Moving Toward Quantifying Reliability – The Next Step in a Rapidly Maturing PV Industry

Preprint

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Presented at the 43rd IEEE Photovoltaic Specialists Conference
New Orleans, Louisiana
June 14–19, 2015

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Conference Paper
NREL/CP-5J00-63520
December 2015

Contract No. DE-AC36-08GO28308

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Moving Toward Quantifying Reliability – The Next Step in a Rapidly Maturing PV Industry

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***Abstract* — Some may say that PV modules are moving toward being a simple commodity, but most major PV customers ask: "How can I minimize chances of a module recall?" Or, "How can I quantify the added value of a 'premium' module?" Or, "How can I assess the value of an old PV system that I'm thinking of purchasing?" These are all questions that PVQAT (the International PV Quality Assurance Task Force) and partner organizations are working to answer. Defining standard methods for ensuring minimal acceptable quality of PV modules, differentiating modules that provide added value in the toughest of environments, and creating a process (*e.g.* through IECRE [1]) that can follow a PV system from design through installation and operation are tough tasks, but having standard approaches for these will increase confidence, reduce costs, and be a critical foundation of a mature PV industry. This paper summarizes current needs for new tests, some challenges for defining those tests, and some of the key efforts toward development of international standards, emphasizing that meaningful quantification of reliability (as in defining a service life prediction) must be done in the context of a specific product with design parameters defined through a quality management system.**

***Index Terms* — photovoltaic module, reliability, service life prediction, PV system performance.**

I. Introduction

As the world seeks ~$100 billion/year to install PV plants, investors seek confidence in long-term PV performance. Incentive programs have sometimes allowed investors to gain a return on their investment even before the project is completed, but as incentives shrink, profitable investment in PV will increasingly require decades of reliable operation.

While PV module efficiencies continue to inch up and module costs inch down, reliability features (*e.g.*, resistance to potential-induced degradation, PID [2], or to humid conditions) are increasingly advertised for new products. PV customers would like to quantify the value of these added features, just as they quantify the value of increased efficiency.

Toward better quantifying risk, PV customers have increased their demands on manufacturers. Table I shows Trina Solar's experience with customers' requests for module acceptance and factory surveillance in recent years. While there is value in these, repeating extended tests for each customer may add more cost than value. Ideally, PV customers and manufacturers will work together to identify the most valuable tests and optimize the cost-benefit ratio.

TABLE I
SUMMARY OF EXPERIENCE WITH CUSTOMER REQUESTS

Common customer requests	Year
IEC or UL certificate	2009-2010
IEC or UL certificate & *Pre-shipment inspection &* *3rd party acceptance test (STC power test/EL)*	2011-2012
IEC or UL certificate, *Beyond IEC test, PID test & Factory audit* + Pre-shipment inspection & 3rd party acceptance test (STC power test/EL/*some reliability tests*)	2013
IEC or UL certificate, Beyond IEC test, PID test & *Salt mist corrosion test, Ammonia test &* Factory audit & *Manufacturing supervision &* Pre-shipment inspection & 3rd party acceptance test (STC power test/EL/*some reliability monitoring tests*)	2014

Decades of research on PV testing [3]–[4] have laid a strong foundation for growth of the PV industry. PV reliability has drawn increased interest in recent years with organizations around the world developing new tests [5]–[13].

However, multiple factors prevent the desired confidence, including:

1) Long desired service life (>25 y),
2) Rapidly evolving product designs (typically < 0.5 y),
3) Complexity of use environments, and
4) High cost of testing for large sample sets.

As PV products mature, the relationship between product lifetime and product design and quality will slowly become clear. As product designs stabilize, it will be more feasible to test the specific bill of materials and associated process window to provide more quantitative predictions for specific use environments.

This paper first builds on the previous analysis used for creating Qualification Plus [5], [14] by citing a few recent field observations, then summarizes efforts to implement international standards and strategies to address these needs. Finally, we discuss service life prediction for a specific product that has a well-defined bill of materials and a process window defined by a quality management system.

