Fraunhofer PV Durability Initiative for solar modules: Part 3

Module performance | 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. In this paper, teams from Fraunhofer CSE and Fraunhofer ISE present the results of the Fraunhofer PV Durability Initiative's third round of testing, which now includes 10 module types

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 (PVDI) is a joint venture between the Fraunhofer Institute for Solar Energy Systems ISE and the Fraunhofer Center for Sustainable Energy Systems CSE, with a goal of establishing a baseline PV durability assessment programme. 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 were reported in the second round [7], and another two module designs are reported here for the third round.

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 PVDI 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 ten module types from the three rounds of testing to date.

> "The correlation between the accelerated tests and actual operation in the field is an ultimate goal of the PVDI programme"

PVDI's accelerated test component is an extension of familiar reliability stress tests [8–12]. 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 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 (see Table 1), and the modules are rated for performance. Modules in group 1 (potential-induced degradation) are rated based on their performance at the end of the test, following light exposure, whereas modules in the remaining groups are rated based on their 'weighted normalised performance'. The weighted normalised performance is the performance in each test interval, weighted by the final performance value and normalised 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 remain (an anonymous) part of the dataset, for ongoing comparison with the rest of the field. As the PV Durability Initiative continues, a record of previous results will be available for comparison with the recent additions. To date, testing to this protocol has been completed in three rounds, on ten commercial module types. The manufacturers of four modules have attached the following identifications to the results:

- PVDI01*: SunPower E20 module
- PVDI06*: Aleo (Type S18) module
- PVDI09*: First Solar Series 3 Black (FS-395-Plus) module
- PVDI10*: First Solar Series 4 (FS-498/497) module

The PVDI01*, PVDI09* and PVDI10* modules were tested at Fraunhofer CSE / CFV Solar Test Laboratory, Inc., and the PVDI06* modules were tested at Fraunhofer ISE.

The PVDI test protocol comprises five different tests, which are discussed in detail in the following sections; a summary of the test results for each group is given. The performance of the modules tested in the third round of PVDI is presented together with the results from the previous two rounds of PVDI for comparison purposes, for each of the test groups. Any changes to the testing procedures from the first two rounds have also been indicated where applicable. Finally, the results of all the modules tested in all three rounds of PVDI have been summarised (see Table 2), and the modules have been given a rating according to their likelihood of performing reliably over their lifetime.

Test sequences and results

The test protocol is broken down into five test groups (Fig. 1). A minimum of fourteen modules is currently required to complete the tests. Modules are initially characterised, 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 assigned test sequence, it is repeatedly characterised: for example, in group 4 each module is characterised 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 characterisation and stabilisation

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

Following the visual inspection, the modules undergo light-soaking to allow any light-induced degradation to occur, if no manufacturer-specific preconditioning procedure is in place. During light-soaking, the modules are maintained at their maximum power point, and *I-V* curves are collected periodically. Light-soaking is terminated 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 $(P_{max}-P_{min})/P_{mean} < 2\%$. Light-soaking requires a minimum of 60kWh/m^2, and may take upwards of 600kWh/m^2 to complete. The time to complete this preconditioning is technology dependent: thin-film technologies generally take longer to stabilise than crystalline or polycrystalline silicon technologies. PVDI09* and PVDI10* are thin-film modules, which are known to exhibit a transient behaviour as a result of dark storage. Measurements of modules affected by dark storage that are taken without following the proper conditioning procedures will not provide a true power characterisation. A First-Solar-specific preconditioning procedure was applied.

Once stabilisation is complete, the initial characterisation 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.

