Qualification Testing Versus Quantitative Reliability Testing of PV - Gaining Confidence in a Rapidly Changing Technology

Preprint

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QUALIFICATION TESTING VERSUS QUANTITATIVE RELIABILITY TESTING OF PV – GAINING CONFIDENCE IN A RAPIDLY CHANGING TECHNOLOGY

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ABSTRACT: Continued growth of PV system deployment would be enhanced by quantitative, low-uncertainty predictions of the degradation and failure rates of PV modules and systems. The intended product lifetime (decades) far exceeds the product development cycle (months), limiting our ability to reduce the uncertainty of the predictions for this rapidly changing technology. Yet, business decisions (setting insurance rates, analyzing return on investment, etc.) require quantitative risk assessment. Moving toward more quantitative assessments requires consideration of many factors, including the intended application, consequence of a possible failure, variability in the manufacturing, installation, and operation, as well as uncertainty in the measured acceleration factors, which provide the basis for predictions based on accelerated tests. As the industry matures, it is useful to periodically assess the overall strategy for standards development and prioritization of research to provide a technical basis both for the standards and the analysis related to the application of those. To this end, this paper suggests a tiered approach to creating risk assessments. Recent and planned potential improvements in international standards are also summarized.

Keywords: PV reliability, accelerated testing, risk assessment, lifetime prediction

1 INTRODUCTION

As the total investment in the solar industry has increased, persistent questions arise: "What is the degradation rate of the module and system and how do they compare to the component manufacturer's stated warranty and system performance guarantee?" "How much more should I be willing to pay for a module/system that has demonstrated improved reliability?" or, conversely, "What information demonstrates higher confidence to justify a higher price?" While there is ample evidence that PV installations have performed mostly as expected [1-3], there have also been some product recalls and observations of new (unexpected) failures.[1]

Fig. 1 shows our simplistic starting point: certifying a module design by testing 8 engineering samples to the IEC 61215 qualification test [4] is inadequate (and not intended) for making 25-year risk assessments[2]. While IEC 61215 has been demonstrated to be valuable for rapidly uncovering well known failure mechanisms, it is insufficient for assessing long-term risk, evaluating newer or less common materials and designs, establishing field performance degradation, setting insurance rates that must consider power generation over at least 25 years, or selecting the best product for a specific project. Today's rapidly changing PV technology requires many companies to launch new versions of their product every few months while requiring warranties that are decades long.

Today, in addition to qualification testing (IEC 61215 and IEC 61730 [5]) most PV companies require a robust quality management system that controls many aspects of the manufacturing process (incoming materials, processes, etc.) as well as testing beyond IEC 61215. As the PV industry matures, the methods used for quality control (QC) are evolving to utilize new knowledge and to be more consistent, enabling lower QC costs, as with IEC TS 62941 [6]. We expect this evolution to move from pass-fail qualification testing to more sophisticated analyses that provide more quantitative assessment of risk specific to a particular location or type of location, and, thus, enable more quantitative assessment of the value of high-quality components, both in terms of degradation rates and failure rates. One proposed approach to completing a quantitative assessment assigns a Cost Priority Number (CPN) that reflects the cost of repair or loss of revenue associated with a problem [7]. Assignment of a CPN or other rating methodologies [8] relies on being able to link knowledge about the components and system with the anticipated outcomes. The industry has not yet agreed upon the best approaches for gathering and using the information needed for quantifying overall risk.

This paper begins by describing approaches for risk assessment that range from an initial qualification test to the ideal for quantitative assessments. It then proposes a strategy for building on the foundational qualification testing to use standardized data collection from extended stress testing and thoughtful analysis of that data within the context of known field results to provide a useful risk assessment. An overview of a subset of recent and planned international standards development is also presented, highlighting the joint work of the International PV Quality Assurance Task Force (PVQAT) and IEC Technical Committee 82. While this paper is largely focused on PV modules, the concepts must be applied to all components as well as to the entire system.

[1] Here, "failure" broadly refers to any problem that may cause risk for a business partner.

[2] Most investors today plan to obtain return on investment in < 25 years; we refer to 25 years to reflect warranty time lines as well as the needs of second owners.

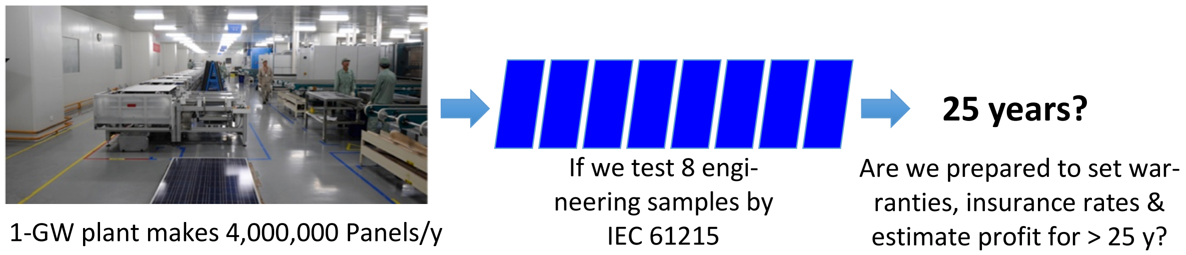

Figure 1: Our challenge with this rapidly changing technology is to use a few months of testing to provide the basis for business decisions that may have impacts for decades. This paper discusses strategies for improving risk assessments.

2 QUALIFICATION vs QUANTITATIVE TESTING

As shown schematically in Figure 2, risk assessments of PV can evolve to be more quantitative. The initial idea (see left side of Fig. 2) is evaluated and analyzed; prototypes are stress tested to qualify a design, and samples from a production line are subjected to extended-stress testing. Finally, a mature product with a specified bill of materials manufactured within a defined process window for a specific application may be tested and modeled quantitatively. From left to right in the simplistic description in Fig. 2, the quantitative nature of the assessment increases. Differentiating the roles and utility of each type of test encounters many complexities, as discussed in this section to set the stage for the strategy discussed in section 3.

