Fraunhofer PV Durability Initiative for solar modules: Part 2

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ABSTRACT

The potential for PV modules to fail before the end of their intended service life increases the perceived risk, and therefore the cost, of funding PV installations. While current IEC and UL certification testing standards for PV modules have helped to reduce the risk of early field (infant mortality) failures, they are by themselves insufficient for determining PV module service life. The goal of the Fraunhofer PV Durability Initiative is to establish a baseline PV durability assessment programme. PV modules are rated according to their likelihood of performing reliably over their expected service life. Modules are subjected to accelerated stress testing intended to reach the wear-out regime for a given set of environmental conditions. In parallel with the accelerated tests, modules are subjected to long-term outdoor exposure; the correlation between the accelerated tests and actual operation in the field is an ultimate goal of the programme. As understanding of PV module durability grows, the test protocols will be revised as necessary. The regular publication of durability ratings for leading PV modules will enable PV system developers and financiers to make informed deployment decisions. This paper provides summary data for eight module types from the two rounds of testing to date.

Introduction

Current IEC and UL certification testing is done on a pass/fail basis: assessment of the relative reliability risk, and the guidance provided to manufacturers for improvement, are therefore limited [1–5]. The tests also lack standard protocols for comparing the relative durability risks between different module designs. Without these benchmarks, financial models must instead depend on a patchwork of methods to create predictions for relative durability. This makes it difficult to quantify which solar modules are best suited to a particular installation. The uncertainty creates confusion that increases perceived risk, delays financing and ultimately raises the cost of building PV power plants.

First announced in 2011, the PV Durability Initiative is a joint venture between the Fraunhofer Institute for Solar Energy Systems ISE and the Fraunhofer Center for Sustainable Energy Systems CSE. The aim is to create an open-source durability assessment protocol that will eventually form the basis for an international industry standard. The first round of testing included five module designs [6]; data for three more module designs is reported here for the second round.

> “The accelerated test component is an extension of familiar reliability stress tests.”

The accelerated test component is an extension of familiar reliability stress tests [7–11]. Since the acceleration factors of most stress tests are not yet known, the protocol combines accelerated testing with long-term outdoor exposure testing. Until the acceleration factors for various stress tests are identified, the relative comparison of modules remains the best means of assessing (relative) module service life. To enable a comparison of different module technologies to be made, performance is converted to a rating on a scale of zero to five. The modules are rated for both performance and safety. Modules in group 1 (potential-induced degradation) are rated based on their performance at the end of the test, following light exposure. Modules in the remaining groups are rated based on their ‘weighted normalized performance’. The weighted normalized performance is a piecewise integral of their performance in each test interval, weighted by the final performance value and normalized by the initial value. Weighting by the final performance value is intended to give a higher rating to modules that show the least degradation under the tests with combined stress effects. In the years ahead, outdoor measurements of the modules under test will be used to allocate the proper acceleration factors for the accelerated test sequences.

The programme requires that, where possible, commercial modules be purchased on the open market, to avoid selection bias. If the module design is not available on the open market, the module ID label is annotated by an asterisk to indicate how the modules were acquired.

The manufacturers of modules tested in the programme have the option of withholding their identity from reports. However, the data generated remains (an anonymous) part of the dataset, for continuing comparison with the rest of the field. As the PV Durability Initiative continues, a background of prior results is available for comparison with the recent additions. Testing to this protocol has been completed in two rounds to date, on eight commercial module types. One module manufacturer has attached the identification to the results: PVDI01* is the SunPower E20 module, manufactured by SunPower, Inc.

Test sequences and results

The test protocol is broken down into five test groups (Fig. 1). A minimum of sixteen modules is currently required to complete the tests. Modules are initially characterized, then assigned to a particular test sequence. The modules assigned to the control set are stored in a temperature-controlled environment and are used to confirm the consistency of the power measurement systems. As each module progresses through its

