photovoltaic (PV) modules – design qualification and type approval
IEC 61730-1:2004	EN 61730-1:2007	Photovoltaic (PV) module safety qualification – Part 1: Requirements for construction
IEC 61730-2:2004	EN 61730-2:2007	Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing
IEC 62108:2007	EN 62108:2008	Concentrator photovoltaic (CPV) modules and assemblies – design qualification and type approval
–	EN 50380:2003	Datasheet and nameplate information for photovoltaic modules
–	EN 50521:2009	Connectors for photovoltaic systems – safety requirements and tests
–	DIN V VDE V 0126-5:2008	Junction boxes for photovoltaic modules
–	2PfG 1169:2007	Requirements for cables for use in photovoltaic systems
–	UL 1703.3:2003	Flat plate photovoltaic modules and panels

Table 2. Important standards for PV modules.

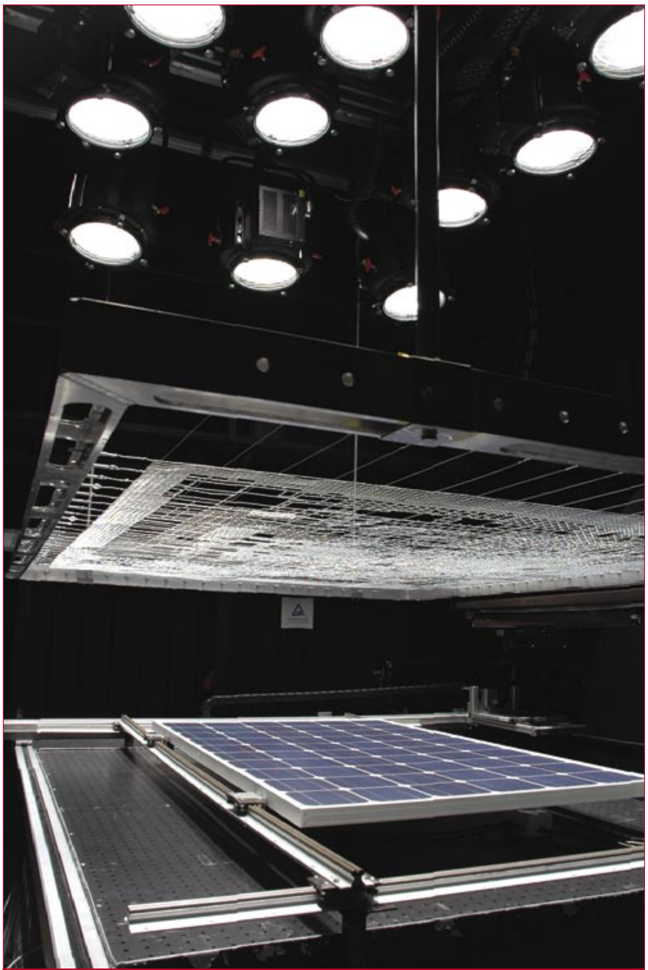

Figure 2. Steady-state solar simulator at TÜV Rheinland, Cologne.

relevant components such as PV cables, connectors and junction boxes. Where IEC 61730 states that a PV cable used on a PV module must be suitable for the application, the TÜV Rheinland standard 2PfG 1169 'Requirements for cables for use in photovoltaic systems' is based on existing IEC standards for cables for outdoor use and includes PV-specific requirements from IEC 61215 and IEC 61730. PV connectors are now tested to the soon-to-be-published European standard EN 50521, 'Connectors for photovoltaic systems – Safety requirements and tests', whereas a PV-junction box standard has only recently been released as the German pre-standard DIN V VDE 0126-5 'junction boxes for photovoltaic systems – Safety requirements and tests', which is translated to a European standard. At the same time, the standardization group working on the international IEC level is also placing more focus on material and component testing.

CPV qualification

Product qualification of concentrator photovoltaic (CPV) modules and assemblies is based on the aforementioned standards. Considerable preliminary work on the definition of special test procedures for CPV modules was laid down in 2001 in IEEE 1513: 'Recommended Practice for Qualification of Concentrator Photovoltaic (PV) Receiver Sections and Modules Design qualification and Type Approval.' In late 2007, the international standard IEC 62108 'Concentrator photovoltaic (CPV) modules and assemblies – Design qualification and type approval' was released and proved to be largely based on its IEEE predecessor. An identical European version of the standard was released in 2008 (EN 62108:2008).

