Achieving Increased Reliability in Photovoltaic Installations

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Photovoltaic (PV) module manufacturers, installers and project owners share a common interest in the long-term performance of PV installations. In evaluating the reliability of a PV system, it is important to focus not just on the PV module but on the entire system. An installed PV system can provide the expected level of service only if all of its components, from the solar cell to the connection to high voltage transmission line, perform as expected, and if the entire PV system is properly maintained.

Specific properties of PV system installation sites, such as ambient conditions, equipment temperatures, soiling and contamination can also have a direct impact on the performance and expected life of a given installation, and can contribute to different site-specific degradation rates. In addition, the ongoing consolidation of the PV industry may result in the demise of some manufacturers, undercutting the potential benefits of manufacturers' warranties. To avoid these problems, PV manufacturers should adopt a holistic quality control protocol to address key issues such as sampling rates, test plans and test durations.

This UL white paper discusses various testing methods that can be used by manufacturers and customers to assess the reliability of PV modules in real world conditions. The white paper begins by reviewing the importance of both module durability and reliability in PV system performance, and discusses the drawbacks of theoretical models of life expectancy in assessing module reliability. The white paper then presents a framework for assessing module PV reliability, and illustrates how three different tests can provide meaningful module reliability data in the context of an ongoing quality inspection program.

Theoretical Approaches to Estimating Service Life

The task of modelling the lifetime or lifetime cycles of PV modules is based on a number of assumptions. These assumptions are combined with lab-measured data and, to some extent, information from field experience and product returns from the field. However, the photovoltaic industry is relatively new, rapidly changing and focused on increased efficiency, i.e., higher efficient cells, new materials, new designs, etc. In contrast, PV lifetime expectations can range from 20 to 30 years. These factors significantly limit the availability and value of data that can be used today to predict expected PV service life.

In order to answer important questions regarding PV modules' service life, accelerated aging test protocols are often used. From these tests, activation energy (Ea) can be determined by using an Arrhenius-approach. Typically Ea measurements for temperature, humidity and ultraviolet (UV) are identified and used for first life time prediction calculations. [1,2,3,4] Eas, combined with local weather data, provide the basis for those calculations of an anticipated service life.

However, the basic problem with this approach is that it relies on the triggering of a single failure mechanism only. In reality, a combination of different concurrent degradation mechanisms occurs, along with random and location-specific weather-related events (wind, wind gusts, storms, snow, ice and hail) that are nearly impossible to predict.

Figure 1 illustrates different observed power loss curves for an assortment of PV modules (dotted lines), together with possible step-warranty curves (blue and orange lines). The green and red curves shown are arbitrarily-combined degradation curves, with each curve the result of three separate factors. The key question posed in this illustration is which of the two step-warranty curves (the orange or the blue) more closely aligns with actual lifetime performance.

To improve on the theoretical approach for estimating PV lifetimes, it is necessary to understand the interaction between various environmental conditions and the observed impact that each of these conditions has on PV modules. This requires the collection of performance data from various locations, and an analysis of the data to determine possible root causes for failures. Table 1 lists various environmental parameters and displays some observed impacts that result in PV module failures.

