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Sarah Kurtz, John Wohlgemuth, Peter Hacke, and Michael Kempe
National Renewable Energy Laboratory

Tony Sample
European Commission, Joint Research Centre, Institute for Energy

Masaaki Yamamichi, Michio Kondo, Takuya Doi, and Kenji Otani
National Institute of Advanced Industrial Science and Technology (AIST)

James Amano
Semiconductor Equipment and Materials International

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ENSURING QUALITY OF PV MODULES

Sarah Kurtz[1], John Wohlgemuth[1], Tony Sample[2], Masaaki Yamamichi[3], James Amano[4], Peter Hacke[1], Michael Kempe[1], Michio Kondo[3], Takuya Doi[3], and Kenji Otani[3]
[1]National Renewable Energy Laboratory, Golden, CO, USA
[2]European Commission, Joint Research Centre, Institute for Energy, Renewable Energy Unit, I-21027, Ispra (VA), Italy
[3]National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, Japan
[4]Semiconductor Equipment and Materials International, San Jose, CA, USA

ABSTRACT

Photovoltaic (PV) customers need to have confidence in the PV modules they purchase. Currently, no test can quantify a module's lifetime with confidence, but stress tests are routinely used to differentiate PV product designs. We suggest that the industry would be strengthened by using the wisdom of the community to develop a single set of tests that will help customers quantify confidence in PV products. This paper evaluates the need for quality assurance (QA) standards and suggests a path for creating these. Two types of standards are needed: 1) QA of the module design and 2) QA of the manufacturing process.

INTRODUCTION — MOTIVATION

As the PV industry has grown exponentially in recent years, the worldwide investment in PV installations is approaching $100 billion/yr. Those financing this market growth want to be able to predict the risk of failure of PV products and are asking for more quantitative tests. Quantitative or comparative tests can: 1) compare module designs, 2) provide a basis for manufacturers' warranties, 3) provide investors with confidence in their investments, and 4) provide data for setting insurance rates.

The definitions of failure and lifetime vary. The warranty can provide a very specific definition of these aspects, but a module that has degraded more than specified by the warranty may still have value for some PV customers. Here, we discuss the durability of a module as its long-term ability to survive environmental stresses. The reliability (often defined as the probability that an item will perform a required function) of a PV module includes the durability as well as soiling, incorrect installation, and many other issues. This analysis focuses primarily on assuring adequate durability within the scope of accelerated testing and quality assurance programs while recognizing that, ultimately, all aspects of the reliability are important.

Ideally, the lifetime of a module would be predicted by a relatively short set of accelerated stress tests. However, a technical basis for predicting lifetimes has not been established. We, therefore, propose comparative standards with efforts to estimate the expected lifetimes as a function of the deployment conditions to guide the range of stress that is applied. Some may argue that this effort is premature. We emphasize that these standards will not be perfect, but are a first step toward providing the desired confidence.

A growing number of test labs, PV manufacturers, and others have been developing new tests [1–4] to meet the need for more quantitative tests, but the community would be best served by a coordinated effort toward a single international standard. This study explores the current status, needs, and challenges, then proposes creation of 1) a QA rating system to communicate the relative durability of module designs and 2) a guideline for factory inspections of the QA system used during manufacturing.

DEFINITION AND CURRENT STATUS OF QA

The assurance of quality of a product has two parts: 1) assurance that the product design suits the needs of the customer and 2) assurance of consistency of the product quality during the manufacturing, shipping, and installation processes. Currently, the former is addressed through testing to International Electrotechnical Commission (IEC) qualification standards 61215, 61646, and 62108 and to safety standards IEC 61730 and UL 1703. These tests were developed largely in response to field experience [5]. For example, in the late 1970s and early 1980s, the Jet Propulsion Laboratory (JPL) purchased multiple sets of PV modules, analyzed the field failures, and developed accelerated tests to quickly duplicate those failures. Today's qualification tests are mainly based on the tests developed by JPL. PV modules currently demonstrate excellent reliability in the field mostly because of such tests.