II. Current Field Experience

Numerous reports have summarized PV field experience [15]–[22]. We previously prioritized electrical-connection failures, cracked cells, PID and weathering of various module components as key issues and described these in Qualification Plus [5], [14]. Table II provides a small update to the Qualification Plus analysis. Although many types of problems are reported, the final experience is usually quite positive: 1) the mean and median of reported degradation rates are typically 0.4-0.8% [15]–[16], but higher degradation rates are observed statistically for hot locations [18]–[19], and 2) failure rates from many different causes are typically <1%/y. Newer modules could have different outcomes if testing of new designs has been inadequate.

TABLE II
RECENT OBSERVATIONS TO CONSIDER IN ADDITION TO QUALIFICATION PLUS SUMMARY OF FIELD EXPERIENCE [5, 14]

Observation	Data source	Needed test
Hotter climates show faster degradation (average of >1.4%/y relative to average <0.6%/y for cooler climates)	[18]–[19]	High-temperature tests
Installers report that modules are differentiated by robustness of frames	NABCEP* meeting: New York	Frame robustness test
PV customers report concern that PV manufacturers may use unqualified materials without adequate testing or engineering control	Rump session WCPEC-6**	Assessment of quality management system

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Conclusions about field experience depend on the climate and mounting configuration. Those in hot climates [18]–[19] or using roof top mounting [23] are more concerned with the heat, motivating a durability test at higher temperatures, whereas those in cold climates are concerned with damage from snow and ice, motivating a snow and ice test for robustness of the module package (see NABCEP reference in Table II). In addition to the climate-specific concerns, some common concerns include the effects of cracked cells and other losses of electrical continuity because these can lead to large losses in power and introduction of safety risks [20]–[22], [24]. Interestingly, although cracked cells have become more common as cells have been thinned in recent years, there are few papers written specifically about cracked cells. Publications more commonly describe “snail trails” (observed when the encapsulant has a different color near the crack than elsewhere – see Fig. 1) and conclude that these decorate cracked cells that lead to substantial power loss [20]. However, instead of identifying the cracked cells as the problem that needs to be fixed, often the cosmetic “snail trails” are identified as “the problem.” We have not seen a report that directly links the snail trails to performance loss, but note that the snail trails provide a simple way to identify cracked cells.

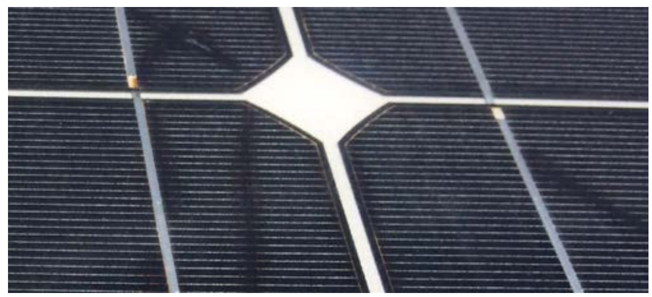

Fig. 1. Image showing “snail trails” that decorate cracked cells; cracked cells often lead to decrease in module performance.

Some PV customers wish to eliminate all cell cracks, but if a cell cracks in such a way that every fragment remains connected, there may not be significant power loss. In order to reduce the silicon usage (and associated module cost) by thinning cells, we need to better understand how to avoid cracks, how to test for them [25]–[27], and how to identify which cracks, if any, are acceptable [28]. Electroluminescence is a useful tool for identifying cracked cells and may help to differentiate cracks that lead to power loss from those that don’t [29].

III. International Standards Efforts

Table III provides a summary of the module-level issues that we have prioritized and the near- and long-term plans to address them by PVQAT and Working Group 2 (WG2) (Modules) of IEC Technical Committee 82 (TC82) on PV. In general, PVQAT provides an open forum for researchers to join together in executing research projects to better understand the degradation modes and mechanisms and ways to test for these. The results from these research efforts are used by the IEC standards project groups. Each issue is described in further detail in the sub-sections below.