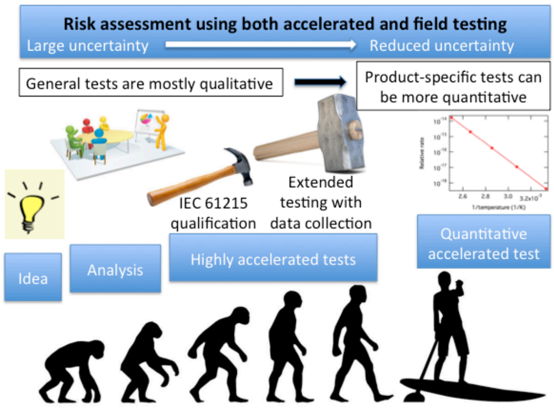

Figure 2: Evolution of maturity of risk assessment as a product evolves from concept to a mature product that can be tested in a more quantitative way because the product design stays fixed long enough to complete the needed testing.

Qualification tests typically provide a pass-fail outcome reflecting whether the test article exceeds a minimum acceptable key indicator. In contrast, a quantitative test is associated with a numerical output providing the user with access to the degree of impact a test has on a key indicator. When multiple data points are measured as a function of varying levels of a stress factor, these may be used to derive a model from which a quantitative prediction may be made. While there is common interest in developing quantitative models (right side of Fig. 2), many such models today fail to provide the desired accuracy and do not include all possible failure mechanisms/stresses; experts are often hesitant to suggest that such models can build confidence over the product's lifetime. While we understand this hesitancy, we assert that we should not let that hesitancy deter us from acquiring and using all relevant data to make increasingly quantitative predictions. It is the purpose of this paper to explore the best strategies to accomplish this goal.

2.1 Can qualification testing be quantitative?

Today, most PV module designs are certified to both IEC 61215 [4] and IEC 61730 [5]; these prescribe a set of stress tests to qualify a prototype with respect to functionality and safety, respectively, before beginning manufacturing. While these two standards are pass-fail by nature, they can provide information beyond a simple pass-fail by:

• Differentiating PV modules with regard to some attributes that are defined on the data sheet, *e.g.* performance, system voltage and mechanical load. As tests mature, additional attributes may be treated in this way.

• Reporting the observations. For example, if one test article fails IEC 61215, the test can be repeated and passed. The failure suggests risk that some samples are defective; such risk can be quantified through statistical sampling from the production population. Many manufacturers decline to share the detailed IEC 61215 test report with their customers even though the data in this report would be valuable toward analyzing the suitability of a module design. Transparency in sharing test results would be beneficial to the community.

2.2 Uncertainty as the metric for quantitative assessment

An accurate model-based prediction of degradation or failure rates of a PV product is very difficult. For example, when a degradation mode involves a multi-step process, understanding each step well enough to model it is a challenge. Furthermore, to test a model may require years of work. Often the most difficult part of creating the prediction is assessing the uncertainty of the prediction, because the uncertainty depends on variations in the manufacturing process as well as uncertainty in the kinetics of the failure mechanism and uncertainty in the applied stresses relative to those in the actual use conditions. At the extreme, a prediction of a service life of 25 years ± 25 years may be the result of the study, providing a scientifically rigorous result that has essentially no value.

Studies of acceleration factors to enable prediction of PV degradation or failure rates often lack statistical confidence, or simply are not comprehensive. Typically, the focus is on some details of the prediction (the identification of failure mechanisms, measurement of the kinetic rates, and application of a model to the intended use environment) derived from a small sample set with little analysis of the uncertainty. An unintended impurity in an encapsulant may change its rate of discoloration; variations in the thickness of a solder bond may change its failure rate; mounting of a module in such a way that it overheats could accelerate its degradation, etc. As a result, many experimentally determined degradation rates are bound to have high uncertainties. The accuracy of the output of any model is subject to the degree of accuracy of its input parameters. Compared with the studies of quantifying failure mechanisms, few studies have focused on quantifying and decreasing the uncertainty related to inputs such as the variability of the manufacturing process. Moreover, it is challenging to model the degradation behavior when parallel degradation processes take place. To overcome the difficulties most of the proposed models initiate simplifications and assume that certain processes will dominate under certain environmental conditions and ignore the perplexity of multi-dimensional reaction paths, which further increase the uncertainty of prediction. Similarly, warranties may not specify the use environment, even though the physics predicts that the life of a module varies with use environment.

A general test such as IEC 61215 is not intended for quantitative predictions of lifetime. Efforts to quantify the implications of passing a general test are inherently limited. Although it is clear that different products may show different acceleration factors, preventing confident predictions from a general type approval test, there is an urgent and practical need to better understand and analyze test results in order to provide the basis for setting insurance rates, estimating return on investment, and making other business decisions.

Thus, studies of the mechanisms and associated acceleration factors to make quantitative predictions should be encouraged, but these should always assess the expected uncertainty in the predictions. *In some cases, the uncertainty may be reduced more by the application of tighter control of the production process (when it is known which parameters need to be controlled), or the definition of the use environment than by improved measurements of the kinetics of the failure rates*.

2.3 Is extended-stress testing useful?

Over the years, many protocols have been developed for extended stress testing [9-19]. The number of these tests and the frequency of their use by the community imply that they provide value. Most such tests are designed to apply stresses in a manner that reproduces relevant field stresses, either in combination or sequentially and records a series of data from the extended sequences. But, there is usually a lot of guesswork and some debate about the "best" number of cycles (see section 2.4) and which sequences of testing should be chosen. There is concern that the tests sometimes cause irrelevant failures, adding unnecessary cost, raising unnecessary concerns, or leading to unwise decisions.

