PV RELIABILITY SCORECARD REPORT 2014

July 2014

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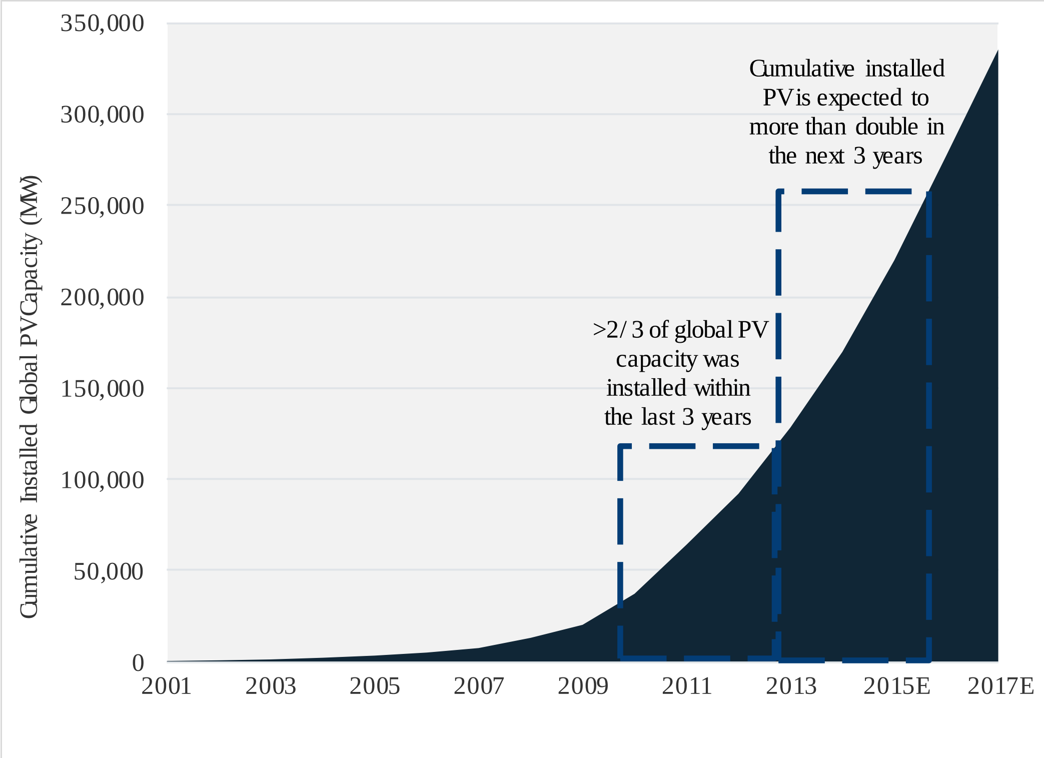
1. Introduction

In spring 1997, Siemens Solar Industries announced the extension of its module warranty guarantee, suddenly expanding it from a ten-year guarantee for purchases made before the announcement to a 25-year guarantee for purchases made afterward. This announcement marked the beginning of an industry standard, setting the 25-year warranty as a fundamental metric for project investors trying to understand the full-life economic viability of solar projects.

Yet even today, the risks associated with module performance over long periods of time remain largely unclear. Though modern software such as PVsyst can provide models on module performance for given environments, the accuracy of statistical analysis is limited. Field data is necessary for understanding module lifetimes. So what is limiting module quality claims?

For systems that have been in the field for a significant amount of time (e.g., more than twenty years), the value of findings is often limited by the quality of data. While this historic data provides critical information on module failure modes, factors such as a focus on prototype modules or compromised degradation data due to the replacement of faulty modules prevent claims about system lifetimes. As for modern capacity, more than two-thirds (~93 GW) of installed global PV capacity has been in the field for less than three years. It will be more than twenty years from now before actual lifetime field data for the majority of today's capacity can be gathered.

