

The Importance of PV Module Reliability Research In South Africa

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Abstract

This paper will introduce the new C450 international standard for PV module quality assurance programs. Quality assurance testing has been on the rise in the PV industry following the rise in development of large scale PV plants, sometimes under the name of “reliability” test programs or “bankability” studies. The test programs are largely based on published International Electrotechnical Commission (IEC) standards for PV module design certification and safety testing. The Council for Scientific and Industrial Research’s Energy Centre (CSIR-EC) in support from its Technology Localization and Implementation Unit (TLIU) is constructing a solar PV module reliability research and testing laboratory at its Pretoria campus to support the growing South African renewable energy market, mainly focussing PV module reliability and quality assurance testing. PV module reliability issues impact degradation rates, future energy production of PV plants, and ultimately the Levelized Cost of Energy (LCOE) paid over the lifetime of a PV system. The LCOE from the CSIR’s 558kW DC single-axis tracker plant would increase from 0.83 Rand/kWh to 0.90 Rand/kWh if the PV module degradation increases to 1.6% per year from the predicted 0.8% per year. The CSIR reliability laboratory supports the decisions made by project developers, installers, contractors, owners and investors that will ultimately lead to more reliable, lower PV generation costs for South African consumers by reducing the risk associated with PV module quality and reliability.

Keywords: Quality; Reliability; LCOE; IEC; C450; Quality Assurance Program

1. Introduction

Reliability research and testing has been an integral part of product development and ongoing quality for a broad range of products used in our everyday lives: cars, computers, mobile phones, and household appliances. When we think of the brand name products we rely on in our lives, we have a sense of a range

in quality that we might expect from one brand to the next.

Reliability research and testing of PV modules is no exception. However, the quality and reliability of a PV module is difficult for the average consumer (residential, commercial, or utility) to judge based on experience. Consumers are simply not exposed to many brands of PV modules, if any at all, so it’s difficult to compare experiences encountered with different consumers. Furthermore, PV modules are designed to last up to 25 years, so any differences with quality and reliability amongst various brands will take years in the field to reveal.

The CSIR is establishing a solar PV module reliability research and testing laboratory that will include, but not limited to, a state-of-the-art solar simulator, environmental chambers, and dynamic mechanical load tester. The lab will be used to support the CSIR Energy Centre’s research agenda, which includes quality assurance testing of PV modules based on the latest international standards and support for the development of local standards.

2. Reliability Statistics

2.1 Weibull Distribution

In 1939, Waloddi Weibull introduced a statistical model to characterize the strength of materials as a better descriptor of material properties than a single value for strength [1]. Mr. Weibull was a contemporary of many famous contributors in the emerging field of quality and reliability science: Walter A Shewhart, Sir Ronald Fisher, Kaoru Ishikawa, and Dr. Edwards Deming to name a few. The Weibull distribution has since become an important model in reliability statistics as it can be applied to many different lifetime datasets depending on the estimates of shape and scale parameters from the data. By comparison, the Normal distribution also has two unknown but estimable parameters, the location and the scale parameters, estimated by the sample mean and sample standard deviation to best fit the data, yet it only takes on one familiar shape. The two parameters of the Weibull are estimated from a sample of lifetime data for a given product, just as the mean and sample

standard deviation are used to fit a Normal distribution. Once the lifetime data is acquired, the process of estimating the unknown parameters and fitting the Weibull is straight forward with many software packages. Figure 1 shows three distinct forms of the Weibull distribution, depending on the shape parameter k , given a scale parameter $\lambda = 1$, as presented on the Weibull Distribution Wikipedia page [2].