We suggest that extended-stress testing can make risk assessment more effective by:

• **Comparisons**: Provides a way to compare two versions of a product, which can be especially useful if a change in the bill of materials or manufacturing process may change field failure rates. Care must be taken to compare products only for test results that are relevant to the use environment. This may be the most common application of extended testing since many companies release new versions of their products every 3-12 months. *The disconnect between the intended lifetime of the product (> 25 years) and the production lifetime (3-12 months) is at the core of our challenge*.

• **More extensive data**: Most extended testing protocols report observations after each step, providing more data than a simple pass-fail at the end of the test. Standardization of the extended-stress test methodology enables comparison of the test data with a larger database of test results, facilitating the comparison of test results from many samples and the correlation of these with field data if accessible records are kept.

• **Identify potential vulnerabilities**: Similar to test-to-failure protocols, overstressing samples can identify vulnerabilities that should be assessed for relevance to the intended use environment. This includes component materials tests that screen out non-durable materials from the design, or identify when mitigation may be required.

• **Use of production modules**: Extended test protocols may be applied to production-line samples, possibly from multiple lines or factory sites, differentiating the extended test from qualification testing of prototypes and potentially leading to an improved understanding of product production controls.

• **Educate the market**: Many experts have reported that buyers and financial institutions often request extended testing, but have minimalistic requirements in terms of test duration, severity and sample size, while expecting that results will provide confidence over the product's expected lifetime. It is therefore important that the scientific community lay the fundamental guidelines for a test protocol with realistic test requirements that can be accomplished in a reasonable timeframe (e.g. 6 months). Such guidelines would provide a basis that will help educate the market over what is realistically achievable and align expectations with reality.

• **Standardization as a means to build a market consensus**: Those who use extended testing routinely report that such testing is very useful toward assessing risk even when the results are not directly associated with quantitative models. But, a plethora of extended test protocols exists. It is often confusing for the buyers, or those who drive financial decisions to understand which one is "best" for their needs. Standardization of the extended-stress test methodology would help build a consensus in the market in terms of both requirements and expectations, and would reduce the time and cost of testing. What the PV community needs is a single, commonly accepted and standardized protocol that provides the information to increase confidence over IEC 61215/61730 qualification and type approval.

2.4 More samples vs. longer stress

For a given budget, one can choose to test more samples for shorter stress or fewer/smaller samples for longer stress. Testing more samples is especially useful when an issue is observed infrequently. On the other hand, extended-stress testing identifies how a product wears out and potential weaknesses in a product, enabling more complete risk assessment, just as test-to-failure is used for risk assessment. While extended-stress testing has become quite popular (see section 2.3) and is offered by most test labs and required by many customers, there is substantial debate about the optimal balance between the number of samples and the length of the stress test. The use of smaller samples (*e.g.* 1- or

4-cell mini modules, or test coupons containing packaging materials with no electrical components or cells) reduces cost (but also introduces new uncertainties), and may be especially useful for screening new materials and for mechanism-specific testing. While it is not well established how to integrate this sort of information, an effective method to screen out materials that are not durable in the application will unquestionably improve the risk assessment. The optimal balance depends on the goal of the testing, as discussed below.

2.5 Risk assessment versus service-life prediction

Although studies often state an ultimate goal of predicting *service life* for PV modules, *failure and degradation rates as a function of time* are much more useful to those who are estimating maintenance costs, setting insurance rates, or quantifying risk of an investment. Failure and degradation rates can be reduced into a single number (service life prediction), but only the use of the time-dependent functions allows calculation of costs and revenues over the lifetime of the system. It's important to describe both the failure rates and degradation rates because failure of a module may require replacement and associated maintenance cost while degradation reduces the electricity generated, both of which can affect the return on investment. In practice, every failure/degradation mechanism must be quantified and the combined effects estimated. Here, we use "risk assessment" as a short way to refer to the evaluation of degradation and failure rates as well as any assessment of risk.

For every risk function, quantifying the uncertainty (which generally increases with time into the project) is essential [7]. As described in section 2.2, quantifying the uncertainty is sometimes more difficult than making the prediction and the challenge is even greater when the uncertainty increases as a function of expected lifetime duration.

Inherent to both risk assessment and service prediction is a means to describe the stresses in the specific application, e.g. the relevant application and climate specifics. The reliability of a given module for 2 different locations, or application types (e.g. field or roof mounted) can be very different, and the relevant parameters (e.g. module temperature, extent of thermal cycling, exposure to salt spray or snow load) need to be understood so appropriate data can be included in the analysis.

2.6 Why should empirical data be included in risk assessments?

Physics-based models (based on understanding the mechanism and quantifying the kinetics) may be required to theoretically explain and understand the development of a degradation process or reaction, but due to the complexity of the processes involved in the field, it is often more practical to rely on experimental observations and correlations of laboratory and field testing. Insurance companies define their rates based on both "exposure rating" (based on physics-based studies) and "experience rating" (based on actuarial-type statistics, which are semi-quantitative and relevant even when they don't reflect the physics of failure).

Using uncertainty as a metric, physics-based models may be inferior to experimental or field observations when the uncertainties in the physics-based predictions are large. In an example of damage caused by hurricanes, historical data may provide a more accurate prediction than a physical model. If the uncertainty of the empirical data is smaller than the uncertainty of the physics-based model, then the empirical data is likely to be superior and should be respected for the value it brings.

On the other hand, experimental data or field observations may be irrelevant if the prediction is made for a product that has different failure mechanisms than described by the so-far observed data. Thus, the best approach is likely to use correlations of accelerated and field test results combined with analyses of how the products differ and how those differences may affect the final results. Comparisons of field data can also provide very useful insight into the effects of design or component selection, if these are analyzed carefully.