Figure 1.1 Cumulative Installed Global PV Capacity



Source: GTM Research

Additionally, while the 57 percent drop in module prices from 2010-2013 helped catapult industry growth by aiding project economics, industry concerns over cost reduction at the expense of module quality have emerged. Driven by the pressures of overcapacity, today's surviving vendors are those which have been able to react to growing pricing pressure and reduce costs (typically by purchasing lower-cost materials). Yet neither price nor top-tier ranking have been proven to indicate module quality competitiveness. While quality experts question whether this rapid cost reduction compromised product quality, module procurement conversations continue to center around balance-sheet strength and price-competitiveness.

With full-life field data more than twenty years away and without access to publicly available data comparing long-term module reliability by vendor, how can buyers and investors factor quality into their procurement discussions?

The PV Module Reliability Scorecard aims to address this critical problem. With its supplier-specific performance analysis, the Scorecard can help investors and developers generate quality-backed procurement strategies to ensure long-term project viability.

1.1. What Does Module Reliability Mean?

The Scorecard defines a reliable module as one which can deliver the energy yield required to fulfill a project's full-life expectations. Module failure is defined as a discrete event signaling that the module's power capability no longer meets warranty obligations.

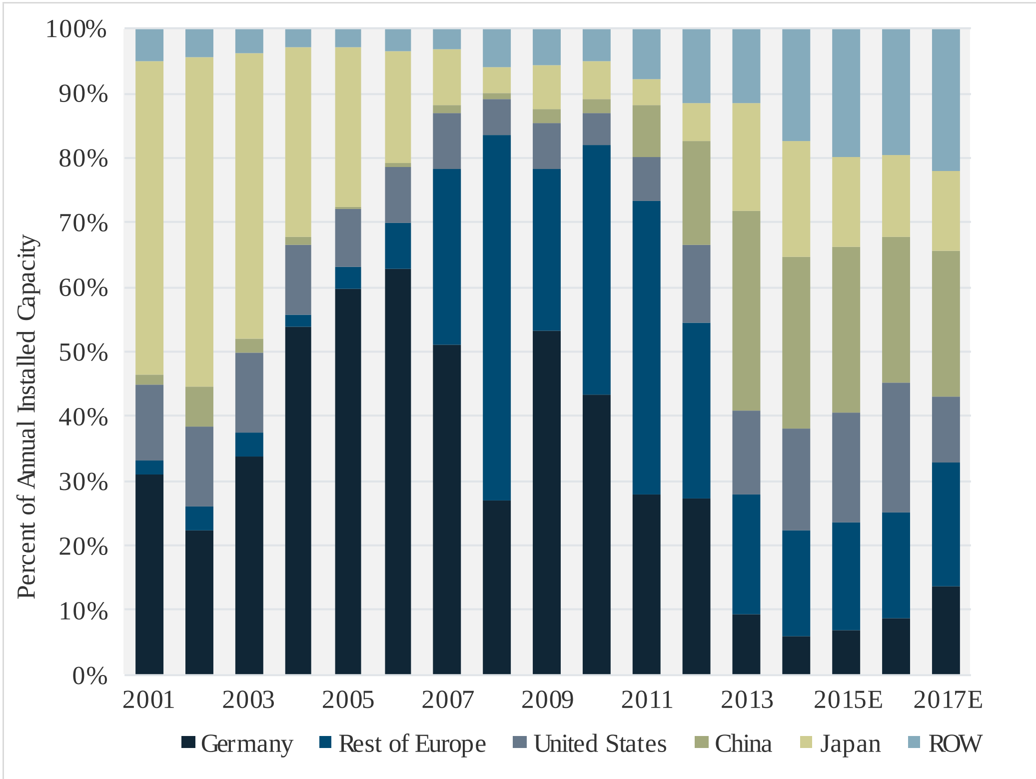
There are three fundamental factors that impact module reliability: technology (bill of material and design), quality assurance (monitoring the manufacturing process), and quality control (monitoring the manufactured products). Variations and errors in these processes have been shown to affect long-term module viability. These factors all play a role in a vendor's module reliability competitiveness. While the Scorecard does not directly evaluate module vendors on their technology or QA/QC processes, the quality resulting from manufacturers' decisions will emerge in the standardized testing process.

