Fraunhofer PV Durability Initiative for solar modules

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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 a necessary, but not sufficient, part of determining PV module service life. The goal of the 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.

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 [1–4]. The tests also lack standard protocols for comparing the relative durability risk 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 Center for Sustainable Energy Systems CSE and the Fraunhofer Institute for Solar Energy Systems ISE. The aim is to create an open-source durability assessment protocol that will eventually form the basis for an international industry standard.

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The accelerated test component is an extension of familiar reliability stress tests [5–8]. Since the acceleration factors of most stress tests are not yet known, the protocol combines accelerated testing with long-term outdoor exposure testing (Fig. 1). 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 ‘normalized cumulative performance’, which is the mean of their performance at 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 from 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 is annotated 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 continuous comparison with the rest of the field. As the Durability Initiative continues, a background of previous results will be available to compare with the recent additions. Testing in accordance with this protocol has so far been completed on five commercial module types, with a second test group currently in progress. The first five module designs tested five of the top eight, by volume, single-crystal silicon module manufacturers in 2012. The module design identified below as ‘PVDI01^{a}’ is the SunPower E20 module, manufactured by SunPower, Inc. (The superscript 'a' highlights a nonstandard characteristic: the modules were selected by Fraunhofer CSE from a list of available modules at a wholesaler).

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

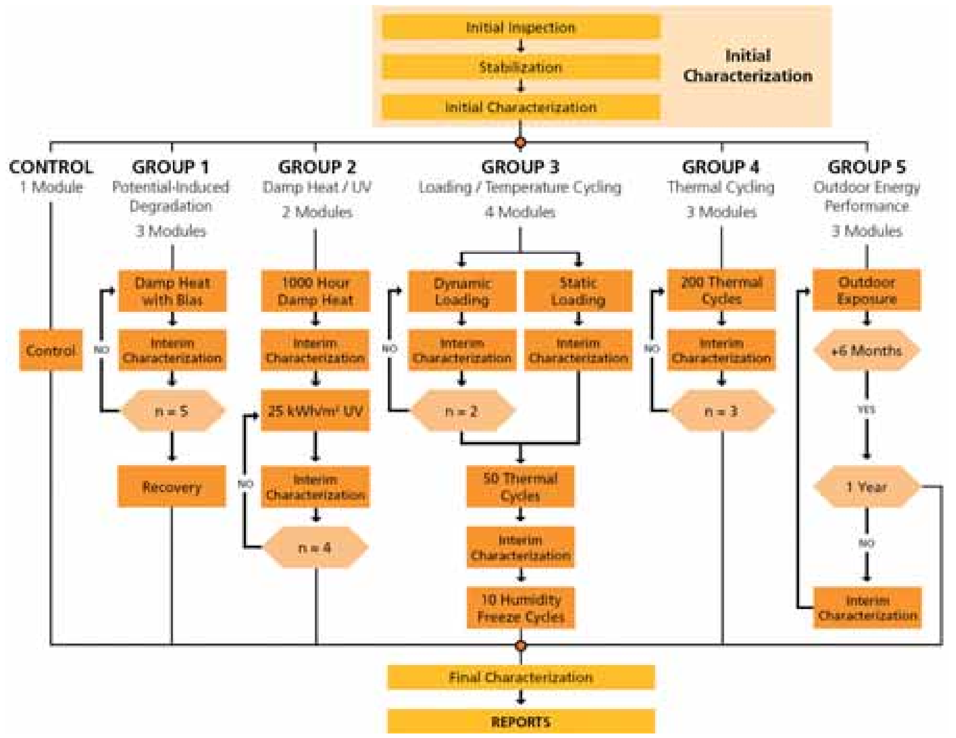

Figure 1. The PVDI test sequences.

Initial characterization and stabilization

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

Following a visual inspection, the modules are light soaked to allow for 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 required 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 current–voltage (IV) 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 check if they satisfy the condition $(P_{\text{max}} - P_{\text{min}})/P_{\text{mean}} < 2\%$.

After stability has been achieved, the initial characterization is performed: measurement of light current–voltage (LIV) at standard test conditions (STC); EL imaging; IR imaging; and measurement 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) [9]. Since PV modules may be installed where the electrical potential between the module and the earth ground can be positive or negative, they 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. Each module is exposed for a total of 400 hours under bias at 85°C and 65% relative humidity. Interim measurements of a module's performance are taken at 50, 100, 200, 300 and 400 hours, and after recovery. Recovery is done by exposing the module outdoors or to artificial light while keeping the module at its maximum power point for no more than 25kWh/m^2.