Currently, each company defines their own QA program. Because no formal oversight is required by the IEC standards, there is no simple way for PV customers to confidently evaluate a company's manufacturing QA process. Test laboratories are accredited to complete the certification process and issue a certificate. Most test laboratories then require periodic factory inspections to ensure that the company has not changed the design of the module, the manufacturing processes, or the raw materials. However, there is no standard guideline for the factory inspections and some test laboratories do not conduct factory inspections at all.

QA OF PRODUCT DESIGN — NEEDS

Customer Needs

The results of product testing need to be communicated directly and clearly to the customer. The test results should be included on the product datasheet and on the nameplate, listing the different tests performed and an indication of the level of test that was passed. Some customers wish to have detailed test results that show the evolution of the product degradation rather than a simple pass-fail result. Such detailed results should be available from the manufacturer, but cannot be recorded on the nameplate and may not be easily included on a datasheet.

Customers would like to see the test result information presented as the expected lifetime of a module. This is not practical for two primary reasons: 1) the lifetime is dependent on the local weather, the mounting configuration, and the quality of the installation, so a single number is not meaningful; 2) a technical basis for predicting the module lifetime has not yet been established. There are dozens of potential failure mechanisms. Quantifying each of these to determine the lifetime for a module for a given application is beyond our current capabilities. Nevertheless, data from modules that have been deployed 20–30 years coupled with modeling of stresses can be used to estimate expected lifetimes as a function of location for specific failure mechanisms. When possible, existing information should be collected and provided to PV customers to help them interpret the QA rating given on the nameplate and datasheet.

When possible, the rating should have a clear meaning. For example, modules are currently given a maximum system voltage rating, which is used by system designers. Similarly, a hail rating specifies the size of the hail ball and its terminal velocity.

It should not be overlooked that some customers may value low price over long lifetime, as in the case of a PV installation on a building that may be torn down in ten years. QA information should be presented in such a way that customers can make choices to match their application rather than providing a pass/fail rating that may not be relevant to their needs.

Finally, the customer needs to have information about the uncertainty associated with the rating system. If studies show conclusively that failure of a test gives a high probability of failure in the field, then it is reasonable for a customer to require that the test be passed. On the other hand, it would be counterproductive for a customer to require passing a test that does not correlate with field experience. In such a case, requiring the test could needlessly increase cost. When there is non-conclusive evidence of a test's value, it could make sense for an incentive program to give somewhat higher rebates for the products that pass the test, but still allow other products to participate in the rebate program. Thus, to empower insurance companies and incentive programs to most wisely use the QA rating system, information must be available about the certainty and uncertainty associated with the predictive value of each test.

Manufacturer Needs

Manufacturers benefit from having a single set of tests that are administered internationally under the International Laboratory Accreditation Cooperation (ILAC). When customers ask that manufacturers certify products in their local area, the duplicate testing and associated factory inspections are unnecessary costs for the company and, ultimately, for the customers themselves. ILAC defines an international cooperation to standardize the accreditation of the test laboratories so that manufacturers maintain a single certification with a single test laboratory.

Manufacturers benefit from shorter tests that are less costly and that cause minimal delay in the launch of new products. Similarly, manufacturers benefit from stable standards (revision of a standard may improve the standard, but may also force all manufacturers to recertify) and reasonable retest guidelines (retest guidelines that require a complete new certification for small changes in a product can increase testing costs prohibitively).

While manufacturers usually prefer simpler test standards, new manufacturers benefit from having a robust test standard that confidently demonstrates new products to customers. Similarly, experienced manufacturers benefit from having tough test standards that can differentiate their very durable products from less durable products that their competitors sell at lower prices. However, it is important for the customer that this differentiation is relevant to field performance of the modules, because tests that are more difficult to pass, but don't indicate longer service life, will needlessly increase costs.