"Some module designs will recover their power performance when the high electrical bias is removed or reversed"

The initial performance data are used throughout the test sequence to normalise successive performance measurements; the data are 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)* [13,14]. 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,

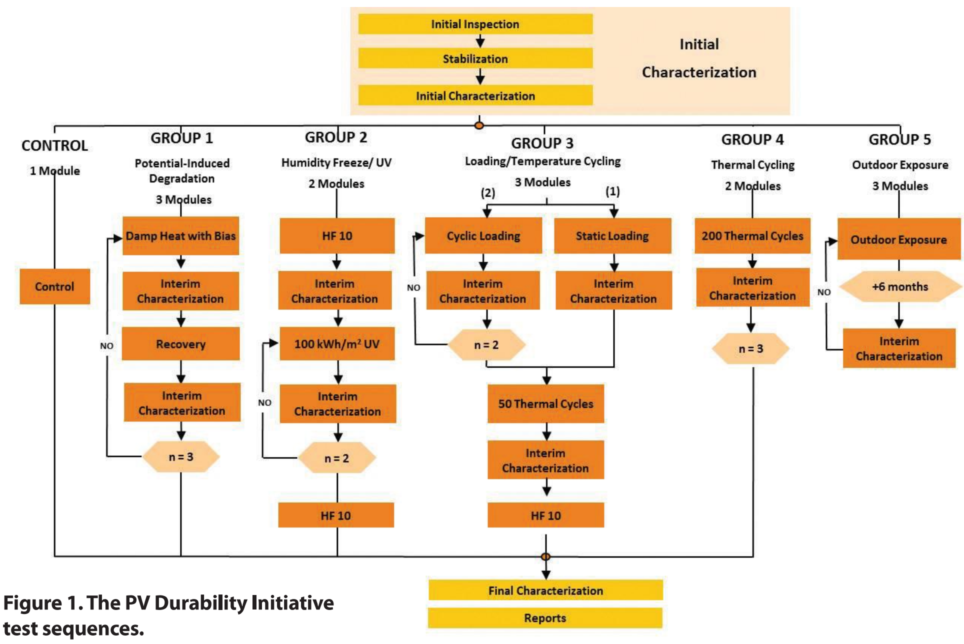
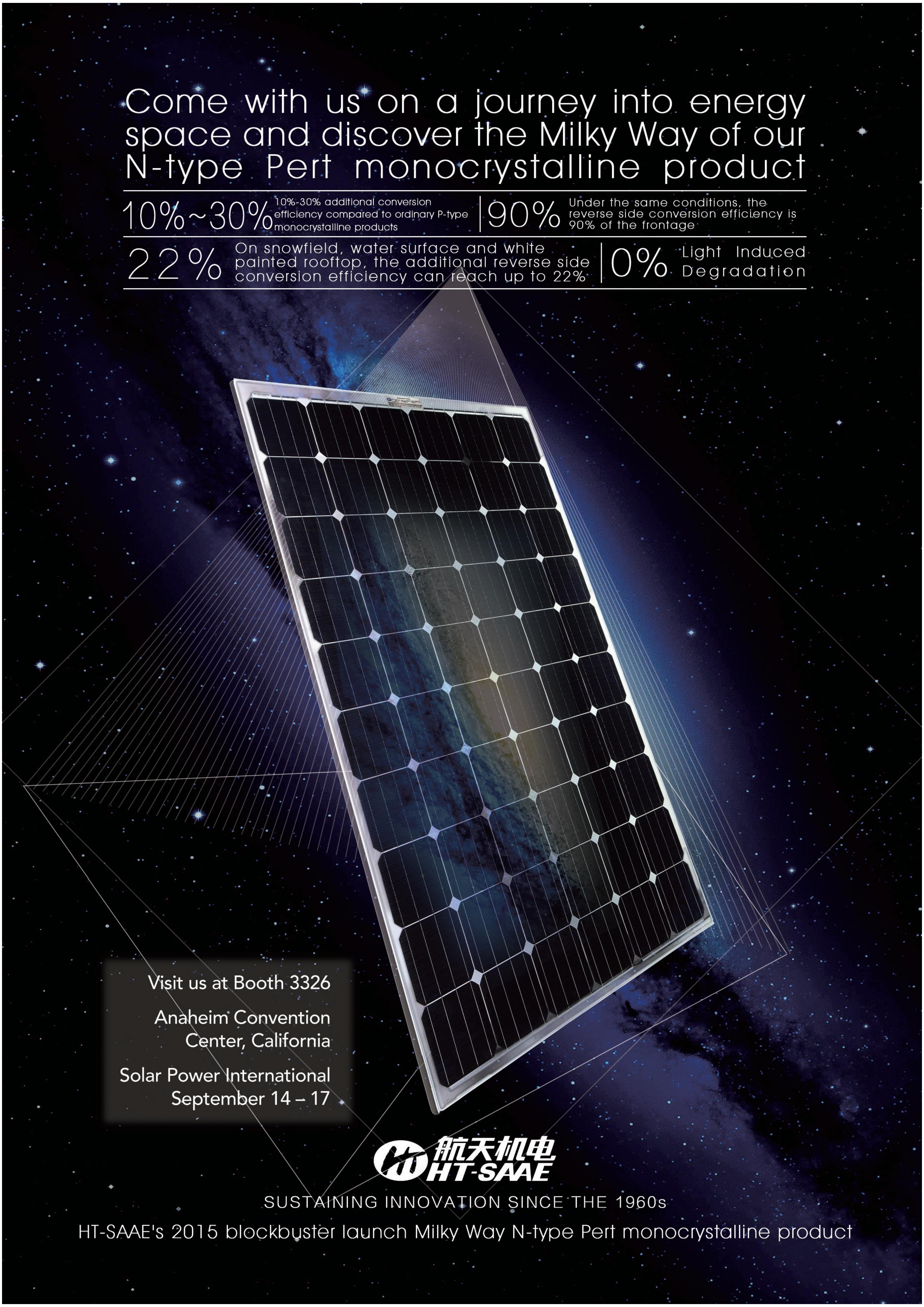