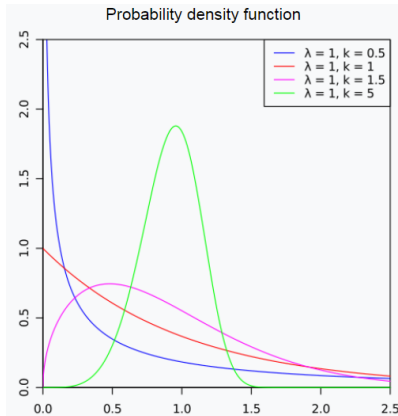


Figure 1. Examples of the Weibull distribution [2]

2.2 Bathtub curve

The Bathtub curve is used in reliability engineering to describe the failure rates of a product over the full lifetime. Figure 2 shows the bathtub curve and the three distinct phases of product reliability: infant mortality, constant, and wear out failures, as presented on the Bathtub Curve Wikipedia page [3]. The Bathtub curve can be modelled with three different Weibull distributions fit to sample data, depending the stage in a product lifetime. For instance, the Infant Mortality Failure rate can be modelled by a Weibull with shape parameter $k = 0.5$. The Wear Out Failure rate can be modelled by the Weibull with shape parameter $k=5$ and location parameter $\lambda=5$ that shifts the distribution to the right. The combined Weibull distributions take the shape of the bathtub curve popularized in reliability engineering. The terms “Infant Mortality” and “Wear Out Failures” are often used in the discussions on PV module reliability, as well.

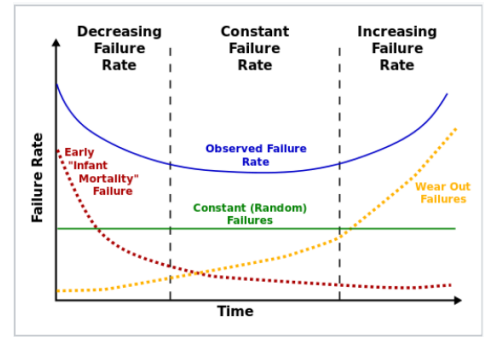


Figure 2. The “Bathtub Curve” [3]

2.2 From outdoor performance monitoring to indoor accelerated stress tests

Lifetime data for PV modules is needed to fit a Weibull distribution, and that data naturally comes from field performance data. Early failures can be modelled as infant mortality failures. However, data on constant failure rates and wear out failure rates can take decades to collect given the typically robust performance of PV modules in the field. Furthermore, PV modules rarely fail completely. According to a 2014 study of 50,000 PV systems installed in the USA, modules were rarely reported as the root cause of hardware failures in the field [4], at least for the first few years of plant lifetime analysed. Module performance does degrade over time, and that has a significant impact on the Levelized Cost of Electricity (LCOE) for those systems. Figure 3 shows the published degradation rates of 2128 PV systems in the United States compiled in a literature review by the National Renewable Energy Lab (NREL) located in the United States [5]. PV module degradation rates from this study averaged 0.8% per year, but some plants reported higher than 3% per year.

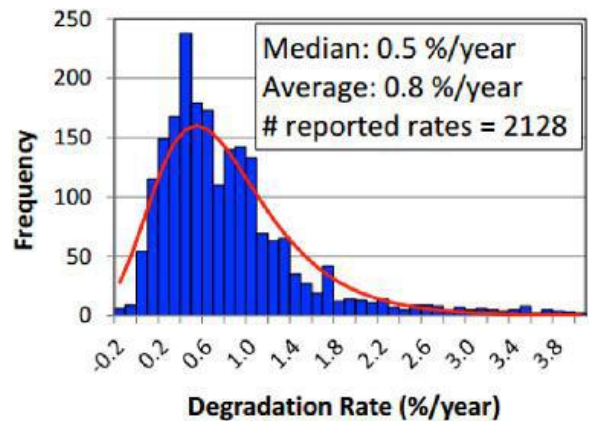


Figure 3. Distribution of annual degradation rates for PV modules [5]

The PV industry is using extended accelerated stress testing of PV modules based on existing design qualification test protocols as a surrogate for product lifetime prediction and field

degradation rates to compare different manufacturers, models, and bill of materials (BOMs). The approach is sometimes referred to as a bankability study, a quality assurance program, or even a “bake-off”, but they are all referring to the same idea. For example, Wells Fargo Bank has financed more than 1 GW of PV projects, and extended accelerated stress testing is typically required in order to reduce risk [6]. The following section will outline some key milestones in the history and development of PV module design qualification and extended reliability testing.