TABLE III
INTERNATIONAL STANDARDS EFFORTS TO ADDRESS ISSUES PRIORITIZED IN QUALIFICATION PLUS [5, 14] AND IN TABLE II

Priority	Current status	Near Term Plan	Long-Term Plan
A. UV durability of polymeric components (encapsulants, backsheets, connectors and junction boxes); requirement for insulation materials (see Qualification Plus component tests 1-4)	Recent and planned changes will add more UV and other testing of polymeric materials	1) Submit IEC 62788-7-2 [30]; 2) Submit amendment to IEC 61730 [31] referencing weathering conditions in IEC 62788-7-2 [30]; 3) Submit additional IEC 62788 parts; publish in 2016	Define climate-specific UV exposures
B. Bypass diode and j-box thermal tests (see Qualification Plus component test 5)	Multiple documents are in progress to address thermal endurance, cycling, and runaway	Five actions are described in text; publish in 2016	Define climate-specific diode tests
C. Electrical failures within the module (see Qualification Plus module test 1)	Ribbon interconnects can be tested with cyclic mechanical loading, but thermal cycling (TC) is also needed	Continue investigations	Define climate-specific thermal-cycle tests and implementation within quality management system
D. Power loss from cracked cells (see Qualification Plus module test 2)	IEC/TS 62782 [32] and IEC 62759-1 [33] are submitted as final drafts; publish in 2015	Submit amendment to IEC 61215 [34] to add 1000 cycles DML before TC and humidity freeze	Define climate-specific tests for cracked cells, if needed
E. Susceptibility to PID (see Qualification Plus module test 3)	IEC/TS 62804-1 [35] has been submitted as a Draft Technical Specification; publish in 2015	Publish IEC 62804 [35] and define standard labels for PID susceptibility	Understand relationship between degradation in the test and in the field; Identify quick tests for screening cells and encapsulant materials
F. Susceptibility to hot spot degradation (see Qualification Plus module test 4)	Revised hot-spot test is proposed in edition 3 of IEC 61215 [34]	Publish edition 3 of IEC 61215 [34] in 2015	Define improved hot-spot test for thin-film modules
G. Improve confidence in Quality Management System (QMS) (see Qualification Plus description of sampling and QMS)	IEC/TS 62941 [36] may be submitted in June 2015 as a Draft Technical Specification	Publish in 2015; Implement through IECRE	Facilitate adoption and assess value of extending to quantitative assessment
H. Structural failure from snow and ice (based on experience in Europe and New England)	IEC 62938 [37] Committee Draft has been reviewed	Complete IEC 62938 [37]; publish in late 2016	Encourage use of the snow load test to differentiate modules
I. Faster degradation in hot climates (see [18, 19])	Delamination, encapsulant discoloration, and thermal fatigue are documented to increase with high temperature	Define difference in use environment	Use IEC 62892 [38] to implement comprehensive tests at higher temperatures
J. Assessment of system functionality	Drafts completed for both energy and capacity tests	Publication of IEC 61724-2 [39] and IEC 61724-3 [40] in 2016	Implement as part of IECRE

A. UV Durability Testing

IEC standards for safety requirements and tests of junction boxes (IEC 62790 [41]) and connectors (IEC 62852 [42]) were published in 2014. These both include UV exposure. Currently, the PVQAT Task Group 5 and the IEC TC 82 Weathering Group have proposed UV tests to be included in a Technical Specification (TS) (IEC 62788-7-2 [30]), which will be referenced by the IEC 62788 component standards and an amendment to IEC 61730 [31] requiring UV stability of insulating materials. The TS and amendment are being finalized in parallel, with publication anticipated in 2016.

The effects of UV are frequently observed to be strongly dependent on temperature (see Fig. 2) [43]. The primary change in exposure conditions between Qualification Plus and the proposed exposure for IEC 61730 [31] is a higher temperature during exposure to reflect the elevated module temperatures encountered in field installations. IEC 62788-7-2 [30] includes several temperatures for characterization purposes. Understanding this temperature dependence will be key to defining climate-specific tests and metrics for service life predictions, and has been a primary focus of PVQAT experiments [43], see Fig. 2.