3 STRATEGY FOR BETTER ASSESSING RISK

This section proposes a strategy for improving risk assessments by using a tiered approach using standards, knowledge, and processes that consider multiple aspects of product design and implementation.

Goals for future improvements include:

1) Address failures that are being observed in the field,
2) Address new failure mechanisms for new products,
3) Reduce cost by removing unnecessary requirements and standardizing testing protocols, and
4) Reduce the uncertainty in reliability assessments.

3.1 Overall strategy and types of tests

Various types of testing and analysis were described in Fig. 2. We suggest that a robust approach to low-uncertainty risk assessment will benefit from using multiple elements in a systematic way (see Fig. 3).

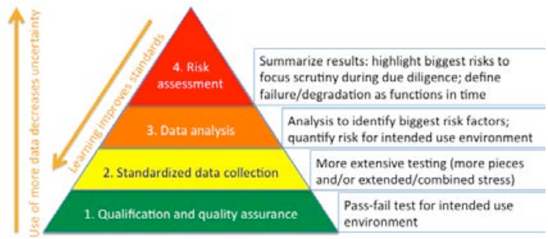

Figure 3: Strategy for improving risk assessments of PV. The colors indicate the time line.

Qualification testing for the intended application provides the foundation (Tier 1 of Fig. 3) of our approach to quantifying risk. The second tier in Fig. 3 describes *standardized data collection for larger sample sets and for extended-stress test sequences that have been found to be useful in identifying product that will be successful in the field*. These *data are analyzed using all available knowledge, including the correlation between laboratory test results and field results for the relevant use environment,* (third tier in Fig. 3) to determine the risk functions that define the final risk assessment (top tier in Fig. 3). The colors in Fig. 3 suggest a time line: Green for Tier 1 suggests that qualification testing is already in place with need for only incremental changes; Yellow suggests completion of a first version of a standard within a year or two; Orange implies that more research is needed before we can standardize our approach. Red implies that a critical confidence has to be reached in observations before making conclusions about risk. The following sections discuss each of these elements.

Table I: Summary of key goals of testing programs and recommended approaches.

Goal	Test element	Approach
1. Identify failure mechanisms for a totally new product	Accelerated test to uncover new and known failure modes; test to failure	Simulate use conditions (including field deployment) to identify expected field failures; test to failure to identify product weaknesses
2. Compare two similar versions of a product	Accelerated test that quickly identifies (known) failures; test to failure	Use extended-stress tests known to cause same failures as in the field, collecting multiple data points; standardize so as to leverage learning from community
3. Quality control	Accelerated test that quickly identifies weakness	Use "smart" (comprehensive) sampling along with tests from IEC 61215, IEC 61730; use standard extended-stress test for fewer samples
4. Reliability assessment	All of the above	Compare data with previously collected data and with literature publications to provide the best analysis possible

3.2 Tier 1: Continued improvements of qualification tests

As products evolve, there is a constant need to update the standards for qualification testing. Based on current reports from PV systems, priority issues include:

1) A range of failures of power electronics associated with both design (IEC 62093) and quality assurance (IEC TS 63157),
2) Potential-induced degradation (PID) of modules,
3) Cracked cells in modules and a range of problems that may be caused during installation,
4) Hot spots, and
5) Quality issues resulting in inconsistent nameplate rating and/or durability.

In response to these and other opportunities, amendments of IEC 61215 and IEC 61730 are being discussed (see section 4). In general, new test methods are first published as IEC Test Specifications (TS), typically without pass-fail requirements. After being used for several years and when well accepted by the community, the test method along with a defined minimum threshold for establishing passage or failure of the test, may be merged into the IEC 61215 and IEC 61730 tests. As an example, IEC 62804-1 was published in 2015 to define how to test c-Si modules for PID. After using the two proposed tests, the IEC committee may now be ready to amend IEC 61215 to include a pass-fail PID test based on IEC 62804-1 experience.

A critical element of starting production of a new design is defining quality assurance procedures. IEC 62941 was developed to guide this process for modules. Methods for consistent implementation of IEC 62941 are being defined by IECRE [20].

Qualification testing provides a "pass" if the conditions of the tests are met, but the conditions may be intentionally varied. For example, the "pass" result may characterize the ability to withstand variable levels of system voltage, snow or wind load, and hail. Now, a Test Specification is being developed for higher temperature operation. If new Test Specifications become well accepted by the community as useful tests, in the future, IEC 61215 may be modified to test for multiple levels for operation at higher temperatures, or extended UV exposure and for robustness to stresses during installation.

3.3 Tier 2: Strategy for additional data collection

While the need for more standardized data is clear, there is not yet agreement on the test methodology and data collection. We suggest that confusion arises from the multiple purposes of the additional data. Table I summarizes key goals and strategies for the data collection.

Outdoor testing in a range of use environments is part of evaluating any product, but getting useful results takes longer than the product-development cycle. Even so, systematic collection of data regarding both the performance and physical changes is essential to analyzing the relevance of the accelerated test data.