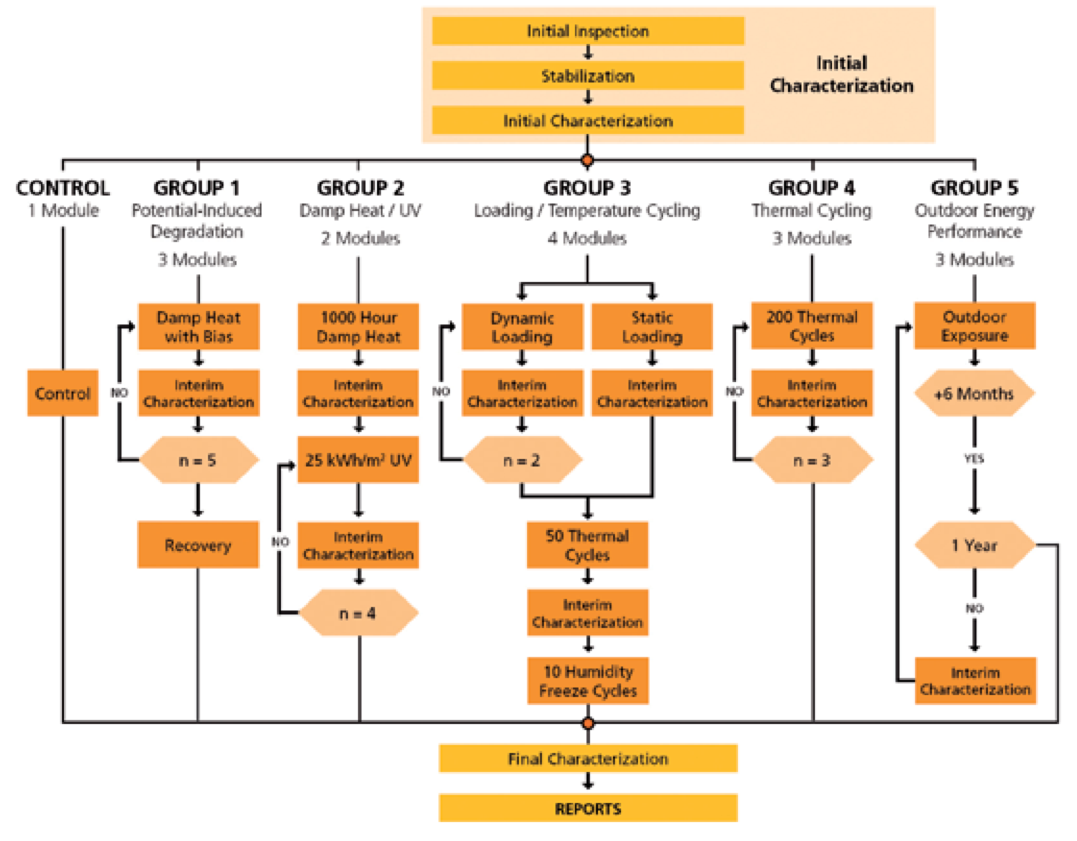
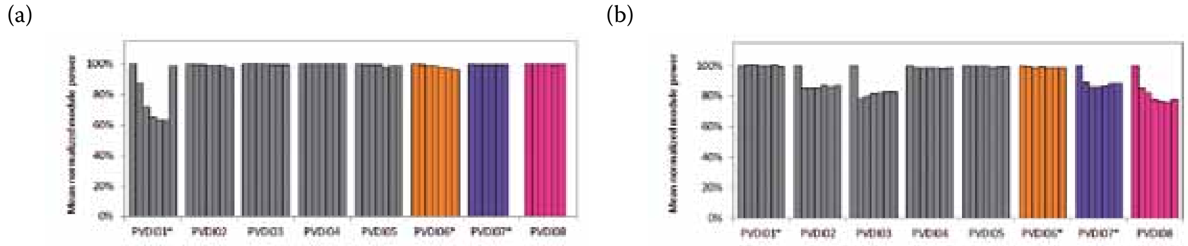


Figure 1. The PV Durability Initiative test sequences.


(a)

(b)

Figure 2. PID tests under (a) positive bias and (b) negative bias. To determine the PID rating, the final performance value after light soaking is used. If the module design was not acquired on the open market, the module ID label is annotated with an asterisk.

assigned test sequence, it is repeatedly characterized: for example, in group 4, each module is characterized after every set of two hundred thermal cycles. At each interim test point, electrical performance is determined, and electroluminescence and infrared images are collected. In some instances, wet leakage current and insulation resistance are also measured.