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, modules are currently exposed to light soaking only 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 [1] 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. Module design PVDI01[a] exhibited degradation under positive bias but recovered after exposure to light when operated at the module's maximum power point. One of the two PVDI02 modules exhibited degradation under negative bias and did not recover. Both PVDI03 modules degraded under negative bias and did not recover.

Module designs PVDI02 and PVDI03 appear to have the greatest risk of PID degradation. PVDI04 and PVDI05 have a low probability of exhibiting PID failures in the field. Under positive bias, PVDI01[a] showed power degradation, followed by recovery after light soaking. Since bias without illumination is unlikely for

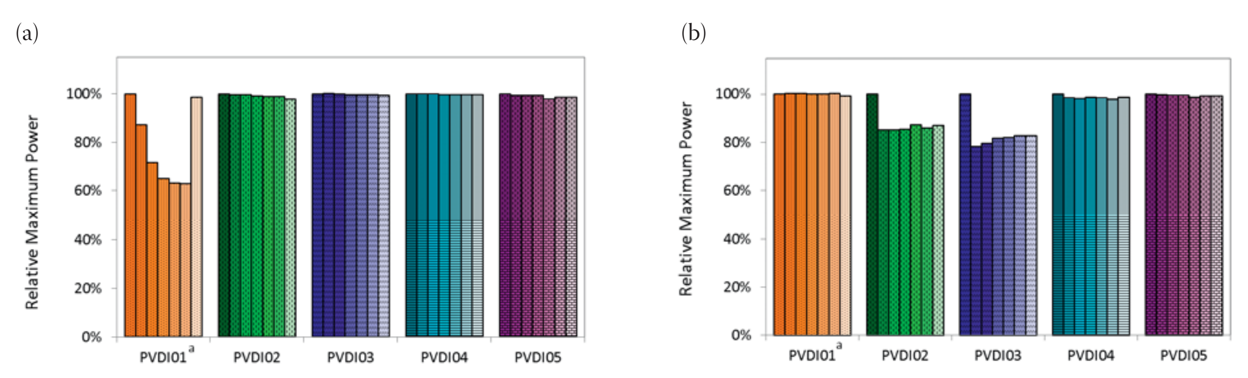

Figure 2. PID tests under (a) positive bias and (b) negative bias. To determine the PID rating, the final performance value after light soaking is used.

modules in operation, this illustrates the need for 'combined effects' testing that better mimics field operating conditions. PVDI01[a] has a low probability of exhibiting PID degradation under field operating conditions.

Group 2: damp heat and UV light

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 assessments were combined into a single test sequence to provide a means of evaluating the effects of UV on modules in damp environments. UV degradation is usually accelerated at higher temperatures. UV exposure can then lead to weakened adhesion of encapsulants, for example, which in a damp environment can lead to corrosion.

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

The current damp heat UV test sequence did not demonstrate significant degradation among any of the modules tested (Fig. 3). The wear-out regime for these conditions had therefore not yet been reached. This test may 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.

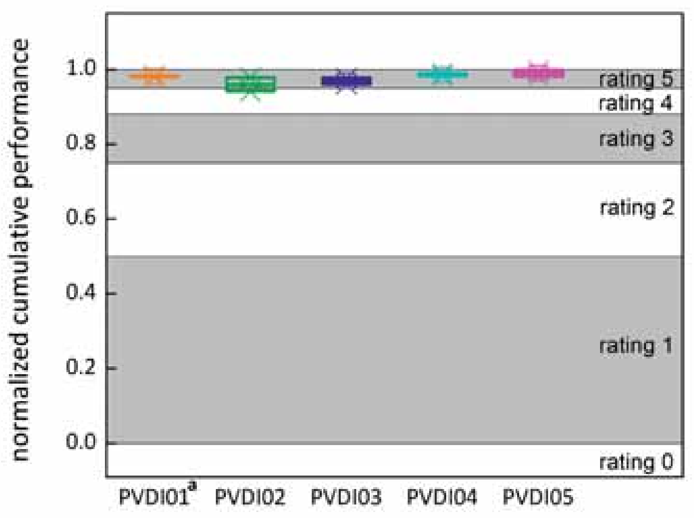

Figure 3. Cumulative performance following damp heat and UV exposure. The box indicates the interquartile range. The whiskers are determined by the 5th and 95th percentiles. The median is shown as a horizontal line within the box, the mean is indicated by a square, and the 1st and 99th percentiles are displayed as x symbols.