Figure 1. The PV Durability Initiative test sequences.


Come with us on a journey into energy space and discover the Milky Way of our N-type Pert monocrystalline product
10%~30%
10%-30% additional conversion efficiency compared to ordinary P-type monocrystalline products
90%
Under the same conditions, the reverse side conversion efficiency is 90% of the frontage
22%
On snowfield, water surface and white painted rooftop, the additional reverse side conversion efficiency can reach up to 22%
0%
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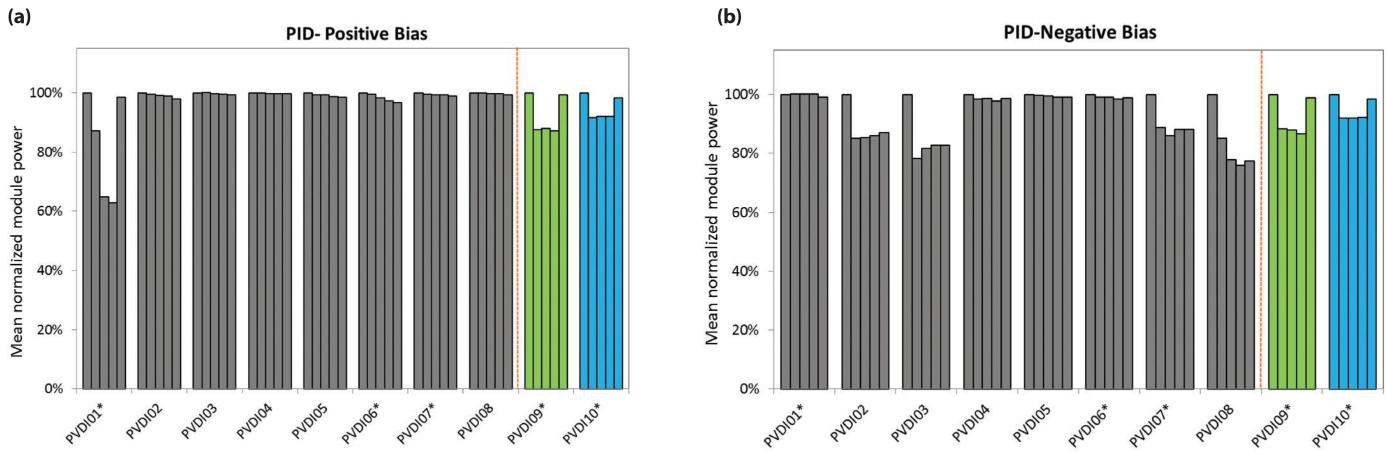