Initial characterization and stabilization

Commercial modules purchased on the open market arrive at the test facility in their standard shipping container and will have undergone typical shipping stresses. The modules are unpacked and visually inspected for any manufacturing defects or for damage suffered during shipping.

Following the visual inspection, the modules are light soaked to allow any light-induced degradation to occur. Light soaking requires a minimum of 60kWh/m^2, and may take upwards of 600kWh/m^2 to complete. The time to complete this pre-conditioning is technology dependent: thin-film technologies generally take longer to stabilize than crystalline or polycrystalline silicon technologies. During light soaking, the modules are maintained at their maximum power point and *I-V* curves are collected periodically. Light soaking is completed once the modules have reached a stable performance level. Stability is determined by taking measurements from three consecutive periods to see if they satisfy the condition $(P_{max}-P_{min})/P_{mean} < 2\%$.

Once stabilization is complete, the initial characterization is performed, consisting of light current-voltage (LIV) measurements at standard test conditions (STC), electroluminescence imaging, infrared imaging, and measurements of wet leakage current and insulation resistance.

The initial performance data is used throughout the test sequence to normalize successive performance measurements. It is also used in the comparative analysis of the nameplate performance ratings.

Group 1: potential-induced degradation

The group 1 test sequence is designed to assess a module's ability to perform under the stress of high electrical potential. The class of degradation mechanisms caused by a high potential between internal and external components is collectively referred to as potential-induced degradation (PID) [12,13]. Since PV modules may be installed where the electrical potential between the module and the earth ground can be positive or negative, modules are tested at both positive and negative electrical biases. The magnitude of the electrical bias during testing is set to the module's rated maximum system voltage.

The test begins by mounting the module in a vertical orientation (to reduce condensation accumulation) in a heat and humidity chamber. The electrical leads of the module are shorted together and connected to the biasing power supply. The opposite polarity of the power supply is connected through a sensing resistor to the frame of the module or to other conductive mounting points. Since the most common PID mechanisms occur under negative bias, the current procedure requires that two modules be negatively biased and one positively biased. In order to represent operating conditions, a light bias (illumination) should also be applied during voltage biasing. Since the configuration of most heat and humidity chambers precludes this, the modules are currently exposed to light soaking after heat and humidity exposure, to assess for recoverability of performance.

Depending on the module design and the failure mechanism involved, some module designs will recover their power performance when the high electrical bias is removed or reversed. Other modules have exhibited resistance to, and recovery from, PID when operated near their maximum power point under light exposure [2] or by raising the cell temperature to the normal operating cell temperature. For such modules, PID is not expected to have an impact in operation.

The results of the PID testing are summarized in Fig. 2. PVDI01* showed power degradation followed by recovery under light soaking. Since bias without illumination is unlikely for modules in operation, this illustrates the need for 'combined effects' testing that better mimics field operating conditions. PVDI01* has a low probability of exhibiting PID degradation under field operating conditions. To date, four out of the eight tested module designs exhibit PID under negative bias.

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Group 2: damp heat and UV

The group 2 test sequence is designed to assess a module's susceptibility to high-moisture conditions, elevated temperatures and high levels of UV radiation. The damp heat and UV procedures were combined into a single test sequence to provide a means of evaluating the effects of UV on modules in damp environments. The damp heat conditions represent a harsher environment, which is expected to accelerate degradation due to UV exposure [10].

The test begins by mounting the module in a vertical orientation in a heat and humidity chamber. Each module receives a small bias current to monitor the continuity through the module during the test. Following heat and humidity exposure, the modules are placed in a UV chamber, where they are subjected to high-intensity UV light for a total dose of 100kWh/m^2. The exposure is carried out in four steps, with characterization and re-saturation of the modules between iterations. The