The dynamic load 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, for example, cell cracking and interconnect failure.

The dynamic loading, to a maximum force of 2.6kPa, is applied normal to the surface, in both positive and negative directions 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.

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 [10,11]. For the static test, the module is loaded in a downward direction (opposite the normal of the sunward module surface) under a force of 5.6kPa for three one-hour periods, with a rest period between these loading periods.

> "A module's ability to withstand static mechanical loads for prolonged periods is significant primarily for regions where snow loads are present."

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 and 5).

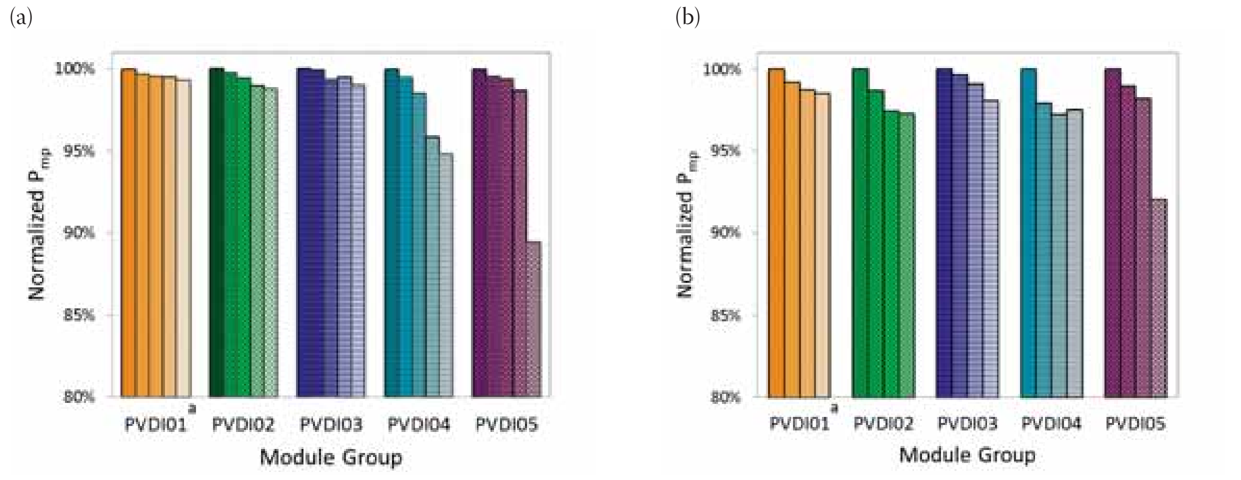

Figure 4. Mean degradation of two modules at the various test intervals of (a) dynamic and (b) static mechanical loading. The specific intervals are: initial, after loading, after 50 temperature cycles and after 10 humidity–freeze cycles.

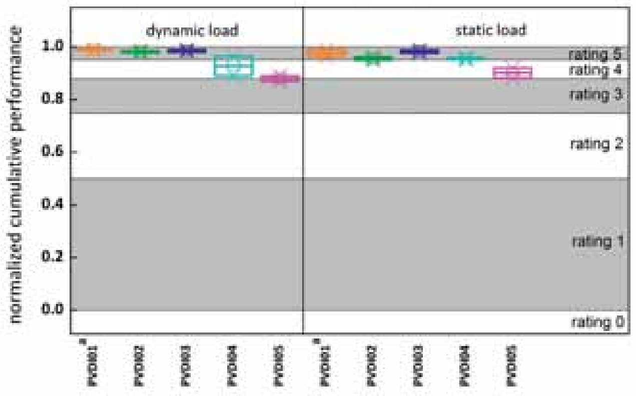

Figure 5. Cumulative performance under dynamic and static loading.

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 [12].

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

The results of the thermal cycling are shown in Fig. 6. It is interesting to note that modules from PVDI03 and PVDI04 exhibited more degradation than they did during dynamic and static mechanical loading.