Safety testing so far is not part of this standard. A separate safety test for CPV modules is under consideration; in the meantime, the safety qualification standard for flat-plate PV modules could form a basis for CPV module safety testing.

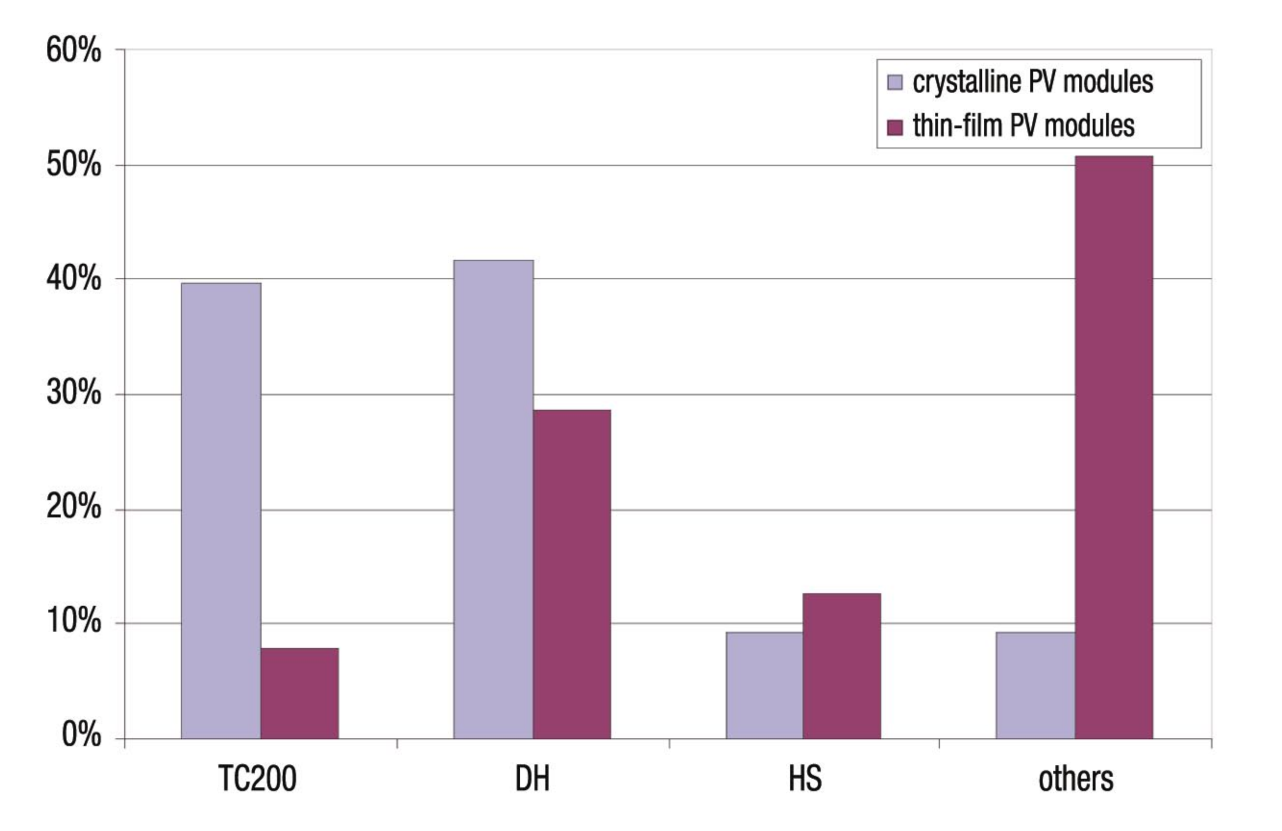

Figure 3. Shares of individual test failures for crystalline PV modules vs. thin-film PV modules.