If a company is developing an entirely new product and has little information about how the product will fail, it is useful to carefully analyze possible problems, as well as to use accelerated stress testing to simulate conditions of the anticipated use environment [17, 18]; it is also useful to stress the product until it fails so as to identify its weaknesses. (See first item in Table I)

It is more common (second item in Table I) to compare two similar designs (e.g. with different bill of materials or similar products from two manufacturers.) For common PV module designs, the probable failure and degradation mechanisms have been well studied and effective tests exist. Using a standard set of tests and data collection methodology enables consistent comparisons and leverages collective knowledge from the community. While these standardized tests should duplicate failures that are relevant in the field, there can also be value in testing to failure in cases where a change in a design may introduce a new weakness in the product. *Thus, attempting to align the accelerated and field stresses (even if it were possible) may be less useful than cost-effectively collecting an extensive extended-stress data set and evaluating that data set based on field experience coupled with an understanding of the physical processes.*

A third goal of collecting data is for quality control. As part of a quality management system (QMS), companies develop reliability or quality monitoring programs that detect changes in the product. Companies may attempt to confirm product quality through a short (incomplete IEC 61215) set of tests before releasing inventory and then may continue stressing a subset of samples to increase confidence in the consistency of the manufacturing process. Some customers require third party testing of random samples from the lots that are shipped to them. To provide effective quality control, it is essential to sample all production lines and to provide feedback very quickly; we suggest leveraging a quality assurance guide such as IEC 62941 and include:

1) Careful and consistent control of incoming materials/components,

2) “Smart” (rather than purely random) sampling to test appropriately weighted sample populations that represent the production population as a whole with respect to the failure modes of interest,
3) Rapid stress testing such as application of parts of IEC 61215/61730 for modules or IEC 62093 for inverters and other balance-of-system components.

In many cases, application of the standard qualification tests adequately identifies problematic variations in manufacturing. However, extended-stress testing of a subset of samples may also be useful. Although one could apply extended tests to the full sets of samples, practically, there is a tradeoff between the number of samples and the length of the stress tests; we suggest that, especially when quality control is the goal, shorter tests (to give quick feedback to the production process) and broader sampling (to test all production hardware) may be better than using extended testing for all samples.

Developing a useful, standardized set of extended stress tests is critical. For modules, multiple versions of extended-stress testing have already been introduced to the community [9-19]. In many cases, these apply IEC 61215 tests multiple times, recording the results after each cycle [11, 12, 15]. In some cases, different types of stress are applied sequentially [14, 15]. Applying stresses in combination more closely simulates the use environment, so including combined-stress tests is preferable if costs are acceptable. Additionally, it can be useful to measure indicators of changes such as adhesion, leakage current and a polymer’s ability to deform without fracturing. *Because acceleration factors can vary by orders of magnitude for different failure mechanisms and use conditions, it will not be possible to design the “perfect” extended-stress test that would identify all relevant failures while avoiding irrelevant failures*. On the other hand, the industry’s extensive experience can be used to identify and standardize a useful test sequence that builds on the huge success of IEC 61215 and IEC 61730 to provide more extensive data at minimal cost.

Reliability assessments should use all of the available data in scientifically appropriate ways, as discussed below.

3.3 Tier 3: Strategy for data analysis

The industry will benefit from an increasing engagement by all parties in understanding and analysing data. *This analysis will be easier and more effective if the set of tests and associated data collection methodology are standardized and if research efforts are directed toward comparing the standardized test results to field results in parallel with development of physics-based models, including more detailed understanding of the physical changes*. As a body of knowledge is developed, that knowledge should be used to systematically improve the qualification tests, standardized extended-test methodology and associated data analysis.

The focus of the data analysis should always be on providing useful inputs into the specific risk assessment (section 3.4), which may vary from project to project. For example, a module design that is susceptible to failure under high snow load may be quite acceptable for application in a tropical environment or an inverter that is operated in an air-conditioned enclosure may not function well in a hot ambient with direct sunshine. Also, the data analysis should include considerations of both testing of the design and of consistency of the manufacturing.

The data analysis should reflect both scientific studies that elucidate the details of the failure mechanisms and experimental or field observation studies that indicate the kinetics of the mechanism at stress levels present in the field. For example, potential-induced degradation depends not only on system voltage, but also on temperature, humidity, light, stress history, and electrical loading. There is opportunity for substantial research to better understand the stresses that cause failures/degradation as well as the material and product attributes that may affect the failures and degradation. This understanding, along with knowledge of the process controls that are used in the manufacturing and installation processes, will aid in making more accurate analyses.

Comparison of field experience with accelerated test results is a critical part of verifying any model, yet the number of years required for completion of such studies often prevents clear conclusions and as indicated above, the production lifetime for a fixed bill of materials and production process is often between 3-12 months leading to low manufacturer incentive for lengthy studies. *If records of accelerated test data and installation procedures can be kept alongside of the as-built plant documentation, the meaning of future field outcomes will be clearer.*

A scientific approach must always be taken when analysing both the accelerated test data and field data. The hardware and application being analysed may differ from those for which the data are available. Relevance of the results of extended-stress testing will depend on the site and application being evaluated.

3.4 Tier 4: Useful risk assessments

The highest tier shown in Fig 3 describes the end goal: *a risk assessment that highlights the greatest risks while providing the comprehensive information needed to make business decisions*.

As discussed in section 2.5, service life prediction is useful, but not sufficient: we must quantify the expected degradation and failure rates as a function of time. Whether non-linear degradation occurs mostly near the beginning or end of life can have a large effect on the levelized cost of energy (LCOE) [1]. Thus, reliability *functions* that reflect both degradation and failure rates are much more useful than a single number that is intended to reflect an average lifetime.

Additionally, better data for business decisions will reduce the associated risk, and, potentially, the cost of capital, lowering the overall project cost. This requires more comprehensive information such as a five-part analysis:

1. **Failure/Degradation Mode**
2. **Failure/Degradation Consequence (severity)** – Assign weight to reflect cost associated with the failure.
3. **Failure/Degradation Timing** – This assesses implication on both time value of money as well as the investment horizon.
4. **Failure/Degradation Cause** – This may facilitate risk improvement and management.
5. **Failure/Degradation Scale (occurrence)** – Identifies the fraction of products that could be affected.

All information used in the risk assessment has an associated uncertainty. Part of the risk assessment is estimating this uncertainty and including the uncertainty and its confidence in the conclusions.

3.5 Risk assessments at the system level

The four-tier approach of Fig. 3 should be applied to all of the components and the summary risk assessment completed at the system level, using any available data from similar systems with as many years of experience as possible. *System design, installation, and operation may affect component reliability functions*, as well as the function of the entire system, so are an essential part of the risk assessment.