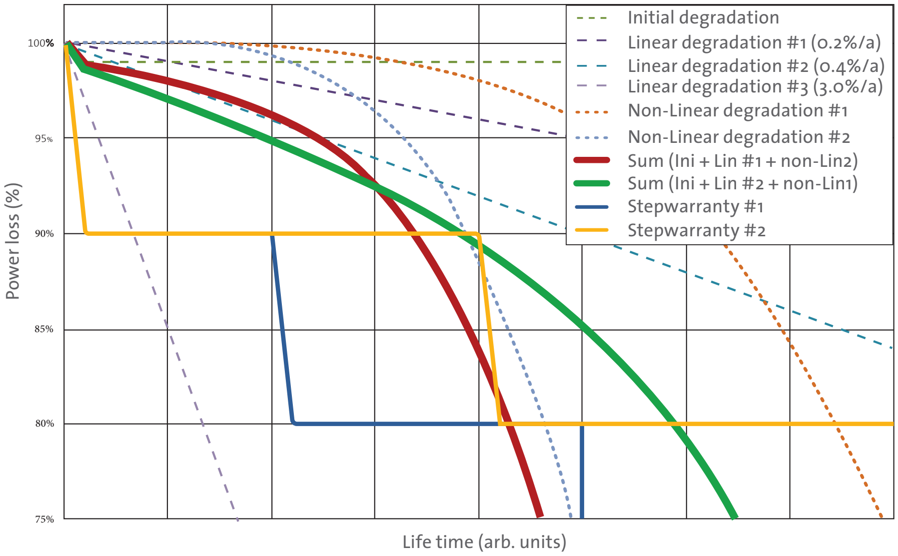

Figure 1: Various degradation rates vs. warranty promises on an arbitrary time scale

Environmental Parameter	Observed Impact on PV Modules and → consequences
Sun (UV+VIS+IR) + total irradiance	• Discoloration (→yellowing)→ reduced power output and • increased brittleness (cracking of e.g. backsheet) → ingress of moisture → faster degradation of cell materials → reduced power output and safety issues
Humidity	Any kind of corrosion inside and outside of the module: • Glass corrosion → reduced power output and • cell material corrosion (interconnection corrosion, solar cell degradation)→ reduced power output and • humidity caused decomposition of encapsulants (hydrolysis) and backsheets, sealants) → reduced power output and • metallic parts, like frame → safety issue, if grounding/bonding is no longer ensured
Temperature	• Impact of different thermal expansion coefficient (cracks, grid-fingers interruptions, opening of soldering points), • Temperature driven degradation / decomposition / cracking rates of encapsulants / backsheets / glasses and other components → reduced power output and safety issues
Wind	Any kind of mechanical fatigue: • cell and solder bond breakage • vibrations that damage underlying construction • glass breakage and more → reduced power output and safety issues
Snow / Ice	• Cell breakage, • bending of framing parts due to icing and • glass breakage → reduced power output and safety issues safe
Voltages	Potential induced diffusion of ions that can cause degradation of module performance: • PID and • electro-chemical corrosion → reduced power output and safety issues
Currents	• Corrosion/aging of cell and interconnects inside the module, but also • connectors/cables between individual cells, combiner boxes and converters → reduced power output and safety issues due to e.g. arcing
Soiling	Moss, sand, leafs, soil, dung → degrading light transmittance, can increase moisture inside the module → reduced power output and safety issues
Atmospheric conditions	Salt, any air pollution: • Ammonia • Sulfur related acids (H_2S, H_2SO_4, etc.) • Ozone

Table 1: List of environmental parameters and observed impacts on PV modules

Addressing Reliability

The durability of a PV module is a byproduct of its design. PV module reliability, on the other hand, is dependent on the quality and integrity of the process used to manufacture the module. Even small variations in material quality or manufacturing processes can impact the reliability of a component.

Testing and certification of a PV module to the requirements of a given standard typically focuses on verifying that the fundamental design requirements have been fulfilled. A different battery of long-term stress tests and test-to-fail protocols have been proposed to verify the durability of PV modules.[5, 6, 7] It is often assumed that such long-term testing also assesses the reliability of a PV module, but reliability testing verifies that a product has been consistently produced within the original design parameters. Reliability testing increases confidence in production quality, and usually takes less time and costs less than durability tests.

To be effective, reliability testing requires checking more than just one or two samples. An industry-based standard, such as ISO 2859-1,[8] can provide guidance on how to select and evaluate production samples, as well as the criteria that can be used to determine whether a batch of tested products should be accepted. Based on an actual history of sample acceptance and rejection, a more or less stringent sampling plan can be used.