3. A Brief History of PV Module Stress Testing

3.1. JPL Block Buys

In the mid-1970s, the Jet Propulsion Lab (JPL) in the USA initiated a quality assurance program for terrestrial PV modules based on NASA tests for space arrays [7]. In Table 1, Kurtz et al highlight the changes from Block IV to Block V and the correlation to field failure rates observed in PV modules purchased in each block. Tougher qualification testing based on indoor accelerated stress tests lead to a more reliable PV module in the field.

Test	Block IV	Block V
Thermal Cycling	50 cycles (-40 to +90°C)	200 cycles (-40 to +90°C)
Humidity (Freeze)	5 cycles 54°C/90%RH to -23°C	10 cycles 85°C/85%RH to -40°C
Hot Spots	None	3 cells, 100 h
Mechanical Load	10,000 cycles, ± 2400 Pa	10,000 cycles, ± 2400 Pa
Hail	9 impacts 20 mm @ 20 m/s	10 impacts 25 mm @ 23 m/s
Electrical Isolation	<50 µA @ 1500 V	<50 µA @ 2*Vs+1000
Reported Field Failures	>50% [13]	~ 1% [13]

Table 1. Changes in the qualification test protocol for JPL block buys in the 1970s [7]

In 1980, similar testing on terrestrial PV modules began at the European Solar Test Installation. Early results from the 1990s showed failure rates on PV modules were 4 to 5 time higher under accelerated indoor stress testing compared with light exposure tests [8]. The accelerated stress test protocols aim to strike the right balance so as to provoke typical field failures on sub-standard modules without provoking faults that would otherwise not occur under the real-world conditions over time on good quality modules. These efforts contributed to the process that eventually led to publication of the international standard IEC 61215 design qualification for PV modules [9]. Over the decades that followed, additional standards were developed and published for the qualification of thin film modules and concentrated photo voltaic modules (CPV). A series of safety testing standards were developed and published, as well as standards for more specific tests such as Potential Induced Degradation [10] and Dynamical Mechanical Load tests [11]. In 2016, a number of the existing IEC standards for PV module

design qualification were updated and combined under the new IEC series beginning with IEC 61215-1 [12].

Continuous effort to develop and implement design qualification and safety testing for PV modules over the decades has played an important role in the success of the global PV module market. Design qualification helps keep sub-standard products from entering the market, thereby reducing infant mortality field failures, and enhancing the “bankability” of PV projects.

3.2. Private protocols for quality and reliability testing

Several test protocols have been developed over the years to fill a gap between PV module design qualification and long-term reliability of specific PV module types [7]. The long-term quality and reliability of the majority of PV modules contributes to low LCOEs from PV power plants that are now competitive with conventional sources of electricity in many markets across the globe. While the population reliability statistics of PV plants is encouraging for the industry, individual projects still experience module quality issues [13]. The quality and reliability test protocols serve to minimize the risk for the individual project by differentiating specific PV module models and specific bills of materials within those models by monitoring performance and safety issues that result from extended indoor stress testing.

Table 2 provides a high level comparison of several quality and reliability testing protocols [7]. The tests listed include Damp Heat (DH), Thermal Cycling (TC), Dynamic Mechanical Load (DML), Damp Heat with bias (DHWB), Humidity Freeze (HF), Hotspot (HS), and Ultra Violet (UV). The indexed references in the first column can be found in the original 2013 paper by Kurtz et al. The Weather test combines multiple environmental factors at the same time in a highly specialized piece of test equipment. The test protocols were presented and discussed during the NREL PV Module Reliability Workshop in 2012 [14].