4 RECENT PROGRESS IN STANDARDIZATION

4.1 IEC and PVQAT efforts

The International Electrotechnical Commission (IEC) Technical Committee 82 (TC82) writes standards for solar photovoltaic energy systems. The International PV Quality Assurance Task Force (PVQAT), initiated in 2011, established a Type A Liaison to IEC TC82 in 2017, supporting discussions and coordinated research to lay the groundwork for new and improved IEC standards.

In 2015, PVQAT-prioritized efforts to address issues identified from failures in the field were summarized (see Table III of [21]). Progress on these and related efforts is summarized in this section.

4.2 Recent progress in PV standards development

Table II summarizes selected recent improvements in IEC documents relevant to this paper.

A key effort of PVQAT has been to improve guidelines for quality assurance. PVQAT initiated discussions of this topic in 2011 and IEC TS 62941 was published in January 2016 to provide guidelines for quality assurance of PV module manufacturing [22, 23]. The IECRE conformity assessment board is implementing IEC TS 62941 [20]. Similarly, opportunities for improved quality assurance were identified for PV system installation and operations/maintenance as described in IEC TS 63049 and implemented by IECRE.

The recent revision of IEC 61215 combined IEC 61215 and IEC 61646 into a single series of documents to align the common testing procedures for silicon and thin-film modules while retaining differentiation of test methods by type of module, where appropriate. The changes to this set of documents were extensive (see Table II for a few highlights).

Two test methods for identifying the susceptibility of silicon modules to potential-induced degradation (PID) were published in 2015 (IEC TS 62804-1).

The cyclic (dynamic) mechanical load test (IEC TS 62782) was published in 2016 with the intent to use, along with thermal cycling and humidity freeze stress, to identify modules that have cracked cells that are likely to degrade in performance after exposure in the field.

Table II: Summary of some recent improvements in IEC standards relevant to this paper

Document	Publication	Description	Value
IEC TS 62941	2016	Quality assurance guideline	Guideline to improve quality of PV modules
IEC TS 63049	2017	Quality assurance guideline	Guideline to improve quality of PV plant installation and operation/maintenance
IEC 61215 series	2016	Hot-spot test measures shunting of every cell	Testing the most vulnerable cells is more likely to identify a problem
		Marking requirements for nameplate and general documentation are better defined	Provides customers important information in a consistent way
		Power output is checked both before and after stress testing	To pass, the modules must perform within specification before *and* after stress
		NOCT (nominal operating cell temperature) replaced by NMOT (nominal module operating temperature)	NMOT reflects the module temperature when biased at the maximum power point
		Robustness of terminations test evaluates both cables and junction boxes	More likely to catch problems
IEC 61730-1 IEC 61730-2	2016	Implemented insulation coordination, overvoltage category, classes, pollution degree and materials groups	Is better aligned with other IEC documents, facilitating better treatment of these concepts
		Definition of creepage, clearance and distance through insulation	Is better aligned with other IEC documents, streamlines introduction of new materials such as edge seals
		Implementation of component qualification	Prequalifying junction boxes and other components reduces time to qualify new design
IEC TS 62804-1	2015	Tests for susceptibility to potential-induced degradation (PID) in Si modules	Provides two tests that may become a basis of a pass-fail test within IEC 61215
IEC TS 62782	2016	Cyclic (dynamic) mechanical load testing	Detects cracked cells in module
IEC TS 62916	2017	Bypass diode electrostatic discharge (ESD) susceptibility testing	Quantifies control needed to avoid damage from ESD; referenced by IEC 62941
IEC 62979	2017	Bypass diode - Thermal runaway test	Tests for thermal runaway when diode switches from forward to reverse bias
IEC 62788 (Materials Testing)	2016-2017	62788-1: Encapsulants 62788-2: Frontsheets/Backsheets 62788-5: Edge Seal 62788-7: Component weathering exposures	Facilitates comparison of candidate materials for use in PV modules and for quality control of incoming materials

IEC 61724 series	2016-2017	Three parts define parameters and procedures for quantifying performance of PV plants	Enables execution of performance guarantee, consistent comparison of systems, and tracking of system health

Two new standards have been published to improve confidence in bypass diodes. The first discusses the control of electrostatic discharge (ESD). Implementation of this standard is one of the key elements in the quality assurance guideline IEC TS 62941. Additionally, to respond to an observed failure mechanism of thermal runaway involving a bypass diode switching from the forward bias state to the reverse bias state while being hot was published as IEC 62979. This failure mechanism is difficult to characterize because it occurs during a quick transient; there is some discussion about whether IEC 62979 is the best approach given the details of the failure mechanism.

A suite of tests (IEC 62788) for characterizing key properties of PV module materials (e.g. encapsulant and back sheet) is being developed with a number of individual documents already published. This set of documents provides consistent data to facilitate comparison of module materials, designed to be very helpful to component suppliers and module manufacturers as they identify ways to reduce cost. These test procedures may also be used for quality control of incoming materials.

The IEC 61724 series describes characterization of PV system performance, including capacity- and energy-test methods. Ultimately, the electricity generated by a PV system is a key metric.

4.3 Planned progress in PV standards development

When the revisions of IEC 61215 and 61730 were published in 2016, there was a decision to delay some changes, but to move forward as quickly as possible with amendments to both documents. Table III summarizes some of the changes that are being discussed. Notably, there is a need for a pass-fail test in IEC 61215 for PID (derived from IEC 62804-1) and there is a plan to introduce the cyclic (dynamic) mechanical load (IEC 62782) as part of a sequence to identify cracked cells in modules. Also, consistent characterization of bifacial and flexible modules will facilitate introduction of these new products into the marketplace. Finally, there has been discussion about modifying IEC 61215's thermal cycling test to include some cycles during which current flows through the bypass diodes instead of the cells. Some failures of bypass diodes have been observed and current flow to cause local heating of thermal fatigued joints accelerates relevant failures without requiring as much stress time as without the current flow. PVQAT Task Group 4 recommends that 50 thermal cycles with current flow through the diodes be added to the 200 thermal cycles that are already done in IEC 61215 with current flow through the cells for a total of 250 cycles. The functionality of the diodes must be verified at the end of this stress.