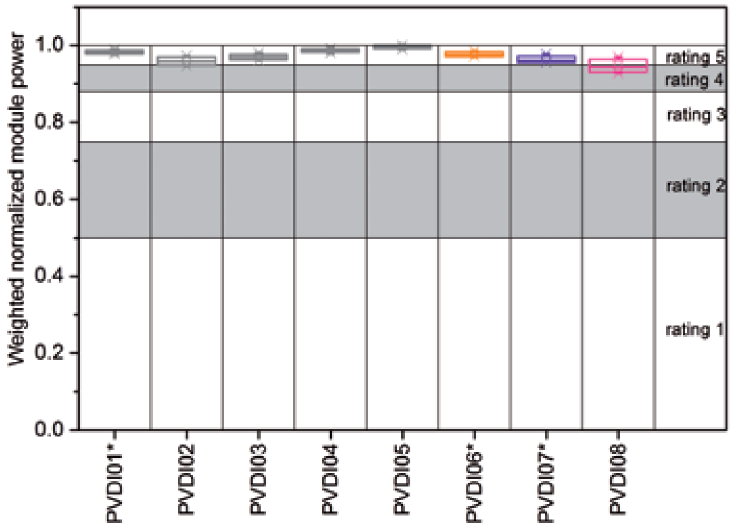

Figure 3. Normalized performance following damp heat and UV exposure.

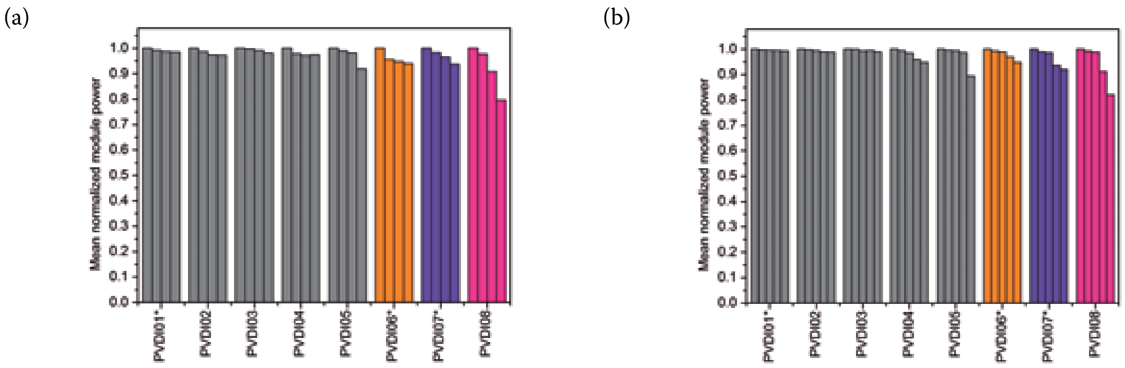

Figure 4. Mean degradation of two modules at the various test intervals of (a) static and (b) dynamic mechanical loading. The specific intervals are: initial, after loading (2× for dynamic mechanical loading), after 50 temperature cycles and after 10 humidity–freeze cycles.

modules are re-saturated by exposing them to damp heat for forty-eight hours to counter the drying effects of the UV light.

The current damp heat UV test sequence did not demonstrate significant degradation in any of the modules tested (Fig. 3). The wear-out regime for these conditions had therefore not yet been reached, and no conclusions can be drawn at this point with regard to relative susceptibility to damp heat and UV stress. This test will be revised in the future in order for the wear-out regime for UV exposure to be reached.

Group 3: static and dynamic loading, thermal cycling, and humidity freeze

The group 3 test sequence is designed to assess the effect of both static and dynamic loading on a module's performance and package integrity.

A module's ability to withstand static mechanical loads for prolonged periods is significant primarily for regions where snow loads are present. The test is performed at a temperature of –40°C in order to increase the stress in and between materials [14,15].

The static test is performed with the module loaded in a downward direction (opposite the normal of the sunward module surface) under a force of 5.4kPa for three one-hour periods, with a rest period between these loading periods.

The dynamic loading portion of the test is designed to assess the effects of intermittent loads, such as wind loads. This test is carried out at a low temperature, at which the effects are expected to be most severe. The modulus of many encapsulants will increase dramatically as the module temperature approaches the encapsulant's glass transition temperature. This stiffening of the encapsulant results in greater stress transmission to the cell and interconnects, which may lead to cell cracking and interconnect failure, for example.