The fundamentals for the electrical characterization and measurement principles of PV modules are described in the IEC 60904 series of standards. Part 1 lays down the principles for the measurement of the current-voltage characteristics. Part 9 defines the requirements for solar simulators, which are classified according to their performance in the spectrum of the light, the uniformity of the irradiance and the temporal stability in the test area.

Finally, the European standard EN 50380 'Datasheet and nameplate information for photovoltaic modules' defines the minimum requirements for information to be given in PV module data sheets and on their type labels.

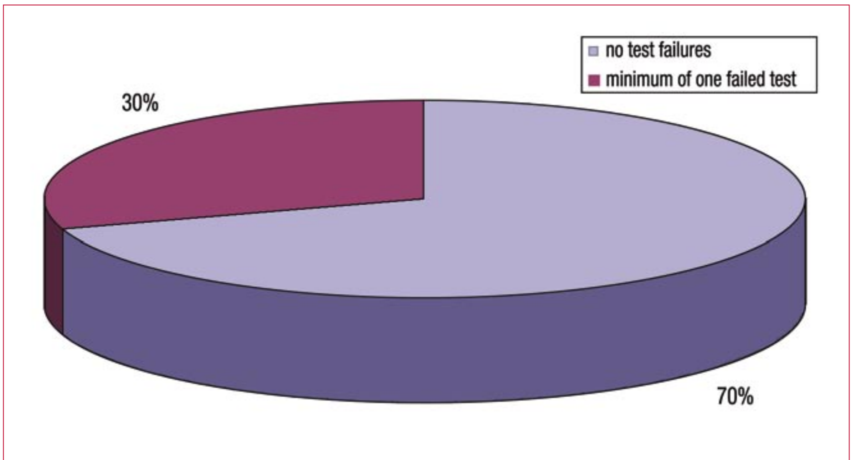

Figure 4. Total failure rate in IEC 61215 qualification testing at TÜV Rheinland, Cologne.

Quality assurance in PV module production

A high level of quality is in the interest of the distributor of the PV module, the manufacturer and, of course, the end user. In the current situation, where we are seeing a change from a demand-driven market to a market with overcapacities, quality plays a much higher role than it did only a few months ago. Competition is much stronger: buyers now have more of a choice and a manufacturer can only achieve higher prices through providing products that are well above average quality level.

Many manufacturers have installed quality management systems and accredited their factories to standards required of ISO 9001. However, the accreditation alone is not a sufficient proof of quality, as ISO 9001 audits vary internationally and the standard defines methods only, not product-specific requirements. A module from an accredited factory is therefore not on a par from a quality perspective with a competing product from another accredited factory.

Of even more importance are the type and frequency of the quality measures in the production. Unfortunately these measures are not standardized and the type approval and safety qualification standards do not include in-line testing methods. Through the annual factory surveillance carried out as part of TÜV Rheinland's certification system, many different test methods have become familiar to the PV experts. The most common tests are listed below:

- incoming inspections of components and materials
- solar cell sorting according to power, colour, etc.
- pull test on soldered cell connectors
- electroluminescence (to find shunts or cell cracks and interrupts in the circuitry)
- determination of the gel content of laminated EVA
- elongation or peel tests on encapsulation materials
- visual inspection (at different stages of the production)
- voltage/current measurement on single strings prior to lamination

- isolation measurement/hi-pot test (following IEC 61215 or UL 1703)
- determination of the maximum output power (IV-curve)
- ground continuity test (following IEC 61730-2)
- programs for performance of long-term tests following IEC 61215 or IEC 61646.

Sample rates as well as frequency for the afore mentioned tests vary from manufacturer to manufacturer. Regarding personal protection, a 100% control of the insulation properties should be binding.

A possible pitfall here is that the insulation tests described in the IEC standards are too time-consuming to be carried out in an efficiently running production. In UL 1703, therefore, a method was described featuring an increased voltage and reduced testing time, which suited some module types, but not all. It is expected that the soon-to-be-reviewed IEC 61730 will include some guidelines for in-line testing in a future version.

A major issue with the standards is the detachment of power rating from the quality assessment. In the scope of IEC 61215, it is pointed out that power rating is not covered by this standard. The result of this is that only relative power degradation due to the performed tests is checked; the correlation of power rating and real power is thus not considered.