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. Three modules of each

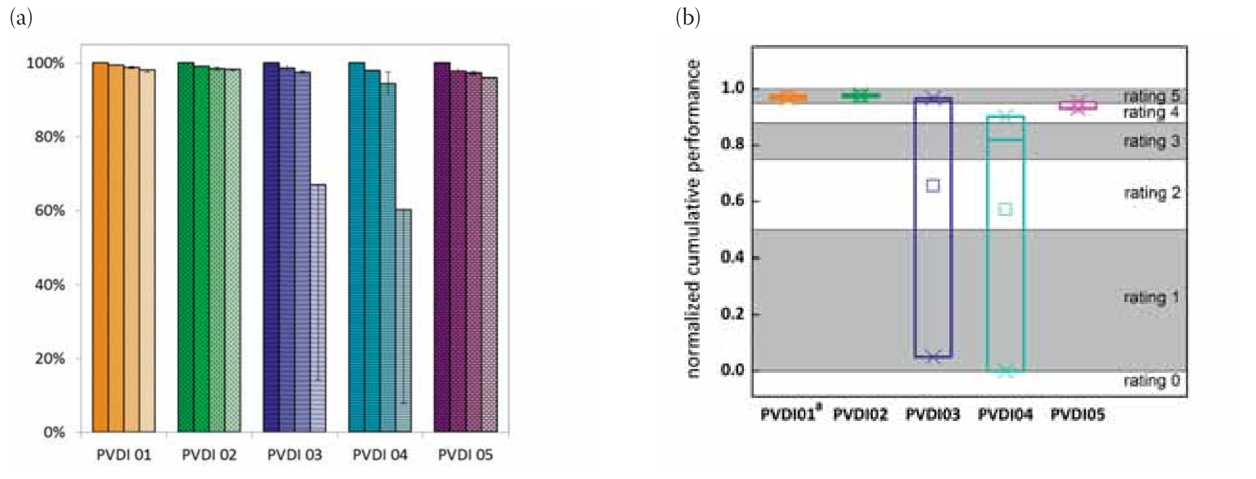

Figure 6. Performance degradation in thermal cycling: (a) results at each interval of 200 cycles; (b) normalized cumulative performance.

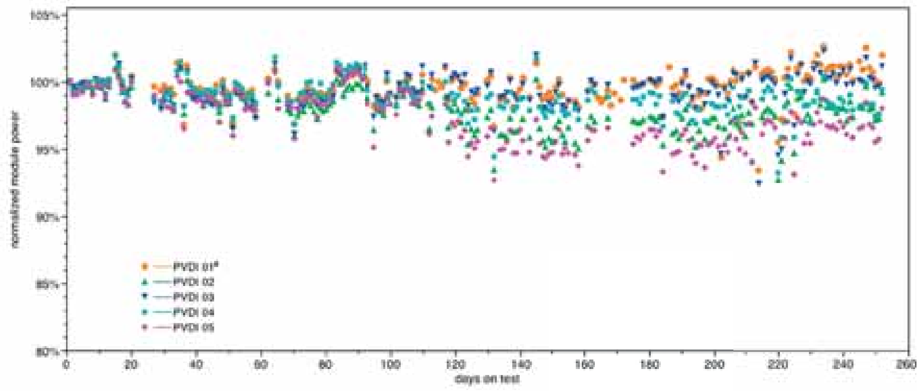

Figure 7. Outdoor performance to date.

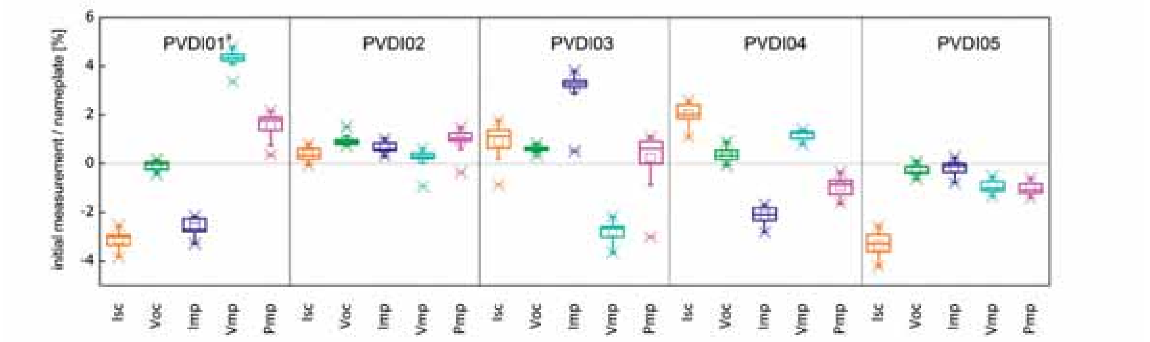

Figure 8. Baseline performance parameters with respect to nameplate rating.

type are installed on an outdoor test station and continuously 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 IV 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 as with outdoor data from analogous module designs at other outdoor 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. 7).