However, given their importance in the reliable operation of PV systems, more sophisticated quality checks are necessary when it comes to PV modules. Table 2 illustrates the range of tests in ISO 2859-1, including:

- Number of samples to be evaluated by inspection level (S1-S4 and G1-G3) and the size of the PV project
- Acceptance quality level (AQL)
- Allowed percentage of failed samples

The number of samples to be evaluated assumes a statistical distribution of product variations. The AQL defines the confidence in accepting or rejecting a given batch of samples. For some critical tests like safety, a low AQL (such as 0.1, for example) would signify no tolerance for failures (zero-failure tolerance). In other tests, such as those used to assess visual defects like misaligned cells, higher AQLs may be acceptable. Industry standards often provide baseline pass/fail

TEST	Inspection level	Number of modules for testing	AQL (% non conforming items)					
			0.1	0.15	0.25	0.40	0.65	1.0
10.1. Visual inspection	G-1	a) 80 b) 200 c) 315	0	a) 0 b) 0 c) 1	a) 0 b) 1 c) 2	a) 0 b) 2 c) 3	a) 1 b) 3 c) 5	a) 2 b) 5 c) 7
10.2. Flash-Test (STC) Flash-List verification	G-1	a) 80 b) 200 c) 315	0	a) 0 b) 0 c) 1	a) 0 b) 1 c) 2	a) 0 b) 0 c) 1	a) 1 b) 3 c) 5	a) 2 b) 5 c) 7
10.7. Low-ight (200W/m^2)	S-4	a) 32 b) 80 c) 80	0	0	0	0	a) 0 b) 1 c) 1	a) 0 b) 2 c) 2
Power at different irradiance and temperatures following IEC 61853	S-2	a) 8 b) 13 c) 13	0	0	0	0	0	0
10.3. Insulation + 10.15. wet-L-Test	S-4	a) 32 b) 80 c) 80	0	0	0	0	a) 0 b) 1 c) 1	a) 0 b) 2 c) 2
EVA cross linkage Test Lamination process/materials	s-3	a) 20 b) 32 c) 32	0	0	0	0	0	0
PID- Test (Destrucative test)	s-3	a) 80 b) 200 c) 315	0	0	0	0	0	0
Electro-Luminescence Cell breakage/Defects	G-1	a) 80 b) 200 c) 315	0	a) 0 b) 0 c) 1	a) 0 b) 1 c) 2	a) 0 b) 2 c) 3	a) 1 b) 3 c) 5	a) 2 b) 5 c) 7

Table 2: Selected test suite for reliability testing

Note: The table shows proposed inspection level, number of samples required for each test and the number of module failures allowed following ISO 2859-1. Entries for “a)” refer to a 1MW plant, “b)” to a 10MW plant, and “c)” to a 50MW plant using 240W modules).[15]

Number	Type of test	Applicability	Test description
#01	PID Sequence (UL definition)	Generally for c-Si party for thin	Evaluate PV modules for stability under high potential in PV power plants.
#02	Extended Temperature Cycle (TC)	All technologies	Evaluate modules for daily temperature changes and resistance to thermal mechanical stressors using IEC/UL 61215/61646
#03	Extended Damp Heat (DH)	All technologies	Evaluate PV Modules to moisture ingress under high temperature using IEC/UL 61215?61646 Optional: applying a current
#04	Dry-Heat Testing	All technologies	Evaluate PV modules abitlity to withstand high temperature exposures (i.e. dessert applications)
#05	Sequential Testing	All technologies	Evaluate PV modules ability to withstand multiple stressors for general application use. Sequential test with damp-heat, thermal cycling and humidity freeze (cycle: DH: 100h + TC: 200 + HF:10)
#06	Salt Mist Test	All technologies	Evaluate PV modules for marine applications and corrosive enviornments utilizing IEC 61701 ed 2
#07	Ammonia Test	All technologies	Evaluate PV modules for use in agriculture applications per IEC 62716 ed 1
#08	Mechanical Load (heavy snow load testing)	All technologies	Evaluate PV modules for use in heavy snow load applicatins per IEC/UL 61215 10.16 with applied loads of 5400, 7000 and 8000 pa
#09	Mechanical fatigue Testing	All technologies	Evaluate PV module for use in high-wind redions and serves as accelerated test for mechnical fatigue (10,000 cycles). Pseudo dynamical load test with 10000cyc in analogy to IEEE/ASTM 1262, but only with positive load.
#10	Severe hail Impact testing	All technologies	Evaluate PV module for use in severe hail enviornment per IEC/UL 61215 10, 17, with ice balls of 35, 45, 55, 65 or 75 mm diameter
#11	Sand Impact test	All technologies	Evaluate PV module for dirt and sand abrasion (ie. dessert applications) Procedure is based on the following standards: NATO-AECTP 300, Methode 313, IEC 60062-2-68, IEC 61215/61646/61730
#12	Gel content	All technologies with EVA as encapsulant	Evaluation of PV module lamination stack to verify production process
#13	Electroluminescence	All technologies	Diagnostic tool for verification of cell integrity. Applied after stress tests or shipping to installation site.
#14	Infra-Red imaging	All technologies	Diagnostic tool for verification of cell integrity. Applied after stress tests or shipping to installation site.