Assessment of PV module performance

Distributors of PV modules and investors of larger-scale PV installations often require verification of the output power of a shipment consisting of a large number of PV modules. The available data sheets and in some cases flash protocols are not sufficient as proof for the real power. A third-party check of a representative sample taken from the delivered PV modules is a more trustworthy source of classification. This missing trust is well grounded in the missing assessment of the power rating as part of the type approval qualification. Unfortunately, PV modules can be labelled with a higher power than they actually provide and still receive an adequate IEC certificate. The reasons for such an efficiency shortfall can be manifold. Some manufacturers use the specified tolerance in the disadvantage for the buyer; others actually take false or imprecise measurements in their factories. The latter might not even be aware of the fact that they over- or even underrate their modules.

Most measurement discrepancies could be avoided were measurement uncertainty calculations done sufficiently and systematic errors avoided. TÜV Rheinland has laid down guidelines for the appropriate use of reference modules in PV module production lines, as well as developing measurement equipment for the assessment and optimization of solar simulators. Such qualification of a solar simulator allows a module manufacturer to check whether a previously agreed classification is actually achieved. Furthermore, the visualized results allow modifications to improve the measurement uncertainties for output power measurements and minimize systematic errors.

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It must be determined how large a sample is required to accurately perform a power check on a module. Based on the assumption that the overall power distribution is unknown, a minimum sample size can be calculated from statistical analysis. A common practice for other products is a so-called 'zero-acceptance level.' This means that from the taken sample, only a given

Figure 5. TÜV's outdoor test facility.

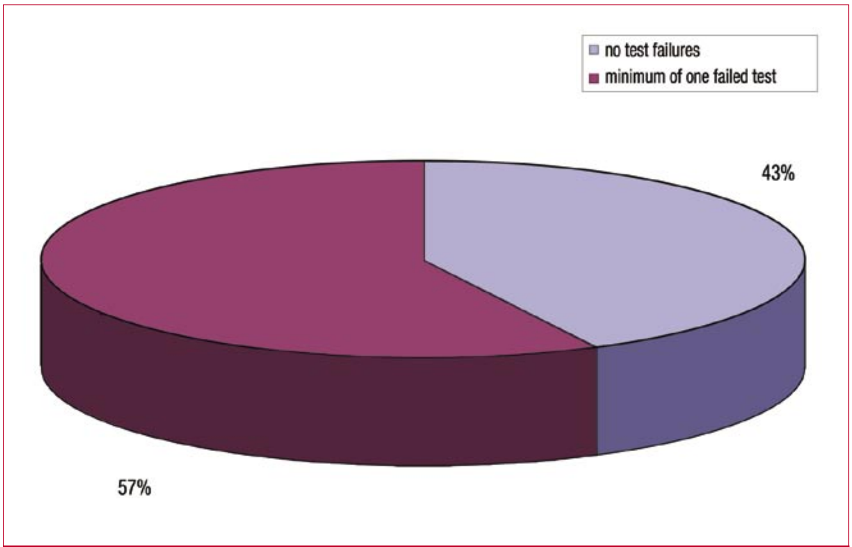

Figure 6. Total failure rate in IEC 61646 qualification testing at TÜV Rheinland, Cologne.

number of modules should be outside the guaranteed values, otherwise the complete charge is to be rejected. TÜV Rheinland together with the Technical University of Aachen (RWTH) has developed software to calculate the sampling sizes depending on P_{max} distribution based on the manufacturer's data. For smaller systems, guidelines for samples sizes have also been calculated [1]. If a system is already installed and its performance suggests a problem with some or all modules, the sample size can be established with similar methods. However, if a fundamental problem with the modules is detected, it is likely that the whole system will be affected.

The equivalence of delivered charges to certified module types is also of interest. Even with the annual factory surveillance being part of the certification schemes, field inspections have shown that modules that are sold under the same type name are sometimes built with different materials and components. In cases such as this it is important to have a competent partner for such inspections that will be able to distinguish materials and looks past the obvious.