Nameplate rating comparison

Fig. 8 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 each of the module designs are within the manufacturers' specified power tolerance limits.

Module ratings: performance and safety

Modules are rated for both performance and safety. The module design's performance (Tables 1 and 2) is based on the measured electrical maximum power at STC. The safety rating is based on module package integrity (Table 3). Wet leakage resistance and dry insulation resistance measurements are used for the safety rating (Tables 4 and 5).

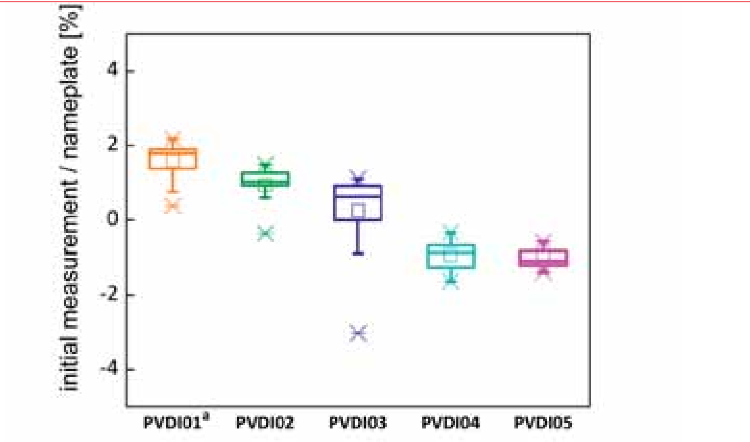

Figure 9. Ratio of initial measured P_{max} to nameplate rated P_{max}.

Rating	Performance (P)
5	P > 0.95
4	0.88 < P < 0.95
3	0.75 < P < 0.88
2	0.5 < P < 0.75
1	P < 0.5
0	0

Table 1. Module performance rating ranges.

ID	Environmental conditions				
	PID	Damp heat/UV	Dynamic load	Static load	Thermal cycling
PVDI01[a]	5	5	5	5	5
PVDI02	4	5	5	5	5
PVDI03	4	5	5	5	2
PVDI04	5	5	4	5	2
PVDI05	5	5	3	4	4

Table 2. Performance ratings.

Module rating	Rating criteria
5	$R \geq 400\text{M}\Omega$ and $\Delta R \leq 1.0\%$
4	$80\text{M}\Omega \leq R < 400\text{M}\Omega$ or $R \geq 400\text{M}\Omega$ and $\Delta R > 1.0\%$
3	$40\text{M}\Omega \leq R < 80\text{M}\Omega$
2	$400\text{k}\Omega \leq R < 40\text{M}\Omega$
1	$200\text{k}\Omega \leq R < 400\text{k}\Omega$
0	$R < 200\text{k}\Omega$

Table 3. Module safety (package integrity) rating.

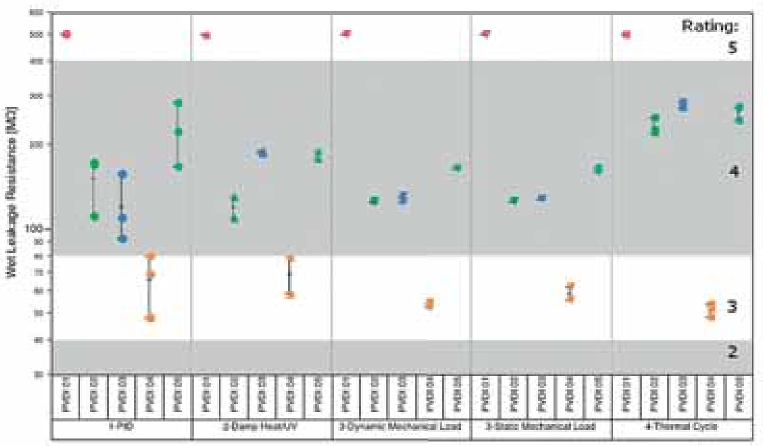

Figure 10. Wet leakage resistance results for all modules by project and test group.

> “Modules are rated for both performance and safety.”