Program Name	Extra Test Sequences*	Key Features	Test Length (Months)**
Holistic QA [15,16]	DH, TC, DML	Extended 61215	~4
Thresher [17]	DHWB, TC, HF	Document degradation after each test cycle	~6
Reliability Demonstration [18]	DHWB, HS	Comprehensive	~6
Durability Initiative [19]	DHWB, Outdoor, UV, HS, DML, TC	Durability assessment	~6+
Test to Failure [20,21]	DHWB, TC	Test to failure	>12
Long-Term Sequential [22]	UV, DH, TC, HF	Sequential (pass-fail)	~12+
PV+Test [23]	DHWB, TC, ML	Assign rating	~4
Weather [24,25]	Multiple***	Simulates weather	~12

Table 2. A sample of extended reliability test protocols [7]

These test protocols serve to differentiate PV modules with respect to their ability to withstand accelerated stress tests that have been designed to provoke known field failures. Figure 4 illustrates many of the common failures known to occur in the field over the lifetime of a PV module [13]. The indoor test data provide critical information to EPCs, owners, and financiers

to help reduce the risk of typical field failures when selecting PV modules for a specific project.

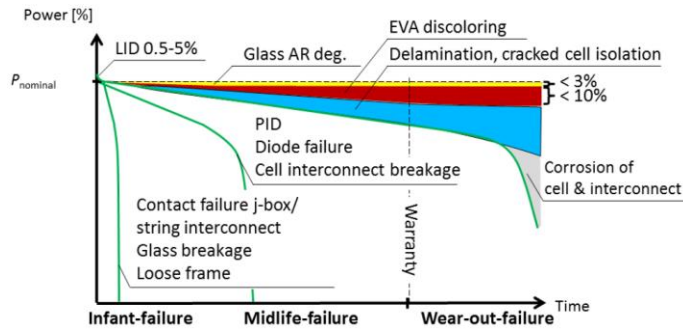


Figure 4. Typical PV module failure modes versus time [13]

In recent years, DNV GL has published their PV module scorecard [15] and Fraunhofer ISE has published their PVDI test results [16]. Both protocols are included in Table 2 above. The results from these tests serve to highlight the importance of quality assurance for the stakeholders. Clearly, some PV modules perform better than others in comparative accelerated stress tests, and downstream clients can use this information to make their decisions about which modules to buy and what price to pay per watt given the results.

3.3 PV Qualification Plus Testing

In 2013, a committee lead by NREL researchers published a test protocol known as PV Qualification Plus [7]. The test protocol was based on the best known science linking laboratory tests to known field failures. The motivation of the test protocol was to forge a link between lab tests and warranty periods. LCOE is dependent on PV system components meeting warranty projections, although warranty claims can be difficult to fulfil in practice. The test protocol serves as a check against the warranty before the modules are deployed in the field. Table 3 describes some of the new tests proposed in Qualification Plus for crystalline silicon PV modules with glass-cell-polymer backsheets construction. Five PV modules are subjected to each of the following test sequences: 500 thermal cycles with weight, UV/DML/TC50/HF10, Hot spot, and Potential Induced Degradation (PID). Damp heat testing per IEC design qualification tests was not included in the protocol.

Module Tests		
1. Thermal cycling	Solder bond or ribbon failure, usually associated with thermal fatigue	This is an extension of IEC 61215. Thermal cycling is known to identify this failure; field and modeling studies imply that longer testing may be beneficial.
2. Dynamic mechanical load (DML)	Cracked cells that cause hot spots and power loss	IEC 62782. Studies have shown that the combination of DML and thermal cycling can uncover this failure.
3. Enhanced hot spot test	Localized heating from partial shading conditions	ASTM E2481-06
4. System voltage (potential-induced degradation)	Power loss for modules operating at large (positive or negative) bias voltage	Test method: IEC 62804; Pass criteria: studies correlating test with field results.

Table 3. Qualification Plus tests for PV modules [7]

PV Qualification Plus also emphasizes the importance of conducting a quality audit of the factory and the importance of proper sampling procedures for the qualification plus testing. The testing must be conducted on a set of modules that is representative of the modules to be deployed. Manufacturers often use different components in the construction of modules with the same make and model ID, especially when large quantities of modules are deployed. For example, modules with the same nameplate label can have different encapsulant, cell, and glass suppliers. The bill of materials (BOMs) may or may not have passed a review for design qualification approval by the certifying body, and it may have passed additional tests based on retest guidelines. However, the interaction of new components can have unintended consequences in the field over time. Quality and reliability testing provides a means to reduce risk when the modules tested are randomly sampled from the population of modules that will be used in the project.