Experience from product qualification testing

TÜV Rheinland's experience has seen the company test PV modules according to IEC standards since 1996. In that period, it has collected test data that shows that certain qualification tests are more critical than others. Aging mechanisms simulated by thermal, climatic and mechanical stress in the laboratory can cause certain test failures in the laboratory. There is no clear correlation between laboratory effects and real failures during the module's service life, but while opinion about such a correlation is diverse, the fact remains that the lifetime of a module depends on the actual location/climate and environmental influences during this time (such as wind, rain, irradiance, snow, salt mist, humidity, etc.). The impact of humidity on the cell encapsulation, for example, might not be adequately covered by the so-called damp heat test (see Table 1; 10.13) of IEC 61215. Data indicate that current testing times might actually be too short to simulate a 20+-year lifetime [2]. At the same time, effects seen in installations have been detected on identical modules in the existing laboratory tests. Ongoing research projects at TÜV Rheinland and their partners aim to help better understand the aging mechanisms in PV modules and establish models for simulation.

The most frequent failures are caused by weaknesses in electrical connections and cell encapsulation. In particular, soldering and bonding connections are stressed during temperature cycling due to different expansion coefficients of materials like copper, silicon and glass. Lamination problems as well as material incompatibilities are detected during long-term exposure to high temperature and high humidity such as in the aforementioned damp heat test. Third in line of the three most failed tests is the so-called hot-spot test; failures here are either caused by solar cells with low shunt resistance or an improper bypass diode concept. Interestingly, these tests show the highest failure rates for crystalline silicon as well as thin-film technology PV modules. There is, however, a shift in the frequency of the failures. The hot-spot test has actually proven to be more critical for thin-film modules than for crystalline modules, while the thermal cycling test (see Table 1; 10.11) is less critical.

"Soldering and bonding connections are stressed during temperature cycling due to different expansion coefficients of materials like copper, silicon and glass."

Of particular note is the fact that for thin-film modules the failures are much more diverse than for crystalline modules. While 90% of the failures of crystalline modules are distributed over these three tests, for thin-film modules about 50% of the failures are in other tests. One major additional reason for failure is the spontaneous glass breakage caused by stress in the not-heat-strengthened glass, in which case a slight waviness of the glass surface can cause non-uniform heat distribution during the lamination and therefore cause internal stress in the glass sheet.

Figures 3 and 4 show that the production of a PV module that fulfils the requirements laid down in the international type approval standards is a sophisticated task. Materials, components and production parameters have to be chosen carefully.

Conclusion

The use of high quality materials/components alone does not necessarily lead to a high quality module. The failure mechanisms for a PV module are diverse; even the well understood failure reasons have a high frequency. Production mistakes that caused failures years ago are still repeated nowadays. In many cases, failures are caused by poor quality control measures in production and are avoidable; in other cases, the reasons for failure are less obvious and a more sophisticated failure analysis is required. For materials issues in particular, it is not immediately obvious from measurements or visual inspections what is the root cause of the problem in question. Further research in PV is required in the field of polymers and their interaction with adjacent materials, as well as in the particular measurement procedures for the different thin-film technologies.

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The assessment of quality and safety of PV installations in the field is quickly becoming more important as the number of installations grows.

Offering services close to both markets and manufacturers, TÜV Rheinland's aim is to establish a worldwide PV network for PV, CPV and solar thermal product testing. Its laboratories in Cologne, Arizona, Shanghai and Yokohama are all increasing test capacities to meet the large market demand. With these multiple locations and an additional outdoor test facility in south Europe, an optimal utilization of expertise is possible, with the future aim of providing test procedures for new technologies such as CPV looking more achievable.

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About the Author

Jörg Althaus is the business field manager for Renewable Energies – PV module Qualification at Cologne-based TÜV Rheinland. He based the final project for his degree in electrical power engineering at TÜV Rheinland on solar cell measurement, and in 2001 started as a project engineer in the PV laboratory in Cologne. Today he coordinates PV module testing in his team and communicates with the other TÜV Rheinland laboratories internationally. Mr. Althaus has presented works on the topic of module testing at several conferences. He is currently participating in standardization work through the IEC working groups for flat-plate photovoltaic modules (IEC TC82 WG2) and CPV modules (IEC TC82 WG7).

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