Figure 2. Mean normalised performance degradation of all modules of a test group in PID testing under (a) positive bias and (b) negative bias. To determine the PID rating, the final performance value after light-soaking/conditioning is used. (If the module design was not acquired on the open market, the module ID label is annotated with an asterisk.)

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.

In the case of PVDI09* and PVDI10* modules, the manufacturer-specific procedure was applied. It should also be noted that, for the third round of PVDI testing, the PID testing protocol was modified on the basis of the new draft IEC62804 TS. In this round the modules were subjected to 288 hours of PID testing, and interim measurements were taken at 96, 192 and 288 hours and after a recovery step.

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 summarised in Fig. 2. PVDI01*, as well as PVDI09* and PVDI10*, showed power degradation before a recovery conditioning procedure. These three types of module have a low probability of exhibiting PID degradation under field operating conditions, because they demonstrated recovery, which would probably also be the case in the field. To date, four out of the ten tested modules designs exhibit PID under negative bias.

Group 2: humidity freeze (HF) and ultraviolet (UV)

The group 2 test sequence is designed to assess a module's susceptibility to moisture in the presence of freezing conditions caused by sub-zero temperatures after the module has been saturated by humidity, and at high levels of UV radiation. In the first two rounds of PVDI testing, the damp heat UV sequence was combined into a single test sequence to provide a means of assessing the effects of UV on modules in damp environments. However, no distinction between different module designs was possible, which led to a change in this test group 2: the intention was to make the testing regime harsher in order to induce detectable degradation, as the PVDI test protocol aims to reach the wear-out regime of modules. In the third round, the test was therefore modified to combine humidity freeze with UV.

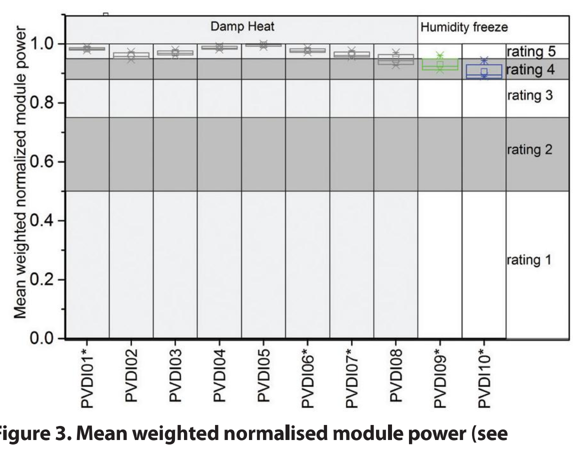
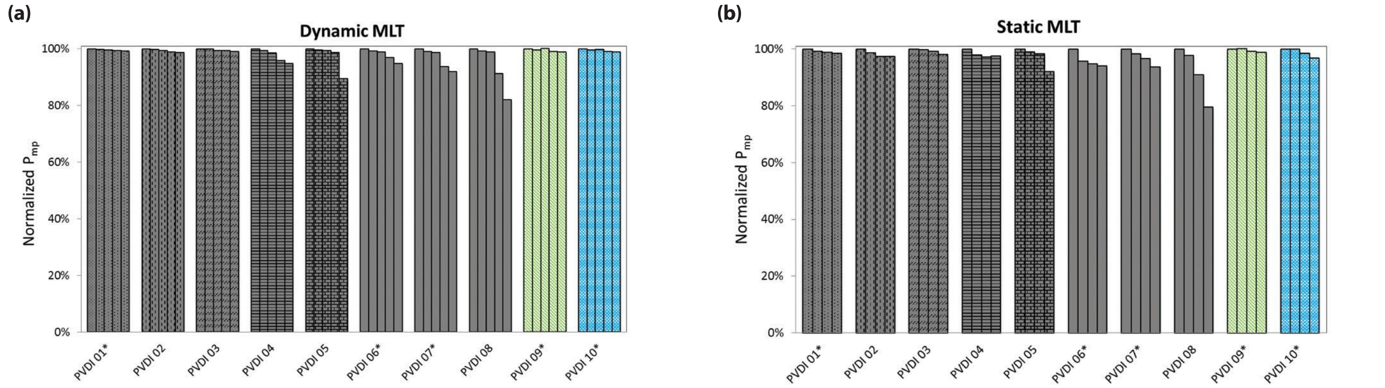