Table 3: Overview of UL's test offerings to address quality and durability needs

criteria, and more or less strict criteria can also be applied depending on customer requirements. However, specific pass/fail criteria must be identified for each test prior to the project and its testing.

UL's own suite of test offerings include short-term quality tests as described above, as well as extended versions of each test to evaluate long-term durability or test-to-fail limits. Table 3 provides an overview and a brief description of each test as well as the PV technology to which each test is applicable.

Details of Selected Tests

The following sections discuss selected reliability tests for PV modules, and illustrate their potential value in assessing PV module reliability. It is important to note that, while these tests are not overly time-consuming or costly, they require the evaluation of a minimum number of samples in order to produce statistically significant results.

Flash test

The flash test is an efficient way to verify the output power of PV modules within a given range of uncertainty. The uncertainty is primarily driven from the spectral response of a given PV module, the used light source and general measurement uncertainties from the calibration chain. The last uncertainty is usually constant, but the first two can result in a significant impact on absolute measurements, especially for thin film technologies.

Aside from these limitations, the flash test can be used to investigate the following areas associated with module reliability:

- Determination of initial power loss resulting from preconditioning
- Production flash list verification
- Verification of name plate rating

These three factors are critical for any valid yield estimation. To achieve even greater levels of confidence in yield estimation, it is best to rely on measured data from the actual PV modules that will be used in an installation. This can be achieved by picking testing samples on site.

Depending on the absorber technology used in a given PV module, there is an initial power loss of the solar cell. The average initial degradation is typically below 1% for multi-crystalline cells, but could be as great as 5% for mono-crystalline cells. Figure 2a illustrates the potential spread in actual values of initial power loss. However, in an installation with several thousand modules, this spread is averaged out over all of the modules.

Production flash list verification is an important first step in selecting a PV module manufacturer. The production flash list verification compares the measured power output parameters from production with labeled values as well as those derived from third-party measurements. This verification validates the calibration chain of the PV module manufacturer. Flash list verifications are typically conducted on at least 20 individual modules to assure a normal distribution of defects and to lower uncertainty. Generally higher measurement uncertainties should be taken into account in cases where fewer modules are being tested.

PV modules are usually sold on the basis of their name plate rating. The Watt rating that appears on a PV module nameplate is used in conducting energy yield simulations, which means that accurate nameplates are a critical factor in achieving the energy yields predicted for a given installation. Consistent with the requirements of standards EN 50380 and UL 4730, [9, 10] the ratings that appear on name plates must account for all initial degradation or light soaking effects. Therefore, PV modules should be stabilized prior to measurement, and the measurement should be compared with the rating that appears on the name plate.