Scientific Needs

While customers would like a test sequence that tells how many years a product will last, the scientific knowledge does not exist yet to create such a test sequence. Nevertheless, the community has collected a wealth of information about failure mechanisms of PV modules and how to test for these. The QA standards can use the existing knowledge while identifying the most important gaps to prioritize for near-term research.

A very important opportunity is to design the QA test standards to facilitate learning about lifetime prediction. Decades from now, the QA standard we design now can facilitate correlation between lifetime and the QA rating.

The challenge of designing a QA test standard is complicated by many scientific challenges, as described in Table 1. Table 1 raises the question of whether a single set of tests can be used to predict service life or even to equitably compare expected durability of different designs. For example, the acceleration factors between a damp-heat test and real-time exposure differ dramatically for modules with glass-glass or glass-PET construction.

Table 1. Factors that affect the correlation of accelerated tests with service life prediction

Concern	Acceleration factors (AF)
Multiple failure mechanisms	AFs vary by orders of magnitude for dozens of failure mechanisms
Variable weather	AFs differ for each location
Mounting configuration	AFs can be a factor of ten lower for roof mount than rack mount
Cross terms	Combined stresses can have AFs that are orders of magnitude different than for each stress alone
Module geometry	AFs can vary by orders of magnitude
Degradation versus failure	AF for degradation may differ from the AF for the final failure (degradation rate may change with time)
Module variation	A failure mechanism that affects a small fraction of the sample population may not be identified by testing a handful of modules

While the complexities in Table 1 highlight the monumental challenge of creating a test that accurately predicts long-term PV module performance, useful progress can be made if the scope is limited by prioritizing the most problematic failure mechanisms and if only a handful of weather conditions are quantified.

QA OF PRODUCT DESIGN — PROPOSAL

Our proposal is designed to optimally address the points raised above. We propose a QA rating system that defines comparative tests to differentiate products with respect to their durability, and then propose scientific studies to help the community interpret the meaning of the tests. Thus, we do not propose that the standard be used for service life prediction, but that the standard be designed to help collect information to enable lifetime predictions in the future. However, even if the standard is not intended for lifetime predictions, it is useful to define the severity of the tests to span the range of durability that is of interest to the customer. This requires estimation of the lifetimes associated with the tests for a range of climates.

Stresses

A customer would prefer to be told the expected lifetime of a module, but this is not possible without knowledge of the intended application. From a scientific perspective, evaluation of the durability of a module requires analysis of the stresses that will be encountered. A list of stresses is shown in Table 2 along with a proposal for how a rating system might communicate to the customer the durability associated with each stress. Columns are also included to describe existing or proposed tests and how these relate

Table 2. Stresses encountered by PV modules and proposed system for rating PV modules

Stress	Rating system	Accelerated test	Environmental definition
Voltage	Numeric value for maximum system voltage	As per IEC 61215 [6], or revised to be applied during damp heat	System voltage
Temperature	Class Hottest, Hot, Warm, Cool	Damp heat, possibly with voltage bias applied	Use Arrhenius behavior and create maps for rack and roof mounting
Thermal cycling	Class A, B	Thermal cycling as per IEC 61215 [6], but two levels of 200 or 500 cycles	Thermal cycling is greater for partly cloudy environments, because variable irradiance causes frequent changes in module temperature
Humidity	Class Humid, Dry	Damp heat, possibly with voltage applied	Average humidity; make map
Snow	Numeric rating for kg of static load	IEC 61215 [6] static load test	Snow load from local building code
Salt spray	Numeric severity rating	Existing IEC test (edition 2) [7]	Distance from ocean
Hail	Numeric rating for size of hail ball	Current default is 25 mm; method as in 61215 [6]	Size of hail balls experienced locally
UV	Class A, B	Use UV component test being drafted by WG2	Class A indicates high-altitude or high-irradiance site
Wind	Numeric rating for maximum wind gust	Combination of dynamic load test and vibration	Maximum wind speed seen during gusts
Transportation	Rough/Smooth	Vibration	Truck on paved and unpaved roads, train, etc.
Farmland	Pass/Fail	Use ammonia test drafted by WG2	Ammonia in agricultural area