4. C450 Quality Assurance Program

In April 2018, the CSA C450 international standard for PV module quality assurance testing was released for public review, after one year of development within a committee that included both public and private sector players across a broad range of the PV value chain [17]. The standard is intended to provide a uniform set of tests built upon the IEC qualification tests, the NREL Qualification Plus protocol, and the private sector so that extended reliability testing can be conducted in a standardized way across the globe. With the introduction of this standard, redundant testing can be minimized and test results from many different sources can be compared, both of which enhance the value of extended reliability testing for PV industry. The quality assurance test protocol requires a large investment in time and money, so the ability to re-use and compare test results is critical.

Figure 3 shows the testing protocol for C450 in detail, and Figure 4 defines the characterization steps conducted at various stages within the stress testing protocol. Each block in the protocol provides a reference to the latest, published IEC 61215 standard, so that the C450 will keep up to date as those IEC standards are updated. The test sequences bear a strong resemblance to the IEC test protocols by design, as those standards represent the common consensus among the global experts in the field.

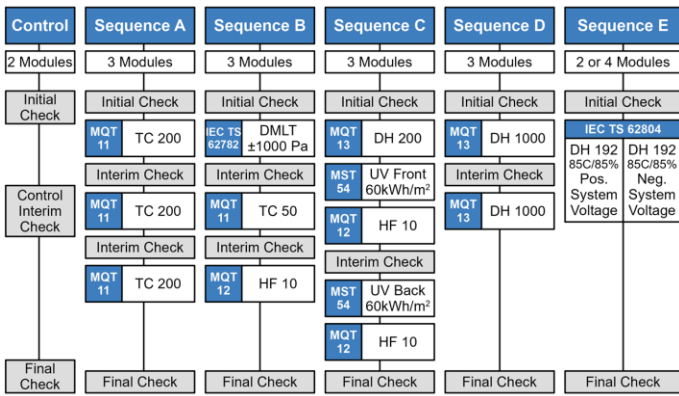


Figure 5. EXP C450 test protocol [17]

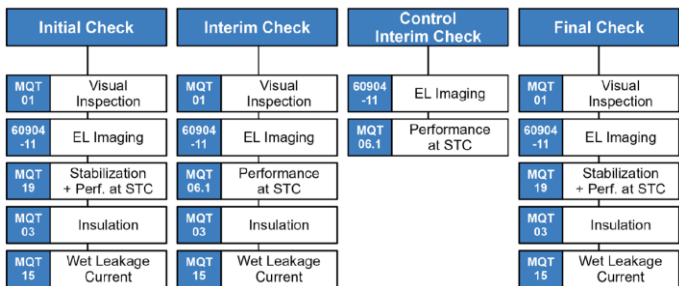


Figure 6. EXP C450 characterization steps [17]

The C450 test protocol is meant to be used for comparative testing of existing modules on the market, different BOMs, different production plants, etc. The test protocol specifications are clear and are easy to follow so that it can be implemented uniformly across the industry. However, the results cannot be used to make a scientific prediction regarding lifetime or degradation rates of modules in the field.

5. LCOE and PV Module Degradation

Reliability matters when quantifying LCOE. Energy generation over the lifetime of a plant is effected by many factors, including PV module degradation rates. While C450 does not purport to estimate degradation rates in the field, it does provide a standardized platform to compare degradation in performance for different PV modules subjected to simulated stresses designed to provoke typical field failures. Thus, there is some logic in selecting PV modules that perform well under these stress tests in order to minimize the risk of infant mortality failure and/or excessive degradation rates in the field. The quality assurance testing protocol is designed to provoke these failures in sub-standard modules.