Figure 3. Mean weighted normalised module power (see Equation 1) of all modules of a test group after damp heat and 100W/m² UV exposure for PVDI01*–PVDI08, and after humidity freeze and 200W/m² UV for PVDI09* and PVDI10*.

The HF 10/UV sequence ('10' signifies 10 cycles) was combined into a single test sequence to provide a means of assessing the effects of UV on modules in the presence of moisture that forms ice crystals at extremely low temperatures. The HF 10 conditions represent a harsher environment, which is expected to accelerate degradation because of UV exposure; the sensitivity of module interfaces – such as junction box/back glass, edge seal/glass and interlayer/cell and glass – under low-temperature conditions and UV exposure is tested.

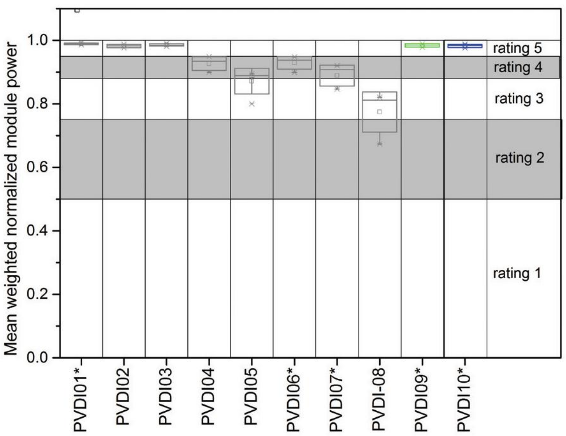
The test begins by mounting the module in a vertical orientation in a climatic chamber. Each module has a temperature sensor attached to either the front or the back surface in order to monitor and record the temperature of the module during the test. After 10 complete cycles, the modules are placed in a UV chamber, where they are subjected to high-intensity UV light for a total dose of 200kWh/m^2, which is double the UV dose in the previous rounds of testing. The exposure is carried out in two steps, with characterisation and re-saturation of the modules after each iteration. After a recovery time of 2–4 hours, the HF 10 and UV tests are repeated.

In the previous PVDI rounds one and two, the damp heat UV testing 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 could be drawn with regard to relative susceptibility to damp heat and UV stress. This test was hence

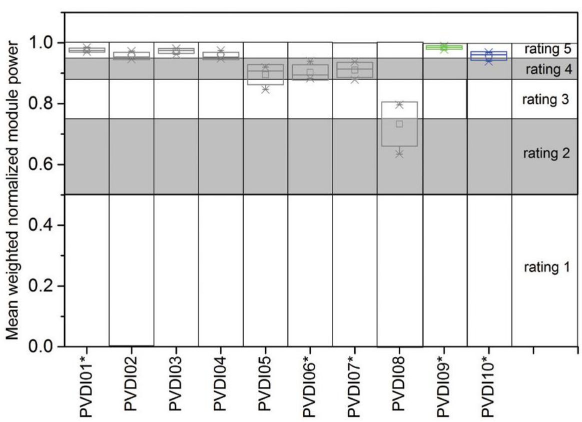


▲Figure 4. Normalised average performance degradation at the various test intervals of all modules of a test group in the case of: (a) dynamic loading; (b) static loading. The specific intervals are: initial, after loading, after 50 temperature cycles and after 10 humidity–freeze cycles.

revised in order for the wear-out regime for UV exposure to be reached, by replacing damp heat with humidity freeze and doubling the UV dose. Both the module designs PVDI09* and PVDI10* exhibited some degradation after the second round of UV testing: the module power output decreased by 5.1% in both cases. After exposure to the second HF 10 testing, however, the power recovers somewhat.