A suite of climate-specific tests was originally proposed as IEC 62892. In 2017, TC82 decided to revise the approach to climate-specific testing. The document describing extended thermal cycling for a range of applications will be published as a separate document. The stress conditions for encapsulants that have been discussed as IEC 62892-3 is now being discussed as IEC 62788-1-7.

A new effort (IEC 63126) is defining how to apply IEC 61215 and IEC 61730 tests to modules destined for operation at higher temperature. A key element of IEC 63126 may be to increase the thermal endurance testing of bypass diodes; there is a common view that the current thermal endurance test is inadequate for hotter applications. Once established, the option for higher temperature testing may be rolled into IEC 61215 and IEC 61730 much like these currently enable tests to be completed for a range of system voltages.

To address the common problems that are reported for inverters, IEC 62093 is being rewritten to reflect experience with testing inverters; the draft now includes tables differentiating testing of central, string, and micro inverters. A guide for quality assurance of inverter manufacturing (similar to IEC 62941) is also being developed as IEC TS 63157. Given the dominance of inverter problems, a meaningful inverter qualification test, coupled with the planned quality control guideline, should make a substantial difference to overall PV system reliability.

A test for permanent damage resulting from partial shade is being discussed as IEC TS 63140. The procedure includes methods for determining the size of an adverse shadow and for repeatedly applying that adverse shadow. The method is applicable to monolithically integrated PV modules with one series-connected cell group or with multiple series-connected cell groups that are in turn connected in parallel.

While IEC 62759-1 identifies modules that may be damaged during transportation to the installation site, it is widely noted that modules can also be damaged during installation if bounced, dropped, carried on hard hats, walked on, or installed with too much stress. It is anticipated that it would be useful to write a part 2 of IEC 62759 to identify the care that needs to be taken to avoid damage during installation.

Similarly, there is interest in developing tests for various building-integrated PV (BIPV) products. The approach for testing BIPV products is challenging because of the many potential form factors and because of a lack of data identifying all failure mechanisms. A single project team will be discussing the various types of BIPV products to define an approach to tackling this problem.

As discussed above, there is widespread interest in creating a standard for collecting data during and after application of extended stress. Existing extended-stress test sequences will be reviewed to identify commonalities and differences and users will be surveyed to select the test sequences that have been most useful in identifying weaknesses that correlate with field failures. As noted above, it is not possible to define a test that uncovers all field-relevant failures without also causing some failures that will not be found in the specific use environment.

5 CONCLUSIONS

Practicality calls on us to do the impossible: Confidently predicting decades of performance for products that are designed and launched in a few months is a formidable challenge. Yet, billions of euros of investment each year require assessment of the risk in those investments. Here, we propose a multi-tier strategy for collecting and using information in the most effective ways, striving toward meeting this tremendous challenge.

Table III: Summary of priorities for planned amendments of IEC 61215 and IEC 61730 and development of new documents.

Document	Anticipated Publication	Description	Value
IEC 61215 new edition	2019	Add cyclic (dynamic) mechanical load test (IEC TS 62782)	Detect cracked cells in modules
		Add pass-fail requirement for PID (IEC TS 62804-1)	Define consistent way of characterizing PID resistance
		Methods for testing bifacial and flexible modules	These new products are entering the marketplace without consistent ways of communicating their value
		Correction of hot-spot test	Addresses problem with testing certain modules with series-parallel architecture
		Improve simulator requirements	More accurate power output measurements, with less effect from spectral mismatch
		Thermal cycling with current flow through bypass diodes	Thermal fatigue associated with the bypass diodes is sometimes observed; application of current flow through the diodes will increase probability of detecting a problem
IEC 62892	2018	Extended thermal cycling	Provides greater confidence, especially for locations that experience more thermal fatigue
IEC 61730-1 amendment	2018	Allow for insulation thickness to be determined by distance-through-insulation test of 62788-2 or MST-04	Ensures required minimum insulation thickness after lamination
		Addition of weathering requirement for relied-upon insulation	The current test only tests safety of initial conditions; this change gives confidence in safety after weathering
IEC 61730-2	2018	How to deal with bubbles, in particular for a module with a cemented joint	Ensures that reduction in distance between edge of module and active cells is still safe
IEC 62788 (Materials Testing)	2018-2020	62788-1: Encapsulants 62788-2: Frontsheets/backsheets 62788-5: Edge seal 62788-6: Multiple component tests 62788-7: Component weathering exposures	Facilitates comparison of candidate materials for use in PV modules and for quality control of incoming materials
IEC TS 63126	2019	Defines modifications to module qualification tests for modules that will operate at higher temperatures	Useful for modules that will be deployed in the hottest locations and applications
IEC 62093	2019	Updates qualification test for inverters to reflect years of experience	Identify problems with inverter designs
IEC TS 63157	2019	Guideline to improve quality control of power electronics manufacturing	Improve quality of power electronics
IEC TS 63140	2019	Partial shade endurance test	Quantifies permanent changes after part of the module is shaded
IEC 62759-2	2020	Test ability of modules to withstand stresses applied during installation	Rough handling of modules during installation (or walking on after installation) can cause cracks or other damage
Not assigned	2022	Various forms of BIPV will be considered by a single project team	BIPV applications are growing and more comprehensive standards will support growth
TS Extended-stress test	2020	Apply longer stress, periodically reporting changes	Provides additional information about module durability to be analyzed as discussed here

The strategy starts with accelerated tests standardized as qualification tests that quickly identify design problems for the intended application. In manufacturing and installation, the initial qualification testing must be coupled with robust quality assurance programs such as described by IEC TS 62941 and IEC TS 63049. Not only should incoming materials/components be tested, but smart sampling should be used to select finished product from all manufacturing lines and shifts to confirm uniform and appropriate production; during installation, systematic inspections should confirm that all crews have appropriate training and oversight. Qualification tests should be updated to reflect failures observed in the field and should provide options for testing to multiple levels of stress when that is shown to be useful, e.g. for varying snow loads and system voltages.