1.2. How Big Is the Module Reliability Problem?

As noted, two-thirds of today's cumulative capacity has been installed within the last three years. This increased pace of installation is expected to continue, with GTM Research forecasting cumulative capacity to quadruple by the end of the decade, growing from 128.3 GW by the end of 2013 to 528.1 GW by the end of 2020. Against this backdrop of strong demand and growing concern that systemic quality issues will affect an exponentially increasing proportion of PV projects, the extent of the module reliability problem has been largely misinterpreted and ill understood. Traditionally, the source of potential quality issues has been rooted in two areas.

- **The potential negative effects of material-focused cost-cutting measures.** As suppliers fought to remain viable in a price-competitive market during the recent downturn in the upstream solar space, the pace and extent of cost-reduction efforts surpassed expectations. The majority of cost reductions were achieved through lower material costs, with little publically available data on those reductions' effects on material quality. Procurement processes often focus heavily on financial bankability and price, but the effectiveness of current evaluation programs on module quality remains a subject of debate. As module manufacturers continue to face cost reduction pressures, procurement agents must improve their quality evaluation processes to ensure that cost reduction measures do not result in compromised module reliability.
- **The environmental impact of more diverse demand.** While the majority of solar demand historically has been in the EU, incentives to ship modules to a broader array of regions drove stronger global development. In 2013, for example, installations in China, Japan and the U.S. exceeded those of longtime market leader Germany. As demand grows more diffuse, modules must be able to meet the physical demands of various climatic conditions. Because the amount and type of environmental stress exerted on modules varies from region to region, power loss for the same module may be more significant in certain regions.

Figure 1.2 Annual Installations by Region



Source: GTM Research

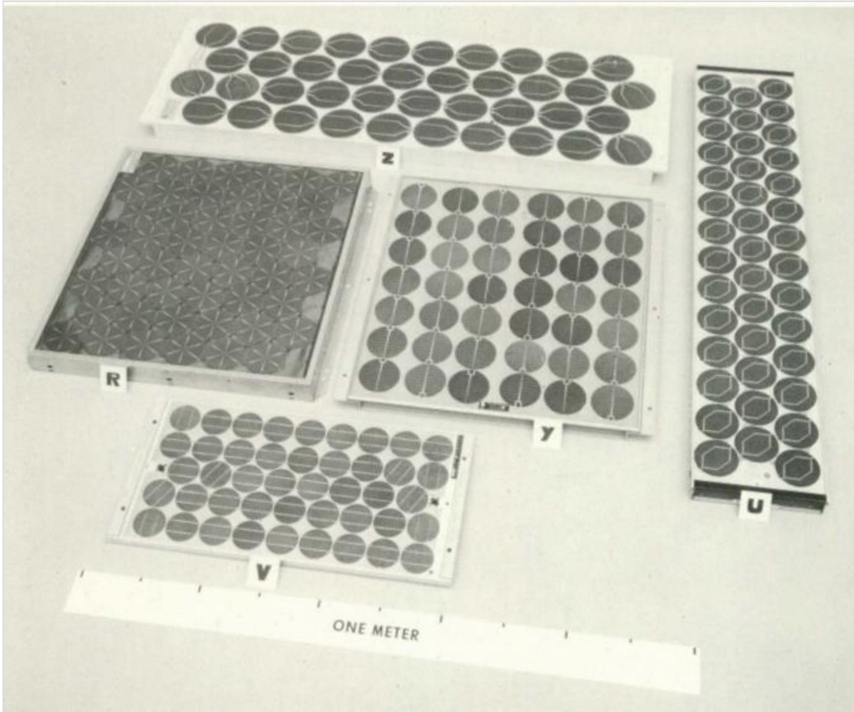
So how big is the module reliability problem? Quality experts agree that there is a spectrum of modules that perform well and there is a spectrum of modules that perform poorly. The problem exists on a case-by-case level. In order to ensure that projects are not saddled with modules that fall in the poor-performance end of the spectrum, downstream players must commit to the ongoing vetting of vendors.

2. Module Reliability and Testing

2.1. A Brief History of Module Reliability

When discussing the origins and early phases of terrestrial module reliability assessment, two bodies of work are typically cited: the Jet Propulsion Laboratory's Block Buy program and the Joint Research Center's European Solar Test Installation.