▲Figure 5. Mean weighted normalised module power (see Equation 1) of all modules of a test group after dynamic loading.



▲Figure 6. Mean weighted normalised module power (see Equation 1) of all modules of a test group after static loading.

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 static test is performed at a temperature of –40°C and the dynamic test is performed at –30°C in order to increase the stress in and between materials [15,16]. To perform the static test, the module is loaded in a downward direction (i.e. the side that is usually exposed to the sun faces the ground in this set-up) by 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 the most severe. The encapsulant modulus 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 interconnections, which may result in cell cracking and interconnection failure, for example.

The dynamic loading, with a maximum force of 2.4kPa at a frequency of 1.0Hz, flexes the module normal to the surface, in directions both positive and negative with respect to the plane of the module at rest. This is performed for two sets of 500 cycles each, with an interim characterisation to record any change in performance and to inspect for the appearance of cell cracks and damaged interconnects.

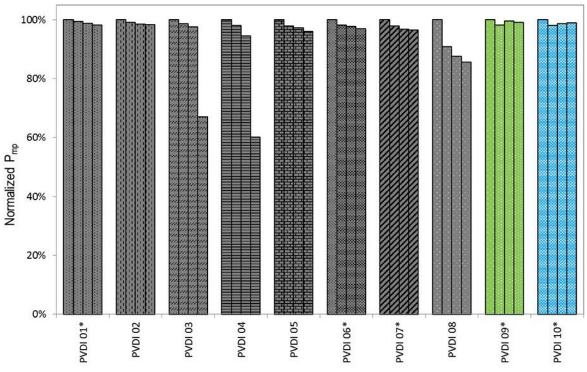
Following load testing, the modules are subjected to thermal cycling and humidity–freeze stresses: this is done to amplify crack propagation initiated during the load tests (Figs. 4–6). PVDI09* and PVDI10* did not exhibit any significant degradation after mechanical load testing or after thermal cycling and humidity–freeze tests. The likelihood of degradation due to static or dynamic mechanical loads is therefore very low for these modules.

Group 4: thermal cycling

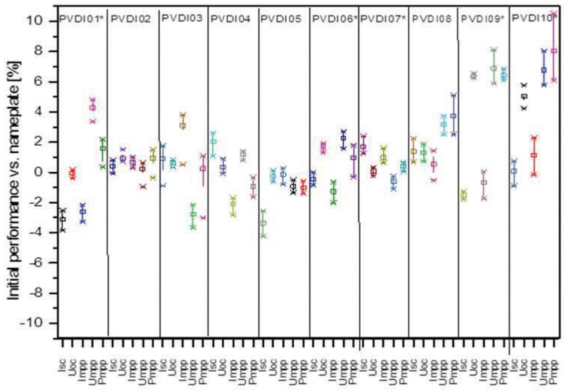
The group 4 test sequence assesses a module's ability to withstand the effects of shade-induced, diurnal and seasonal temperature changes. Under normal operating conditions, a module will be subjected to daily temperature excursions as well as more rapid temperature changes due to transient cloud cover. When temperature transients occur, stresses can be induced inside the modules as a result of the different thermal expansion characteristics of the various materials [17].

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; characterisations are performed after every 200 cycles.