Building on the tests used for qualification testing and based on experience obtained during deployment of many GWs of PV, standardized extended-stress tests should be developed, widely used, well documented, and well understood. Such testing provides a means to compare different versions of products to facilitate improvements of the bill of materials and other aspects of the products. Standardization and openness of such data collection will facilitate scientific analysis, by leveraging data from the broader community to identify test results that do or do not correlate with field problems in the application of interest. The extended tests should be designed to cost-effectively apply relevant stresses, testing to failure when the added cost is acceptable, and providing preventative measures to reduce technical risks in investments. Predictive models based on a detailed understanding of relevant failure mechanisms can then be applied to both the extended-test and field data to assess the accuracy of the models, identify indications of product weakness that may be relevant to the intended application, and to estimate the uncertainty associated with the risk assessment.

The final risk assessment should use all available data (published in the literature, as well as collected for the product of interest) to facilitate estimation of the anticipated return on investment (ROI) and the associated risk that the ROI may be less. This estimation process will need to include not only an understanding of the physics of failure, but the variability in the manufacturing, installation and maintenance in order to assess the timing, consequence and scale of possible failures and degradation. Many details must be understood to provide the best risk assessments; by pooling data and coordinating studies to better understand failure and degradation, the community will be able to accelerate progress toward the end goal of low-uncertainty predictions.

Standardized qualification and extended-stress testing can play an important role in accelerating this progress. Recent and planned progress in new standards is summarized in section 4.

6 REFERENCES

[1] D. C. Jordan, S. R. Kurtz, K. VanSant, and J. Newmiller, Progress in Photovoltaics: Research and Applications 24 (2016) 978.

[2] U. Jahn and W. Nasse, Progress in Photovoltaics: Research and applications 12 (2004) 441.

[3] D. Jordan and S. Kurtz, 29th European PV Solar Energy Conference and Exhibition, (2014).

[4] IEC 61215 Terrestrial photovoltaic (PV) modules - Design qualification and type approval, 2016.

[5] IEC 61730-1 Photovoltaic (PV) module safety qualification, 2016.

[6] IEC/TS 62941 Guideline for increased confidence in PV module design qualification and type approval, 2016.

[7] U. Jahn, M. Herz, E. Ndrio, E. Janknecht, D. Moser, G. Belluardo, et al., Solar Bankability WP1 Deliverable D 1.

[8] S. M. Shrestha, J. K. Mallineni, K. R. Yedidi, B. Knisely, S. Tatapudi, J. Kuitche, et al., IEEE Journal of Photovoltaics 5 (2015) 174.

[9] D. Cunningham, B. Jaeckel, and A. Roth, PV Module Reliability Workshop, Golden, CO, (2012).

[10] B. Jaeckel, A. Krtschil, D. Cunningham, N. Forney, C. LaMothe, A. Nguyen, et al., Proceedings 26th European Photovoltaic Solar Energy Conference, Hamburg, (2011) 4AV.2.1 3484.

[11] A. Funcell, PV Module Reliability Workshop, Golden, CO, (2012).

[12] J. Meydbray, PV Module Reliability Workshop, Golden, CO, (2012).

[13] D. Meakin, PV Module Reliability Workshop, Golden, CO, (2012).

[14] P. Hacke, K. Terwilliger, S. Glick, R. Smith, G. Perrin, S. Kurtz, et al., Proceedings 40th IEEE Photovoltaic Specialist Conference, (2014) 930.

[15] G. TamizhMani, PV Module Reliability Workshop, Golden, CO, (2012).

[16] "Introducing 'Best of modules' Quality assurance," PV Magazine, 2011 (2011) 92.

[17] K. P. Scott and A. Zielnik, PV Module Reliability Workshop, Golden, CO, (2012).

[18] A. Zielnik, "PV Durability and Reliability Issues," Photovoltaics World, Nov/Dec (2009) 10. http://www.renewableenergyworld.com/rea/news/article/2009/12/pv-durability-and-reliability-issues

[19] J. Wohlgemuth and S. Kurtz, Proceedings 40th IEEE Photovoltaic Specialist Conference, (2014) 3589.

[20] G. Kelly, A. Häring, T. Spooner, G. Ball, S. Kurtz, M. Heinze, et al., Proceedings 43rd IEEE Photovoltaic Specialists Conference, (2016) 1264.

[21] S. Kurtz, T. Sample, J. Wohlgemuth, W. Zhou, N. Bosco, J. Althaus, et al., Proceedings 42nd IEEE Photovoltaic Specialists Conference, (2015).

[22] G. Ramu, M. Yamamichi, W. Zhou, A. Mikonowicz, S. Lokanath, Y. Eguchi, et al., "Updated Proposal for a Guide for Quality Management Systems for PV Manufacturing. Supplemental Requirements to ISO 9001-2008," Technical Report No. NREL/TP--5J00-63742, National Renewable Energy Laboratory, Golden, CO (United States) (2015).

[23] Y. Eguchi, G. Ramu, S. V. Lokanath, M. Yamamichi, S. Kurtz, J. Wohlgemuth, et al., Proceedings 40th IEEE Photovoltaic Specialists Conference, (2014) 3574.