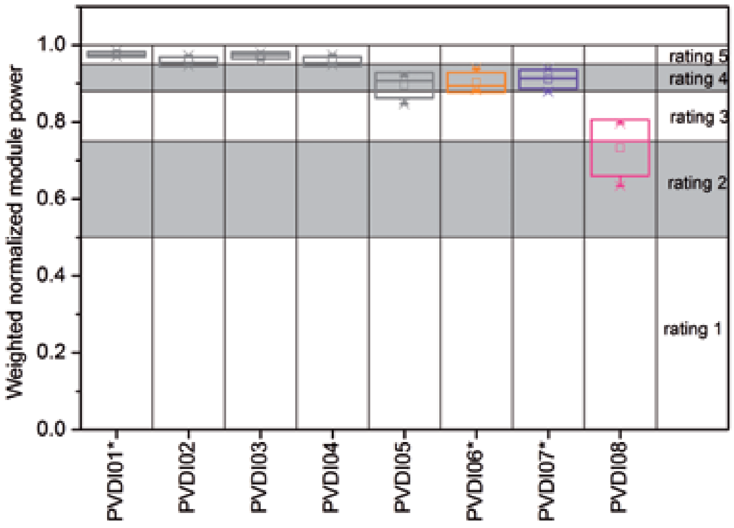

Figure 5. Normalized performance under static loading.

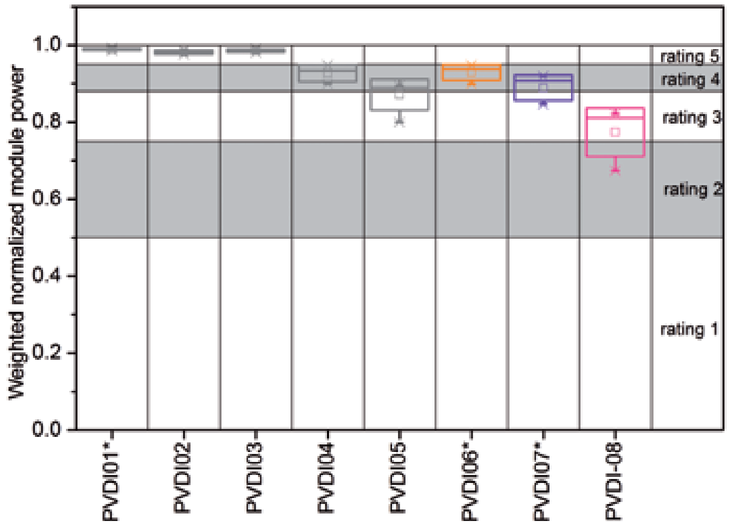

Figure 6. Normalized performance under dynamic loading.

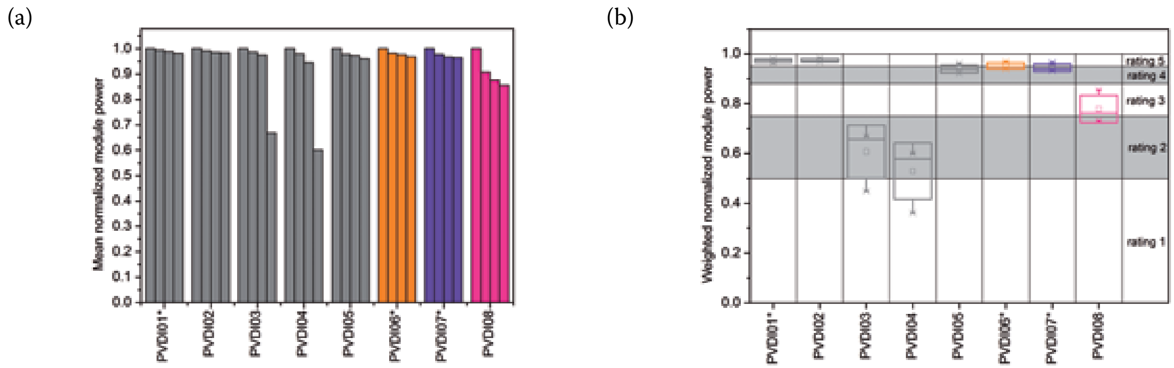

Figure 7. Performance degradation in thermal cycling: (a) results at each interval of 200 cycles; (b) normalized performance.