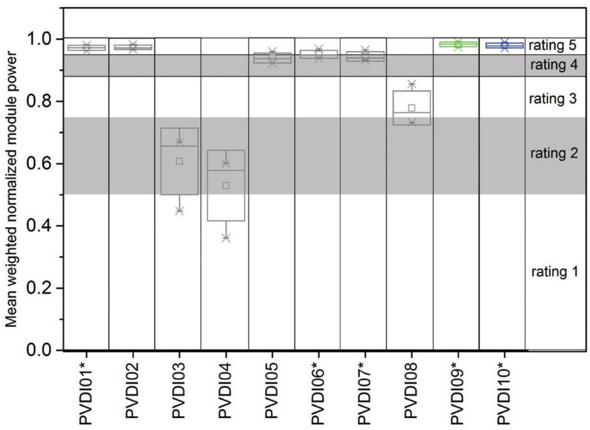
The results of the thermal cycling are shown in Figs. 7 and 8. Both PVDI09* and PVDI10* modules did not show any significant degradation in performance, even after 600 thermal cycles.



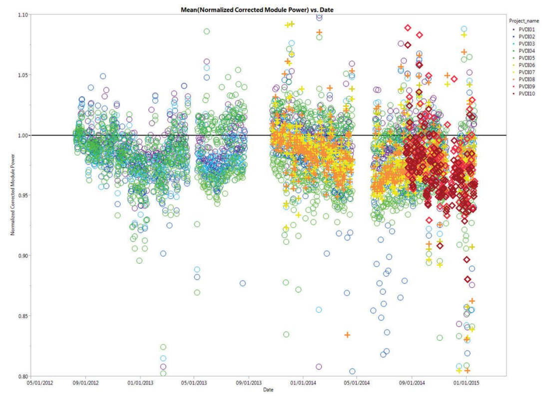
▲**Figure 7. Normalised average performance degradation at each interval of 200 cycles of all modules of a test group after thermal cycling.**



◀**Figure 10. Baseline performance parameters with respect to nameplate rating.**



▲**Figure 8. Mean weighted normalised module power (see Equation 1) of all modules of a test group after thermal cycling.**



▲**Figure 9. Normalised module power for all modules subjected to outdoor testing.**

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 [18]. 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; these data are 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 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. 9 shows the plot of the normalised module power for all the modules from the different rounds of PVDI over the entire duration of the PVDI programme so far.

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

Nameplate rating comparison

Fig. 10 illustrates initial module (STC) performance relative to the nameplate rating. Manufacturers may intentionally rate their modules below their expected initial performance to provide a performance buffer and reduce the risk of warranty claims. The results indicate that all of the module designs are within the manufacturers' specified power tolerance limits.

Module performance ratings

The module's performance is based on the measured electrical performance at STC. For the rating, a mean of the weighted normalised module power *P* is used:

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

where *n* is the number of performance measurements within a test sequence, and $\bar{P}_{n,i}$ is the mean power, normalised 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.

There are four main rating categories for each of the testing groups:

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. **Humidity–freeze and UV:** This category indicates a module's probability of surviving and performing as specified in environments with high temperature and humidity as well as sub-zero temperatures.

3. **Static and dynamic mechanical 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