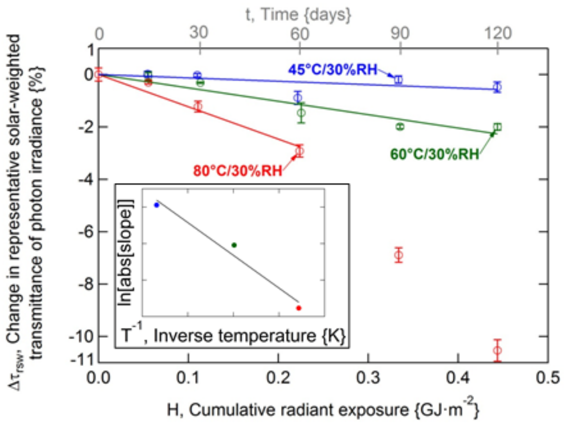

Fig. 2. Data showing temperature-dependent UV-induced degradation of optical transmittance of a susceptible encapsulant material, see [43].

B. Bypass Diode Testing

For bypass diode testing, five issues and associated actions have been identified: 1) prolonged operation at high temperature: requires a thermal endurance test such as was proposed in Qualification Plus, 2) electrostatic discharge (ESD) events may occur in the factory during assembly: IEC/TS 62916 [44] defines the required manufacturing environment to be controlled by the QMS, 3) thermal runaway when the bypass diode temperature exceeds that allowed during reverse bias: IEC 62979 [45], 4) thermal fatigue causes failure of the electrical connection to the diode: propose to flow current through the bypass diodes during the last 50 cycles of thermal cycling, and 5) functionality of the bypass diodes needs to be checked as part of any module stress test (amendments to IEC 61215 [34] and IEC 61730 [31]).

C. Electrical Failures

Failures of solder bonds and ribbon interconnects can lead to arcing and fires, implying a serious safety hazard as well as the potential for substantial power loss. Thermal cycling is effective at identifying poor designs or poor implementations of designs. While ribbon failures may be induced in a one-day cyclic mechanical loading test [46], damage accumulation in solder bonds requires thermal cycling. The failure rate and acceleration factor may both depend on details of the module design and implementation, implying that the thermal cycles needed to give confidence in the warranty depend on control of such things as the mass of the applied solder and the composition and cleanliness of the solder, flux, and bonding surfaces. PVQAT studies imply that the number of cycles needed to give confidence in the warranty depends on the solder composition, the control of the manufacturing process, the deployment location, etc. If the control of these factors is unknown, it is unclear how to account for them when designing the general test. A longer thermal cycling test provides added confidence, but a service life prediction will require a product-specific test.

D. Power Loss from Cracked Cells

It has been shown [25]–[27] that cell cracks caused by application of mechanical load may not result in loss of power output until the module has additionally been subjected to thermal cycling and/or the humidity freeze test. The addition of 1000 cycles of mechanical loading after the UV exposure in IEC 61215 [34], as proposed in Qualification Plus [5], should identify modules that will be susceptible to power loss from cracked cells. A similar approach of applied stress simulating that experienced during transportation [47], followed by thermal cycling and humidity freeze is nearing completion as IEC 62759-1 [33].

E. Potential-Induced Degradation (PID)

Two test methods have been defined in IEC/TS 62804 [35], which should be published in late 2015. However, pass/fail criteria that could be used in IEC 61215 [34] have not been agreed upon. Nevertheless, companies today routinely label their products as “PID resistant,” “PID free,” or “Anti-PID,” often without identifying the associated test. Studies have shown that correlation of test results with outcomes in the field is complex because of variable exposure conditions and because of reversibility of the degradation [48]–[50]. While we learn more about appropriate pass-fail criteria, we recommend standardization of the terms used to describe products.

F. Hot Spot Testing

Edition 3 of IEC 61215 [34] is proposed to have an improved hot-spot test [5]. However, the hot-spot test proposed for *thin-film* modules still needs improvement.

G. Assessment of Quality Management Systems (QMS)

PV customers frequently express concern that the bill of materials is not adequately controlled and that the QMS may not be implemented consistently, possibly resulting in inferior product being shipped. IEC/TS 62941 [36] was written to include PV-specific QMS features including that:

- The design, process controls, and control of incoming materials are aligned with meeting the product warranty,
- The assigned power rating for each module is consistent with the advertised power rating,
- Traceability is maintained in case a recall is required, and
- Factory conditions are maintained to avoid damage of bypass diodes by electrostatic discharge.