Table 3. Partial list of failure or degradation mechanisms and the related stresses

Type of failure/degradation	Related stresses	Priority
Broken interconnects, solder bond failures	Thermal cycling, mechanical	First
Broken glass; structural failures	Mechanical	First
Corrosion, including electrochemical corrosion; corrosion leading to loss of grounding	Humidity, heat, bias V, dry/wet high pot	First
Hot spots	Shading	First or second
Broken cells	Thermal cycling, vibration, mechanical	Second
Delamination and/or loss of elastomeric properties of encapsulant	Humidity, heat, humidity-freeze, UV, dry/wet high pot	Second
Encapsulant discoloration	UV, heat	Second
Junction box and module connection failures	Thermal cycling, humidity, heat, humidity-freeze	Second
Bypass diode failure	Heat (applied to diodes)	Second
Open circuiting leading to arcing	Thermal cycling	Second
Ground fault from backsheet degradation	UV	Second
Ground faults	Dry/wet high pot	Second

to environmental conditions. We propose that a QA test standard differentiate levels of durability to each of these stresses as described by the rating system. To identify the appropriate severity of each test, it is useful to estimate the effects of that stress around the world as related to at least one failure mechanism.

Failure Mechanisms

It is not practical to test a module for all possible failure mechanisms, and any quantitative prediction must be made for a specific failure mechanism. We propose to identify the failure/degradation mechanisms that are most likely to cause field failures by each of the major stresses if not adequately mitigated and prioritize these. If accelerated tests are quantified for the highest priority failure mechanisms, there is a reasonable chance that the same test will identify other problems as well (see Table 3). We propose to first estimate acceleration factors for the prioritized mechanisms listed in Table 3 as "First." Other mechanisms may be addressed in the future.

Test Standards Under Development

In response to the interest in testing "beyond 61215 or 61646," many PV manufacturers and test labs have begun to develop more quantitative tests [1–4]. These will provide a starting point for creation of a single international standard. Tests already exist for each of the stress categories. The test definition for implementing the QA rating system primarily needs to identify how many classes will be quantified for each stress and how severe each test should be. A detailed discussion of these is beyond the scope of this paper, but is discussed elsewhere [8].

QA DURING MANUFACTURING

A robust, upfront certification process can give confidence in a design, but the quality of the product may vary greatly if the manufacturer does not maintain an adequate quality assurance program.

Customer Needs

PV customers would benefit from being able to see a certificate demonstrating that the manufacturer's QA program meets a reasonable standard. Currently, some investors/customers require the manufacturer to document their QA program as part of the investors' due diligence. Although this may continue to be justified for the largest investments, such a review adds cost and could be avoided if a meaningful review is completed as part of the certification process.

Manufacturer Needs

As described above, a manufacturer benefits from needing to certify each product only once. Thus, a certification process that can be implemented under ILAC will allow manufacturers to keep prices low. The factory inspection should require only the documentation that is useful. Onerous requirements that do not translate to added confidence will needlessly increase costs. Similarly, if all factories are operated under a single QA program, inspecting all factories needlessly increases cost.

Scientific Needs

PV products today span a wide range of geometries; the processes used to build the modules span an even wider range of conditions. Thus, it is not possible to define specifics in a QA guideline. A QA guideline should direct the test laboratory on what to look for (*e.g.* control of encapsulant curing process) and the manufacturer on how to present the information to the inspectors (*e.g.* data showing that modules made within a given process window pass the certification test) without stating the exact conditions. It could be useful to define a guideline that differentiates manufacturing QA ratings rather than an inspection process that ends up with a pass-fail conclusion. For example, a company with very few warranty returns would be rated to have better QA than a company with many manufacturing excursions.