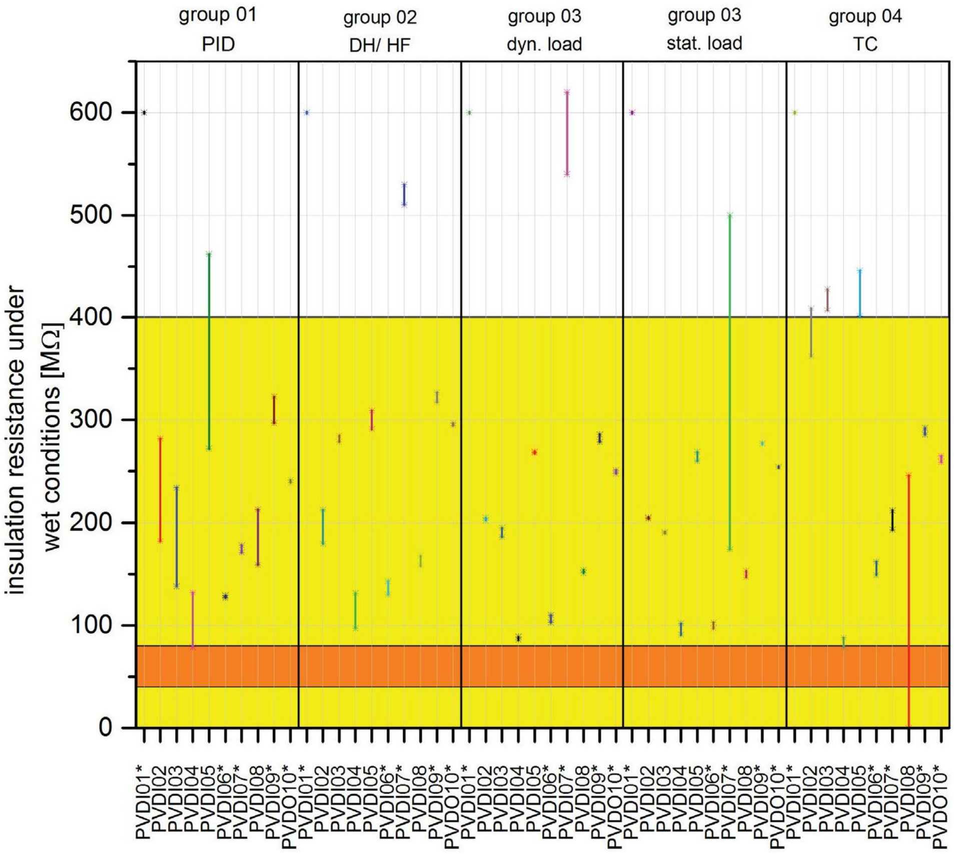
specified in environments where it will be subjected to constantly changing mechanical loads, such as wind.

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.

Table 1 summarises the performance rating criteria, and Table 2 lists the performance ratings for the modules tested.

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.**



▲**Figure 11. Wet leakage resistance results for all modules by project and test group.**

	Environmental conditions					
ID	PID	DH/UV	HF/UV/UV/HF	Dynamic load	Static load	Thermal cycling
PVDI01*	5	5	N/A	5	5	5
PVDI02	4	5	N/A	5	5	5
PVDI03	4	5	N/A	5	5	2
PVDI04	5	5	N/A	4	5	2
PVDI05	5	5	N/A	3	4	4
PVDI06*	5	5	N/A	4	4	5
PVDI07*	4	5	N/A	4	4	4
PVDI08	3	5	N/A	3	2	3
PVDI09*	5	N/A	4	5	5	5
PVDI10*	5	N/A	4	5	5	5

▲**Table 2. Module performance ratings based on mean weighted normalised power measurements.**

	Wet leakage [MΩ]			Wet leakage [MΩ•m^2]		
ID	Min	Max	Mean	Min	Max	Mean
PVDI01*	9,999	9,999	9,999	16,308	16,308	16,308
PVDI02	180	409	258	293	668	421
PVDI03	138	428	260	206	639	388
PVDI04	79	132	98	131	218	162
PVDI05	260	462	338	423	753	551
PVDI06*	97	162	128	154	257	202
PVDI07*	171	620	333	287	1,040	559
PVDI08	0	246	163	0	402	267
PVDI09*	277	327	300	200	235	216
PVDI10*	239	297	259	172	214	186

▲**Table 3. Wet leakage results for different modules tested under PVDI.**

Wet leakage results

The wet leakage current test is performed to evaluate the integrity of the package, which determines the safety of the module. 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 normalise the leakage resistance for the comparison ratings, the measurements are normalised by 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 [19]. 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. The wet leakage resistance results for all the PVDI modules are summarised in Table 3 and Fig. 11.

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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. Before that he was involved in developing new concepts for concentrator PV systems and conducting characterisation measurements on concentrator cells and modules.

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