Module performance ratings

The rating categories are:

- **PID:** This category indicates a module's ability to survive in an environment where there are large potentials (600–1000V DC) between the active circuit of the module and ground.
- **Damp heat/UV:** This category indicates a module's ability to perform as specified in environments where humidity is expected to be a significant environmental condition.
- **Static and dynamic loads:** The static load category indicates a module's ability to perform in an environment where it will be regularly subjected to static mechanical loads, such as heavy leaves, snow or ice. The dynamic load category indicates a module's ability to perform as specified in environments where it will be subjected to changing mechanical loads, such as wind.
- **Thermal cycling:** This category indicates a module's ability to perform as specified in environments where there are temperature extremes and an expectation that the temperature will vary widely diurnally and annually.

Module safety rating: package integrity

The integrity of the package determines the safety of the module with respect to shock and fire hazards. Package integrity is determined by a combination of the wet leakage and dry insulation resistances measured at the conclusion of a test sequence. This resistance is dependent on the voltage applied, the area of the module and the resistance of the module's insulating materials. Measurements are normalized for area and then binned according to the IEC leakage resistance limits [13] and an equivalent resistance for ground fault circuit interrupters per UL 943 [14]. 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 package integrity rating criteria. Resistance values are given for the normalized leakage resistance density R, and ΔR is the change in the resistance relative to the initial measurement.

Appendix: Characterization techniques

Visual inspection

Visual inspection has two purposes: first, to detect defects caused by the manufacturing process and shipping; and second, to detect physical changes in the module after it has

ID	Wet leakage resistance [MΩ]			Dry insulation resistance [MΩ]		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
PVDI01[a]	>500	>500	>500	>500	>500	>500
PVDI02	110	250	158	314	>500	>500
PVDI03	92	286	174	>500	>500	>500
PVDI04	48	80	59	205	>500	>500
PVDI05	159	283	207	428	>500	>500

Table 4. Wet leakage resistance and dry insulation resistance measurements for the project modules, across all test groups.

ID	Environmental conditions				
	PID	Damp heat/UV	Dynamic load	Static load	Thermal cycling
PVDI01^a	5	5	5	5	5
PVDI02	4	4	4	4	4
PVDI03	4	4	4	4	4
PVDI04	3	3	3	3	3
PVDI05	4	4	4	4	4

Table 5. Ratings of module safety based on wet leakage resistance measurements. All modules received a rating of 5 for dry insulation resistance.

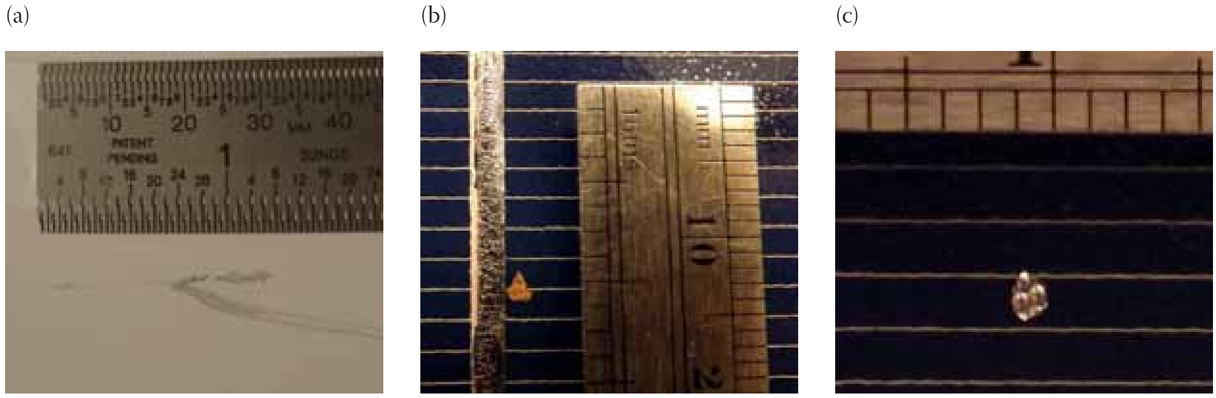
(a) (b) (c)

Figure 11. Defects observed on incoming modules: (a) backsheet scratch; (b) foreign particle; (c) metal particle.

been exposed to stress. In the case of visual defects (e.g. debris incorporated during manufacturing, as seen in Figs. 11(b) and (c)), while some may not affect the performance of a module, others may either have a direct impact on performance or signal larger lapses in manufacturing quality assurance. The scratch in the backsheet shown in Fig. 11(a) and the delamination shown in Fig. 12 are likely indicators of reductions in safety and/or performance. There is a possibility that the scratch shown in Fig. 11(a) will cause the module to exhibit lower wet leakage resistance. This scratch may lead to eventual breakdown in the backsheet, since it has exposed the underlying insulating layer. This layer is now more susceptible to UV degradation and may become embrittled and fail. The delamination in Fig. 12 will cause the underlying cell to underperform owing to loss of transmitted light. It is also possible that temperature/humidity cycles over time will cause the defect to grow.