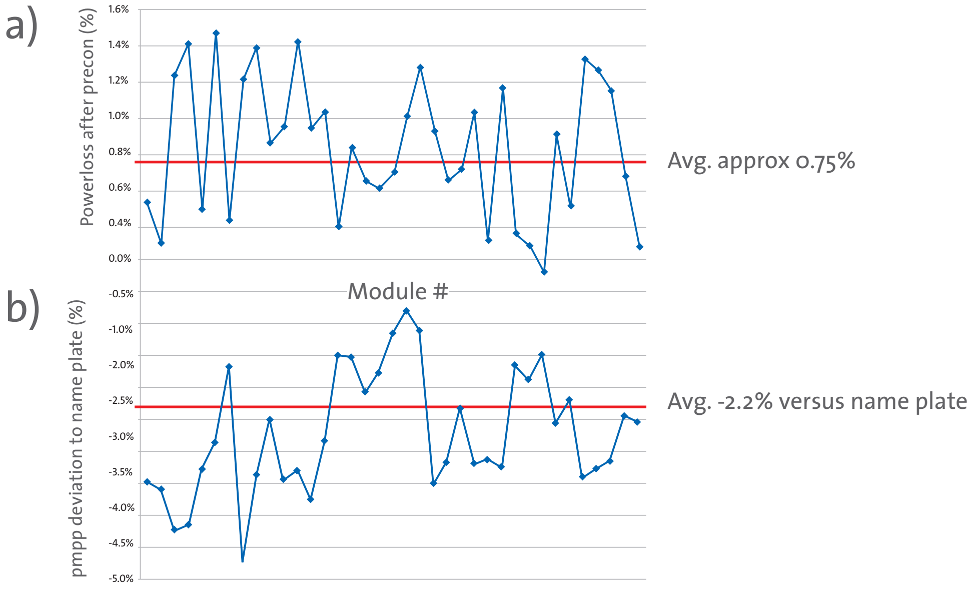

Figure 2: Example of flash test verification. a) Power loss of modules after pre-conditioning.
b) Power deviation vs. power stated on name plate.

An example of name plate rating values is illustrated in Figure 2b. In this instance, the actual power measured is about 2.2% below stated name plate rating. Such a discrepancy would likely result in a gap between anticipated and actual power output.

Electro-luminescence: Failure detection and mapping

A second evaluation method, electro-luminescence (EL) imaging, is primarily used for crystalline silicon PV modules because there is widespread acceptance of the types of module defects that are visible using this method.[11,12] There are several different types of defects that can be identified with EL imaging, each with its own root cause and performance impact. Evaluating EL images according to commonly prescribed methods can provide useful information regarding PV module reliability.

Figure 3 shows two modules, each with a different number of cracks with varying degrees of severity. Modules similar to those depicted in module #1 are usually acceptable and can reliably generate power. Modules similar to those depicted in module #2 often exhibit inactive areas after a short period of time, leading to severe power losses.