As with the design of a QA rating system, a QA guideline should facilitate learning from the community to improve the guideline.

QA OF MANUFACTURING PROCESS — PROPOSAL

Ideally, after certifying the QA rating for a PV module design, a test laboratory inspects the associated factories to ensure that a strong QA program is in place and is carefully followed. We propose, therefore, that IEC is the most logical standards organization to implement a manufacturing QA guideline. This implementation may be simplified by the creation of standards for material purity by Semiconductor Equipment and Materials International (SEMI) or by standards defined for other elements in Table 4.

Table 4. Elements of a QA guideline

Guideline element	Parts of review
Materials qualification	List of materials used in module fabrication; criteria and properties tracked for each of these materials
Process control	Calibration of sensors, acceptable process windows for each part of process, log of data collected
In-line testing	List of measurements completed, frequency of these measurements, log of data collected
Traceability	Documentation from ingot to module shipment; maintenance of records to trace future failures, ID marking of modules
Retest schedule	Frequency of qualification or other module-level testing, log of data
Warranty return program	Documentation of number of returns, identified failures, and corrective actions
Factory inspection procedure	Frequency of inspection, fraction of manufacturing lines inspected, and pass/fail criteria

It is also necessary/useful to ensure quality of the installation design and implementation, but this is outside of the scope of this paper.

CREATION OF QA STANDARDS

Key Steps for Creating QA Standard for Designs

It often takes years, if not decades, to obtain a consensus on a new standard. To expedite this process, we provide a step-by-step plan. Key steps include:

1. Develop a consensus that a single international approach is needed.
2. Identify what information is to be communicated (*e.g.* Table 2).
3. Use existing knowledge to suggest appropriate tests to provide that information.
4. If existing knowledge does not give confidence, then “test the test” by applying proposed tests to module designs with known field success and failure [8].
5. Create maps or other guidance to communicate test implications to customers.
6. Apply a similar procedure to thin-film, CPV, and balance-of-system technologies.

The International PV Module Quality Assurance Forum is scheduled for July 15–16, 2011, in San Francisco, Calif. At this meeting, we hope to accomplish steps #1 and #2 and form committees to develop tests for each of the stresses listed in Table 2. At the Forum, the community will be given an opportunity to discuss their preference for how to best create QA standards. Tables 2 and 3 will be used as a starting point for discussion, but the participants will determine the outcome of the Forum, forming committees to implement the chosen plan. These committees will be asked to present updates at each IEC TC82 WG2 meeting, with a target of proposing a Part 2 to IEC 61215 in spring of 2012 (step #3). If WG2 approves the proposed Part 2, work on steps #4–6 will commence. If the community is willing to work together, testing to the international QA standard can begin in spring of 2012.

Key Steps for Creating Manufacturing QA Standard

A guideline for QA during manufacturing will also be discussed at the International PV Module QA Forum in July. A committee will be formed with a similar timeline as described above.

1. Work with IEC to define factory inspection and retest guidelines that would become part of the IEC 61215 certification process.
2. Work with SEMI and other standards organizations to develop standards for material, component, and equipment qualification and in-line testing.

CONCLUSIONS

The time has come for the PV community to move toward more quantitative standards that can differentiate PV modules according to their durability and provide the basis for improved risk analysis. Many groups are currently working to create such tests, but the community will be better served if these groups can work together to create a single set of QA standards and guidelines. This paper proposes the creation of a QA rating system for adoption as Part 2 of IEC 61215. The proposal suggests that the rating system should document on the nameplate and datasheet the relative durability of the module to each type of stress and that a full test report would include additional information for interested customers. A manufacturing QA guideline for defining factory controls and guiding inspections is proposed to become a part of the certification process. Further work will be required to extend this to thin-film and CPV testing and to quantify the meaning of the test results.

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