> “Dark IV measurements are used to investigate subtle changes in the series resistance and shunt resistance of the module.”

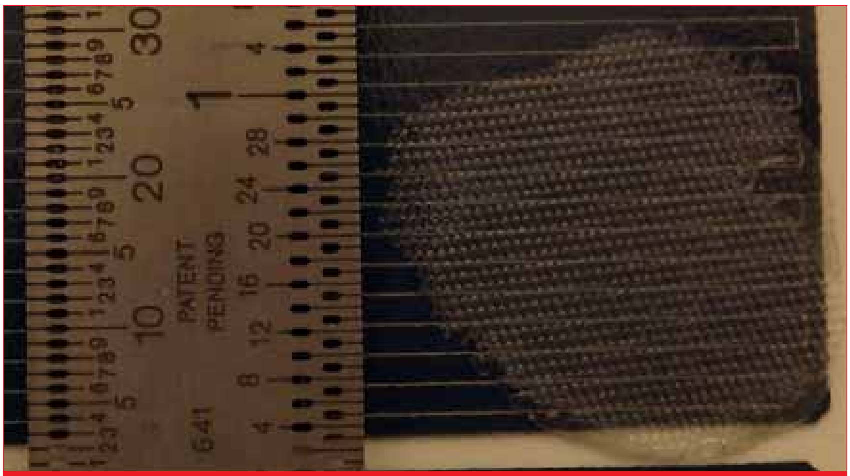

Figure 12. Delamination observed after damp heat exposure.

The observations made during visual inspection are used to determine why one module may be responding to stress differently from others of the same type. Defects are also tracked for progression or growth as a function of continuous stress over time.

Light and dark IV performance

LIV measurements are made under both STC and operating conditions. For operating-condition measurements, the global irradiance, module temperature and wind speed are recorded at the time of the measurement.

Dark IV measurements are used to understand the changes that are taking place inside the module as a function of the stresses applied to the modules. The measurements are used to investigate subtle changes in the series resistance and shunt resistance of the module; these resistances are extracted from the characterization curve (Fig. 13).

Series resistance is the slope of the curve as it approaches the open-circuit voltage (V_{oc}). An increase in series resistance can be an indication that the resistivity of conductive pathways within the module is increasing. This can be caused by loss of contact, corrosion, oxidation, or delamination of the cell metallization.

Shunt resistance is the slope of the curve as it approaches the short-circuit current (I_{sc}). A decrease in shunt resistance can indicate that there are leakage pathways

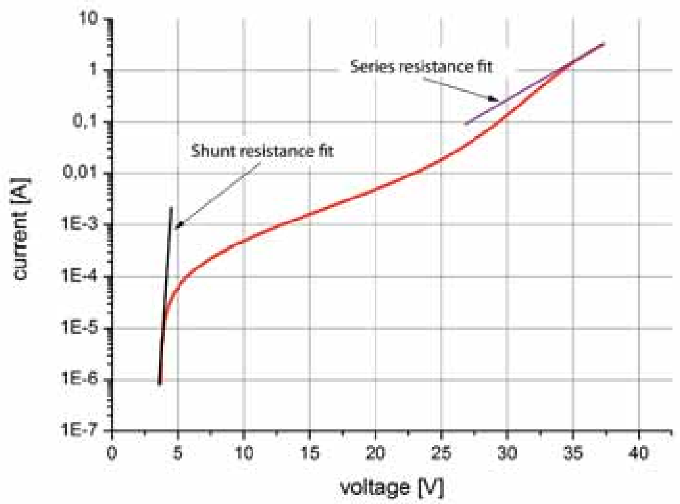

Figure 13. Typical dark IV trace.

developing between the module layers or within the cells themselves (caused by cracks or a breakdown in the cell junction).

Changes in various key parameters following stress can indicate the type of effect the stress has had on the module. For instance, a decrease in I_{sc} can indicate that the module is not receiving as much light as it was before the stress. This can be caused by delamination (leading to light scattering), or by discoloration of the encapsulation (leading to an increase in absorption before the light reaches the cell).