IEC/TS 62941 [36] is scheduled for publication before the end of 2015. For this to be a useful tool, it will need to be implemented consistently. The IECRE is developing requirements for auditor training and audit best practices such as a) documenting all aspects of the QMS, b) asking probing questions, and c) including physical inspections.

The need for a robust QMS, ongoing testing of product from the line, and the need to increase sample sizes were highlighted in the description of Qualification Plus [5], [14].

H. Snow and Ice Damage

Bent frames can occur (Fig. 3) in climates with snow and ice. The snow may partially melt and then refreeze along the bottom edge of the module, causing stress on the frame. IEC 62938 "Non-uniform snow load testing for photovoltaic (PV) modules," [37] is planned for publication in 2016 based on studies by Reil, et al [51]. This test will be valuable for those choosing modules for cold (icy) locations.

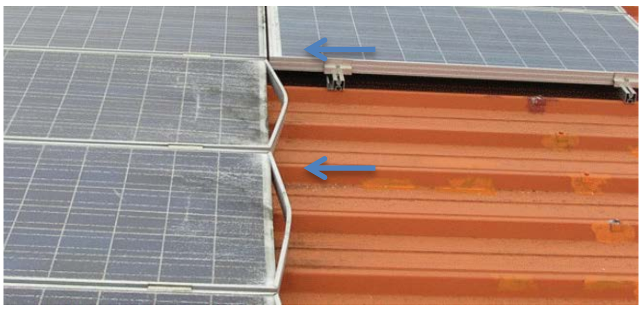

Fig. 3. Snow and ice can bend frames, as noted by two arrows.

I. Special Testing Needs for Hot Climates

Those preparing for massive deployments of PV in India, the Middle East, and Africa recognize that their locations may be more stressful than elsewhere. IIT Bombay has studied PV degradation in various locations in India, finding more degradation in the hotter climate zones [52]. This shared problem has inspired collaboration between PV experts in multiple hot countries and a workshop is planned for fall of 2015 in India to discuss the requirements needed for hot areas.

The climate zones defined in IEC 60721-2-1: 1987 [53] identify peak ambient temperatures of 55-60°C for the "Extremely warm dry climate," which is likely to result in peak module temperatures of around 85°C and 110°C for open-rack and close-roof mounting, respectively. IEC 61730 [31] sets the expectation that modules will be suitable for operation "in an environmental temperature range of -40 °C to +40 °C" by specifying a temperature test (MST 21) that is referenced to 40°C ambient. We propose as a starting point for discussion that modules to be used at a higher temperature, x°C ambient, be tested by:

- Measuring the MST 21 reference temperature [31] using x°C instead of 40°C or increase the default temperature above 90°C by x-40.
- Increasing the maximum module temperature reached in the thermal cycling test by the difference between the measured reference temperature just described and 90°C.
- Applying standard damp heat conditions [31] since the hottest environments seldom observe high humidity at the same time.

A climate- and use-environment-specific set of tests [54] has been proposed in IEC 62892 [38]. The applicability of IEC 62892 to meet the needs of hot climates will be discussed at a workshop in India in fall of 2015.

J. System-Level Standards

Ultimately, a PV customer requires not only that components have been designed and manufactured correctly, but that the entire system has been assembled and functions correctly. IECRE was formed under IEC's Conformity Assessment Board to have oversight of system-level certifications of Renewable Energy Systems [55]. Kelly, et al, reviews standards for design, installation, commissioning, operations and maintenance in this proceedings [1].

Standardization of system assessments will be challenging because of local requirements and component selection. Assessment at the factory alone is not adequate since components may be damaged during transportation, storage or installation. For example, if modules are walked upon or handled by their cables, the effects of the damage may appear later. Installers must follow the manufacturer's guidelines for installation, or the system is at risk.

One very important aspect of assessing the health of a PV plant is measuring the output power and/or energy with appropriate correction for the prevailing conditions. IEC 61724 has defined PV system measurements. IEC is now considering methods for both capacity and energy tests as IEC 61724-2 [39] and IEC 61724-3 [40], respectively. These are expected to be published in 2016 and will be referenced by IECRE as part of a more comprehensive assessment, which should be available in 2016.