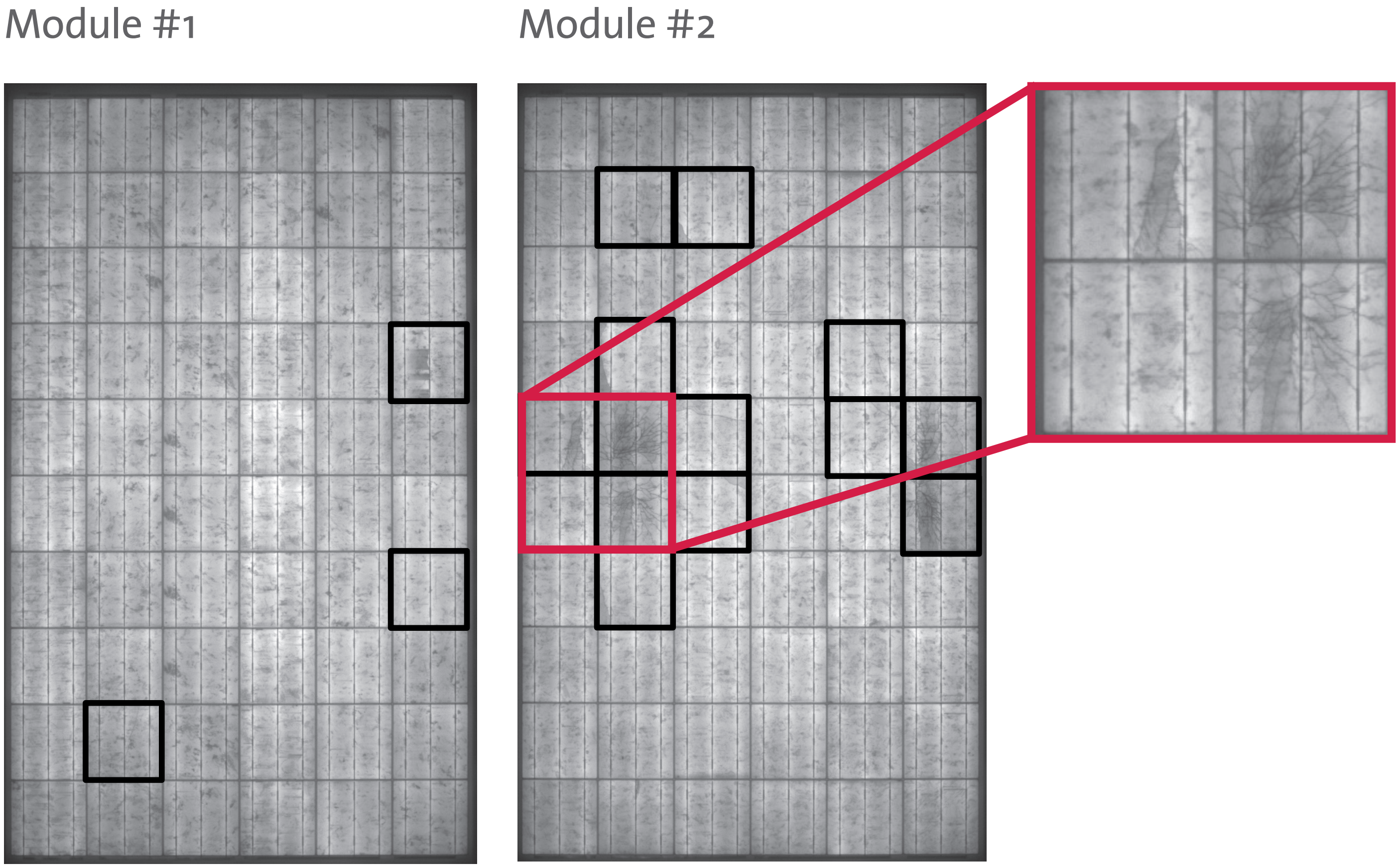

Figure 3: EL image of two modules; Module #1 shows some minor severe cracks, while module #2 shows a number of critical defects.

Shipment #1

	A	B	C	D	E	F	G	H	I	J	K	L
1	0	0	0	0	1	0	1	1	0	1	0	0
2	0	0	0	0	0	0	1	0	0	0	0	0
3	0	0	1	0	0	0	1	1	0	0	0	0
4	0	0	1	0	0	0	0	1	0	0	0	0
5	1	0	0	0	0	1	0	1	1	1	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0

Shipment #2

	A	B	C	D	E	F	G	H	I	J	K	L
1	0	0	1	0	0	0	0	0	0	0	1	0
2	1	1	0	0	2	2	0	0	3	1	0	0
3	0	0	1	0	5	0	2	3	1	3	0	0
4	0	1	2	1	3	2	3	0	5	5	2	0
5	0	1	2	3	3	2	3	2	1	8	0	1
6	0	1	0	0	0	0	0	0	0	0	0	1

Figure 4: Failure mapping using Electro-luminescence to detect production variations between shipments. Shipment #1 shows a normal, randomly distribution of some defects. In contrast, shipment #2 shows 5-times more defects with some locally very high number of defects e.g. cell J-5.

By evaluating multiple images from a single batch, it is possible to determine a general level of quality from the number and distribution of defects. An illustration of such an evaluation is presented in Figure 4. Each shipment includes the same number of modules. In shipment #1, only a few randomly distributed defects were identified, representing an acceptable result. However, in shipment #2, the number of defective modules has dramatically increased, and defects and cell cracks appear concentrated in the region I4 to J5.

Together, these observations point to a significant issue, either in the manufacturing process, the transportation of completed modules, or both. In any event, the results depicted in shipment #2 are not acceptable, and further investigation is warranted to identify root causes. Additional actions could include an EL inspection of all modules prior to installation, or more frequent inspection and testing of PV systems already in operation.

Potential Induced Degradation

At present, potential induced degradation (PID) is primarily associated with crystalline modules. Although a number of c-Si module manufacturers are now offering PV modules that are purportedly PID resistant, PID remains an unsolved problem. Efforts to address PID are further complicated by the use of different test procedures and comparability metrics, as well as a lack of data about the links between PID and recovery effects.