The dynamic load, to a maximum force of 2.4kPa, is applied normal to the module surface, in directions both positive and negative with respect to the plane of the module at rest. This is performed twice, with an interim characterization to record any change in performance and to inspect for the appearance of cell cracks and damaged interconnects.

Following load testing, the modules are subjected to thermal cycling and humidity–freeze stresses: this is done to amplify crack propagation initiated during the load tests (Figs. 4–6).

Group 4: thermal cycling

The group 4 test sequence assesses a module's ability to withstand the effects of shade-induced, diurnal and seasonal temperature changes. Under normal operating conditions, a module will be subjected to daily temperature excursions as well as more rapid temperature changes due to transient cloud cover. When temperature transients occur, stresses can be induced inside the modules as a result of the different thermal expansion characteristics of the various materials [16].

To simulate the heating effects due to current flow under normal operating conditions, the modules are biased with a current equivalent to their short-circuit current. The chamber is cycled between –40°C and +85°C at a constant rate, with a dwell of 10 minutes at both temperature extremes. Each module undergoes a total of 600 cycles; characterizations are performed after every 200 cycles.

The results of the thermal cycling tests are shown in Fig. 7.

Group 5: outdoor energy performance

The group 5 test sequence is designed to assess a module's performance under real-world (non-accelerated) operating conditions [17]. Three modules of each type are installed on an outdoor test station and monitored for long-term degradation effects. One module is instrumented with a power supply that maintains the module at its maximum power point and sweeps *I-V* curves at preset intervals; this data is used to calculate the performance ratio of the module. The other two modules are maintained at a fixed load near the maximum power point.

All three modules are removed from the test rack at six-month intervals, visually inspected and tested at STC, then returned to the outdoors. Modules will be monitored on an ongoing basis for several years. The outdoor data will be compared with the accelerated test data, as well

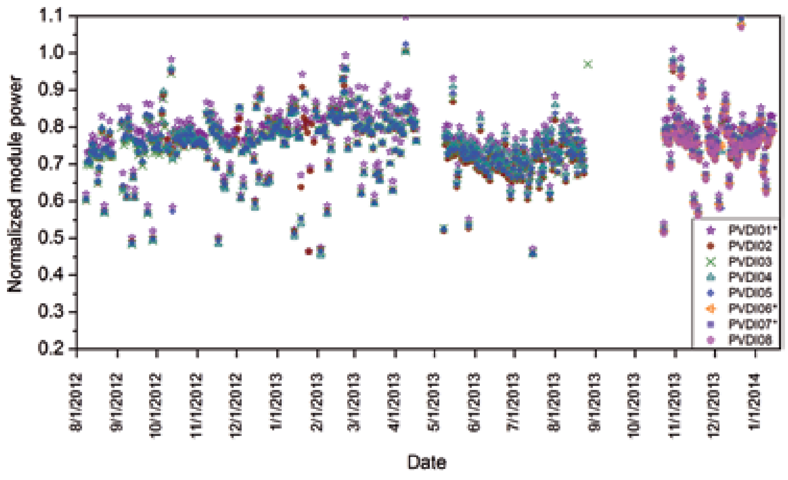

Figure 8. Outdoor performance to date.

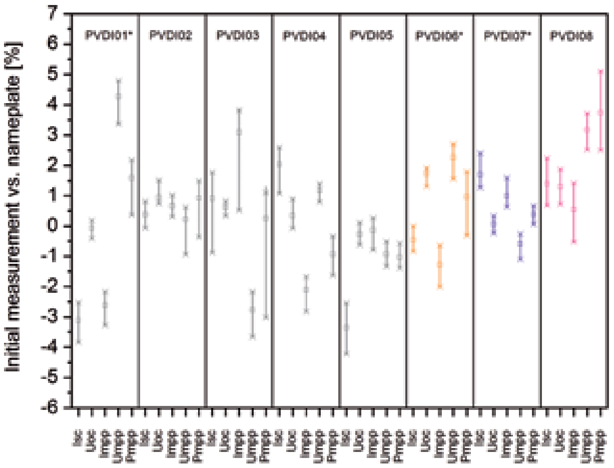

Figure 9. Baseline performance parameters with respect to nameplate rating.