IV. Service Life Predictions

Section III identified pathways to qualification testing relevant to a range of use environments, but the community would also like to define how to predict the service life. Accurate service life predictions are almost impossible when products change faster than the time required to design and verify the model. But, some companies have designs that are stable enough to allow useful lifetime models [56]. These are especially successful if the aspect of a product that determines degradation or failure has been frozen in the design and process window.

Generic lifetime models that can be tested in a short time usually have very high uncertainties [57]. Accurate service life predictions models must be tied to 1) the specific bill of materials, 2) the specific use environment, and 3) the process window defined by the QMS. Figure 4 considers a baseline stress test that predicts 25 years life, then estimates the lifetimes that would be expected if this same test were applied to a similar, but slightly different module. For example, an encapsulant that uses a different UV absorber may exhibit different degradation kinetics (*e.g.* different activation energy). If the baseline accelerated test gives confidence for 25 years in Munich for a module with encapsulant that degrades with an activation energy of 1.1 eV, if the new material degrades with an activation energy of 0.6 eV the same test would give confidence in only ~ 3 y lifetime [58] (Fig. 4). Similarly, if the module predicted to last 25 y in Munich were deployed in Phoenix or Riyadh, the expected lifetime would drop even more [58] (Fig. 4). Finally, if the solder bonds are made with a smaller amount of solder and accumulate damage 5X faster than expected, the service life could be similarly reduced (Fig. 4).

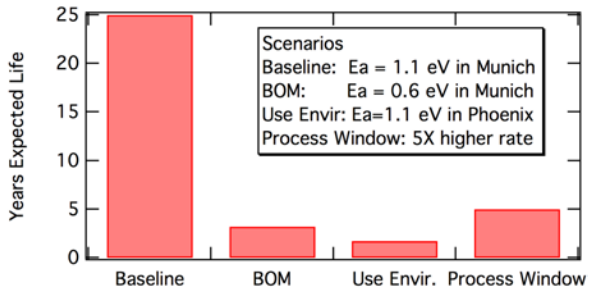

Fig. 4. Extreme examples of how a baseline service life prediction could be in error if there is a change in the bill of materials (BOM), the use environment, or the process window. Smaller variations will be found when stress conditions are chosen with smaller acceleration factors, but then the tests must run longer, as well.

Thus, as clearly seen in Fig. 4, a meaningful service life prediction must be tied directly to the QMS including the specific bill of materials and any variations in the process that affect either the aging rate or the acceleration factor for the test. Ideally, stress testing is applied to reflect the full process window allowed by the QMS. Also, a quantitative predicted lifetime must reflect the desired failure statistics; 'zero failures' is not a practical goal.

Ultimately, as process control windows are tightened, PV manufacturers will be able to reduce the length of the stress test while retaining confidence in the warranty. Thus, ironically, 200 thermal cycles for a company that maintains excellent control over the soldering process may provide confidence in a longer lifetime than a 500 thermal cycle test for a product that is only loosely controlled (though this can be improved if many modules are tested rather than the currently required two modules). This highlights the challenge of defining a meaningful generic test and motivates movement toward product-specific service life prediction away from generic type tests that apply the same test to every product.

V. Summary

PVQAT and IEC efforts to define improved PV standards are moving forward quickly to support the maturation of the industry. IEC Technical Committee 82 is currently working on more than 80 documents with support from twelve PVQAT task groups, representing the enormity of what needs to be accomplished; this paper identifies some of the highest priority documents to be completed soon. The challenge is to identify short test methods that adequately assess durability in a range of use environments while recognizing that quantitative lifetime assessment must be implemented for a specific bill of materials with a defined quality management system that specifies the variability allowed for the product implementation. PVQAT investigations will provide a basis for implementation of both climate-specific qualification tests and more quantitative service life predictions. Today's most critical issues will be addressed by standards completed in 2015 or 2016. We are working toward the end goal of quantitative service life predictions; while models are under development today, these will have lower uncertainties when product designs stabilize enough to allow time for careful model development and validation.

Acknowledgement

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory. We would like to acknowledge and honor the more than one hundred people who are actively involved in the IEC and PVQAT efforts.

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