Wet leakage resistance

The wet leakage resistance test interrogates the insulation of the module under wet operating conditions, such as moisture from condensed humidity, rain, fog or melted snow. If moisture enters the module, it can cause corrosion and/or a ground fault, leading to both performance degradation and safety hazards. The test detects defects in packaging integrity that would allow electrical power to pass from the internal, active circuit of the modules to the outside surfaces.

The wet leakage resistance test is performed by shorting the module leads together and placing it in a bath of water, with surfactant added to increase the water's conductivity. The measurement is made by applying to the leads a voltage equivalent to the module's rated system voltage, and measuring the current flowing out of the module and into the water bath.

The resistance is calculated to account for the difference in size of different modules: if leakage is distributed across the module area, the leakage current will scale with module area. IEC module qualification standards IEC 61215 and IEC 61246 require that a module have greater than 40MΩ•m^2 resistance to pass qualification. Normalized for a 1m^2 module area, the threshold is therefore 40MΩ; this is equivalent to currents of 15μA and 25μA at system voltages of 600V DC and 1000V DC, respectively.

Dry insulation resistance

The dry insulation resistance test measures the quality of the insulating materials that isolate the electrically active components of the module from the exterior surfaces. It is similar to wet leakage resistance testing, except that the module is tested dry and the voltage applied (6000V) is higher than most rated system voltages.

Electroluminescence imaging

EL imaging is a non-destructive test which is used for spatially resolved characterization of silicon solar cells. This imaging method can be used to detect and characterize defects in solar cells (including cracks), ribbon defects and electrical degradation of cells (Fig. 14).

Infrared imaging

IR imaging is used to characterize defects that are recognizable by their heat signature when injected with an electrical current. These defects are typically hot spots, non-uniform current distributions within a cell, or open-circuit conditions. IR imaging was performed on each module after the application of a forward bias current equivalent to I_{sc}. The baseline images were used to differentiate between pre-existing thermally related phenomena and those that manifested during stress testing (Fig. 15).

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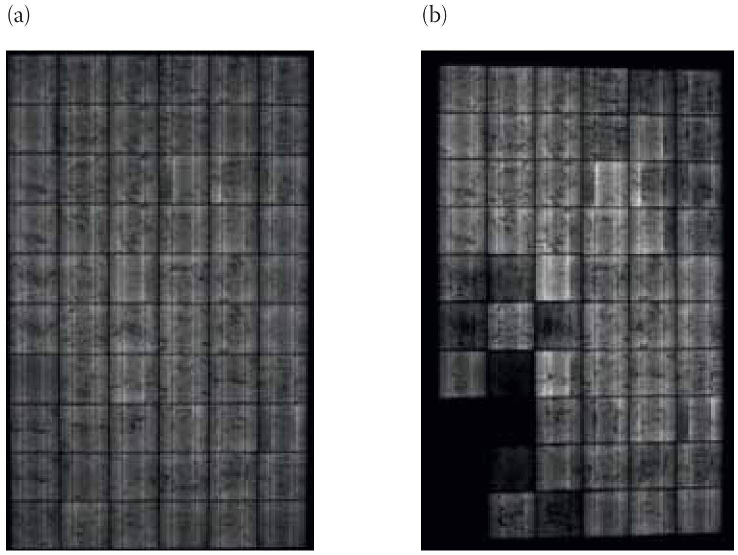

Figure 14. EL image of a module (a) before and (b) after PID stress testing.

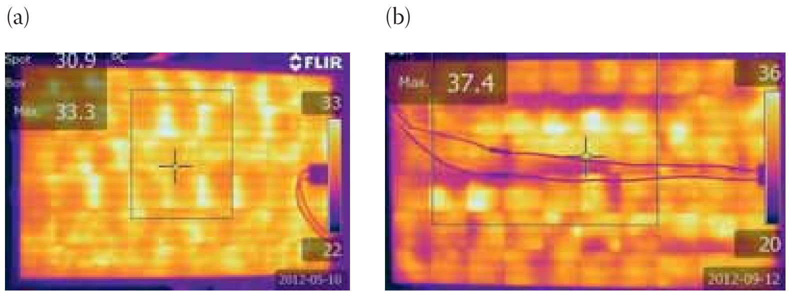

Figure 15. IR image from (a) initial characterization and (b) after 600 hours of thermal cycling.

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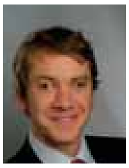

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