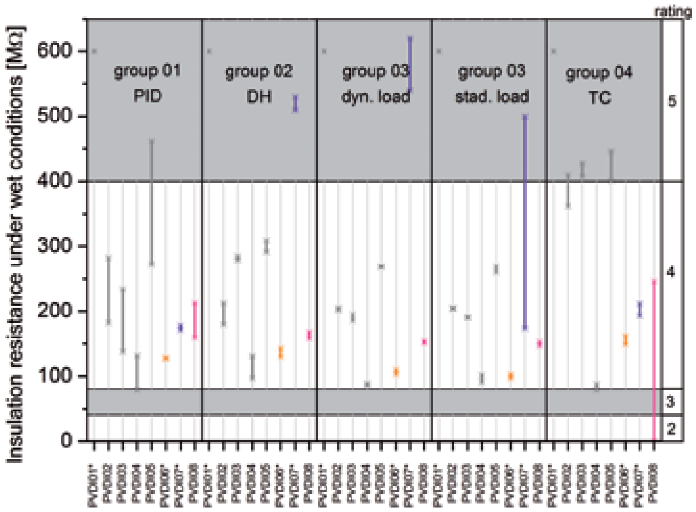

Figure 10. Wet leakage resistance results for all modules by project and test group.

as with outdoor data from analogous module designs at other sites around the world. The ultimate goals are to understand long-term wear-out, identify new failure modes and determine the acceleration factors that are necessary to correlate the accelerated test results to outdoor operating lifetime (Fig. 8).

Nameplate rating comparison

Fig. 9 illustrates initial module (STC) performance relative to the nameplate rating. Manufacturers may intentionally rate their modules below their expected initial performance in order to provide a performance buffer and reduce the risk of warranty claims. The results shown in Fig. 9 indicate that all of the module designs are within the manufacturers' specified power tolerance limits.

> "All of the module designs are within the manufacturers' specified power tolerance limits."

Rating	Rating criteria
5	$P \geq 0.95$
4	$0.88 \leq P < 0.95$
3	$0.75 \leq P < 0.88$
2	$0.50 \leq P < 0.75$
1	$P < 0.5$
0	$P = 0$

Table 1. Module performance rating ranges.

	Environmental conditions				
ID	PID	Damp heat/UV	Static load	Dynamic load	Thermal cycling
PVDI01*	5	5	5	5	5
PVDI02	4	5	5	5	5
PVDI03	4	5	5	5	2
PVDI04	5	5	5	4	2
PVDI05	5	5	4	3	4
PVDI06*	5	5	4	4	5
PVDI07*	4	5	4	4	4
PVDI08	3	5	2	3	3

Table 2. Module performance ratings based on mean weighted normalized power measurements.

Module ratings: performance and safety

Modules are given a rating on the basis of both performance and safety. The module's performance is based on the measured electrical performance at STC, for which the mean of the weighted normalized module power is used. The safety rating is based on module package integrity; wet leakage resistance and insulation resistance measurements are used for this evaluation.

Module performance ratings

The rating categories are:

1. **PID:** This category indicates a module's probability of surviving in an environment where there are large potentials (600–1000V_{DC}) between the active circuit of the module and ground.
2. **Damp heat/UV:** This category indicates a module's probability of surviving and performing as specified in environments where high humidity is expected to be a dominant environmental condition.
3. **Static and dynamic loads:** The static load category indicates a module's probability of surviving in an environment where it will be regularly subjected to static mechanical loads, such as heavy leaf-fall, snow or ice. The dynamic load category indicates a module's probability of surviving and performing as specified in environments where it will be subjected to constantly changing mechanical loads, such as wind.
4. **Thermal cycling:** This category indicates a module's probability of surviving and performing as specified in environments where there are temperature extremes and an expectation that the temperature will vary widely diurnally and annually.

Rating	Rating criteria
5	$R \geq 400M\Omega$
4	$80M\Omega \leq R < 400M\Omega$
3	$40M\Omega \leq R < 80M\Omega$
2	$400k\Omega \leq R < 40M\Omega$
1	$200k\Omega \leq R < 400k\Omega$
0	$0 < R < 200k\Omega$

Table 3. Module safety (package integrity) rating ranges.