Figure 7 shows one potential pathway to achieving utility scale solar LCOE of 0.03 USD / kWh by 2030 [18]. In this scenario,

PV module degradation rates must decrease to 0.2% p.a., accounting for over 25% of the improvements towards reaching the 2030 cost goal. Quality assurance testing of modules will help to ensure that only high quality modules are installed, reducing risk to investors and reducing LCOE.

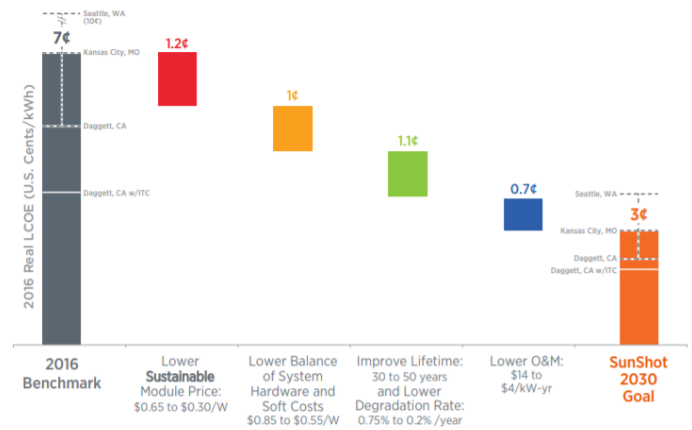


Figure 7. US DOE Sunshot Initiative potential pathway to reduce LCOE for utility scale PV plants [18]

Figure 8 shows the effect of PV module degradation rate on the LCOE from the CSIR's 558 kW DC single-axis tracker PV plant. During the initial LCOE model of the plant, a PV module degradation rate of 0.8% p.a. was assumed, which is consistent with the average PV module degradation rate reported by Jordan above. The model predicted an LCOE of 0.84 Rand / kWh over the lifetime of the plant. Predicted LCOE for the same plant varies from 0.79 Rand/kWh to 0.95 Rand/kWh when PV module degradation rates vary from 0.4% p.a. to 2% p.a., all other modelling assumptions remaining constant. That is a 19% range in LCOE relative to the initial LCOE, depending on the actual degradation rate, clearly illustrating the importance of selecting higher quality modules with low degradation rates.

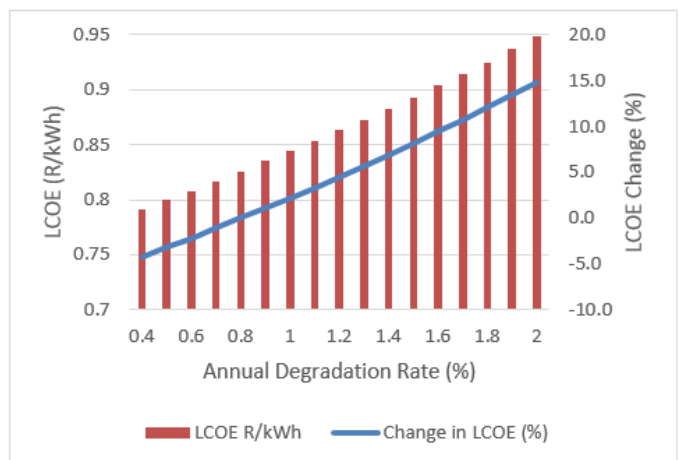


Figure 8. LCOE versus PV module degradation rate relative to 0.8 % p.a.

6. Conclusion

The CSA C450 PV Module Testing Protocol for Quality Assurance Programs is the first international standard to be published on extended reliability testing of PV modules, beyond certification. The protocol is built upon a long history of published IEC standards for PV module design qualification and other targeted reliability tests published under the IEC scheme. The CSIR Energy Centre is implementing all the necessary equipment and procedures to conduct this test protocol for the benefit of the PV industry in South African and the Sub-Saharan region. The goal of quality assurance testing of PV modules at the CSIR is to minimize PV module quality and reliability issues in the region, support consumers, and partner with key stakeholders to ensure LCOE projections are met.

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