Unfortunately thin-film PV modules are also not always resistant to potentials versus ground. Early thin-film modules exhibited a number of problems with transparent conductive oxide (TCO) corrosion (also known as bar graph corrosion), a clearly visible defect. But today's thin-film modules can also exhibit severe PID, a condition that is not as easily detected by standard test protocols.[13]

The focus of PID testing can vary, depending on the desired outcomes. However, some options include:

- Screen PV modules for PID susceptibility
- Shipment-to-shipment verification for PID susceptibility
- Screening of module materials (cells and encapsulants)
- Standard testing conditions (STC) and low-light performance testing after PID testing

The first item on this list may seem obvious, but the additional options can provide further insights into long-term module reliability, enabling more expeditious actions to identify and address PID.

Figure 5 illustrates the results of a PID screening test of three types of modules from different manufactures. Type 1 modules show a nearly linear degradation over time with different

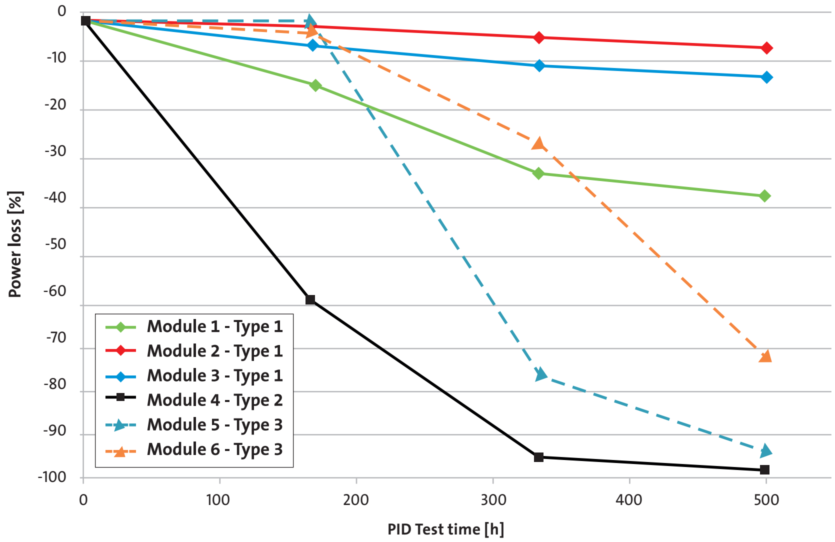

Figure 5: Survey of different modules regarding their susceptibility to PID, with three different degradation rate types

susceptibilities. The Type 2 module shown is actually an extreme case of a Type 1 module, since it quickly reaches 100% of possible degradation and cannot degrade further over time. Type 3 modules are typically stable during the first phase of the PID test, but begin to degrade quickly once they reach a certain threshold of potential application.[14] It is crucial to find out the general behavior (Type 1 or 3) under continuous laboratory voltage stress tests, but also to investigate recovery aspects of the module and possible system-related options.[16]

Since PV modules can produce such widely different results, it is important to set reasonable test parameters. Selected parameters might depend on prior knowledge of the module type or the actual scope of the test, for example, quality check or durability investigation. UL's own default test program subjects modules to system voltage for two weeks by applying the potential via a conductive foil, resulting in a homogeneous screening of the entire module and all of its solar cells. This default set of parameters can be adjusted and customized to address the specific needs of a given project.

Summary and Conclusion

In an increasingly competitive marketplace, manufacturers are expected to provide customers with PV modules that meet promised performance specifications. Consistent module reliability depends on the quality and integrity of the manufacturing process, and even small variations can adversely impact the reliability of a component and compromise PV system performance. An effective, statistically-relevant reliability testing protocol can help identify modules that fail to meet design specifications, thereby providing customers with greater assurances that expected PV system performance is actually achievable.

UL has consolidated years of PV industry research to develop proven scientific test procedures to screen PV modules for reliability, performance and safety. UL's performance and reliability services for PV modules provide third-party evidence of industry standard testing to assess consistency in the manufacturing process that also includes technical inspections of PV module factory operations. Additional tests can be conducted to demonstrate the impact of long-terms stresses on PV module performance and safety.

For additional information about UL's performance services for PV modules and systems, contact Bengt Jaeckel at Bengt.Jaeckel@ul.com, or Christopher Flueckiger at Christopher.Flueckiger@ul.com.

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