Table 1 summarizes the performance rating criteria, and Table 2 shows the performance ratings for the modules tested. The mean of the weighted normalized module power P is determined from the equation:

$$P = \frac{\bar{P}_{n,n}}{n} \cdot \sum_{i=1}^{n} \bar{P}_{n,i} \qquad (1)$$

where n = the number of performance measurements within a test sequence, and $\bar{P}_{n,i}$ = the mean power, normalized with regard to the initial measurement, of all modules in a test group at the measurement step i. In the determination of P for test group 1 (PID), only the values of the initial and final measurements are used – this is because of the recovery process after the PID stress test.

Module safety rating: package integrity

The integrity of the package determines the safety of the module. Package integrity is determined by the leakage resistance density at the conclusion of a test sequence.

> "Package integrity is determined by the leakage resistance density at the conclusion of a test sequence."

The magnitude of the leakage resistance density is dependent on the voltage applied, the area of the module and the resistance of the module's insulating materials. To normalize the leakage resistance for the comparison ratings, the measurements are normalized for area to yield resistance per square metre. The resistances are then binned according to the IEC leakage resistance limits and an equivalent resistance for the OSHA ground fault leakage current of 5.0mA [18]. The equivalent resistance at 5.0mA is 200kΩ for a system voltage of 1kV_{DC}. This method ensures that no module receives a rating above zero if it has a leakage current greater than 5.0mA.

Table 3 summarizes the module safety (package integrity) rating criteria, and Table 4 shows the safety ratings of the modules tested. The normalized leakage resistance density R is given by the equation:

$$R = \frac{1}{k} \cdot \sum_{i=1}^{k} R_{M,i} \qquad (2)$$

where k = the number of modules in a test group, and $R_{M,i}$ = the insulation resistance under wet conditions of the final measurement of a module in a test group. R is therefore the mean of all insulation resistances from the final measurements of all modules in a test group.

Wet leakage resistance results for

	Environmental conditions				
ID	PID	Damp heat/UV	Static load	Dynamic load	Thermal cycling
PVDI01*	5	5	5	5	5
PVDI02	4	4	4	4	4
PVDI03	4	4	4	4	5#
PVDI04	4#	4#	4#	4#	4#
PVDI05	4	4	4	4	5#
PVDI06*	4	4	4	4	4
PVDI07*	4	5	5	4	4
PVDI08	4	4	4	4	4

Rating has changed from the 2013 publication [6] because of a modification of the rating procedure.

Table 4. Module safety ratings based on wet leakage resistance measurements.

all modules, along with the rating thresholds, are shown in Fig. 10.

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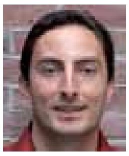
Sandor Stecklum studied physical technology at the University of Applied Sciences Ravensburg-Weingarten, and has been working as a test engineer in the TestLab PV Modules at Fraunhofer ISE since 2012. Previously, Sandor spent four years as a scientific assistant in the Materials – Solar Cells and Technologies Department at Fraunhofer ISE, where he worked on new concepts for concentrator photovoltaic systems and conducted characterization measurements on concentrator cells and modules.

Dr. Cordula Schmid has been with the Fraunhofer CSE PV Technologies team since 2010. She specializes in the assessment of module packaging materials and the mechanical and electrical testing of modules. Prior to that, Cordula worked at the Fraunhofer Institute for Mechanics of Materials (IWM), where she focused on identifying and mitigating mechanical and thermal loads in solar cells and modules. She has also carried out consulting work in the area of failure analysis.



Cameron Stark has served since 2010 as a primary technical member of staff at Fraunhofer CSE in Albuquerque, where he focuses on outdoor testing. He previously worked as the primary production test engineer and a cell R&D engineer for Advent Solar. He later became the senior PV designer for a commercial-scale PV integrator, where he designed and commissioned systems throughout the USA and Latin America.

Geoffrey S. Kinsey is Director of Photovoltaic Technologies at Fraunhofer CSE. He was previously Senior Director of Research and Development at Amonix, where his group was the first to demonstrate a module outdoor operating efficiency rating over 30% and, successively, over 33%. He received his B.S. from Yale University and his Ph.D. from the University of Texas at Austin. He has two patents issued and over eighty publications in optoelectronics.

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