Figure 2.1 Jet Propulsion Laboratory's Block Buy Modules



Source: Jet Propulsion Laboratory

The JPL Block Buy program started in the mid-1970s as terrestrial PV module development started to gain traction. Throughout the program's lifetime, it had the goal of developing and implementing environmental tests for crystalline silicon modules. By the project's end, it had established many of the tests that are still used for reliability assessment today, including temperature cycling, humidity cycling and dynamic mechanical load.

The European Solar Test Installation (ESTI) project was initiated in the late 1970s and focused on both testing modules and creating standard performance metrics for solar cells. The project is ongoing and is currently focusing on developing an industry standard for module power verification.

These two programs formed a foundation for today's basic module qualification test, the International Electrotechnical Commission 61215, and safety test, the Underwriters Laboratories 1703.

2.2. The Limitations of Existing Certification and Qualification Regimes

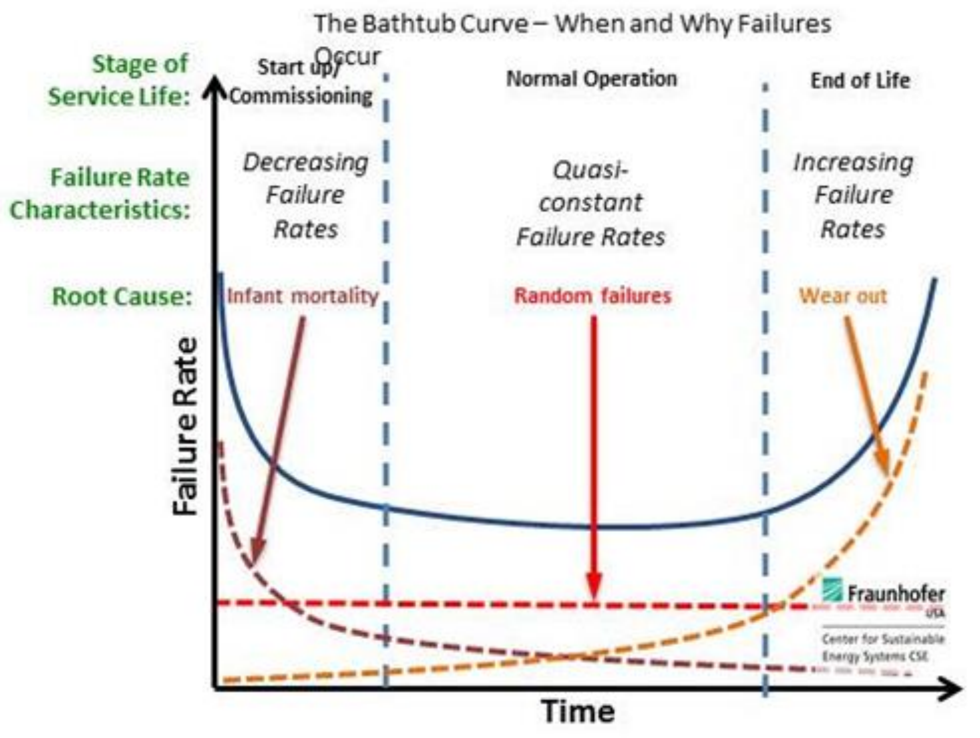
Though most projects require certification testing to ensure module quality, quality experts view industry-accepted standards as rudimentary and not truly indicative of module reliability.

First, it should be noted that the UL 1703 is purely a safety test. The goal of the test is to ensure that the module does not pose an electrical hazard during operation.

The IEC 61215 is the industry-accepted module quality assessment standard, applying environmental stress tests first developed in the JPL's Block Buy program. However, the scope of these tests accounts only for so-called infant mortality. This means the IEC 61215 is only well suited to weed out modules that would be likely to fail within the first years in the field.

Additionally, the IEC 61215 only functions as a pass/fail test. It does not report degradation rates after the test regimen, nor does it seek to discern the root cause of module failure. Since the magnitude of degradation at the beginning of a module's lifetime can have a significant impact on energy yields for the following twenty-plus years, information such as degradation rates can help differentiate which suppliers performed at the top end of the degradation spectrum, as opposed to those whose modules barely passed the infant mortality test.

Figure 2.2 The Bathtub Curve

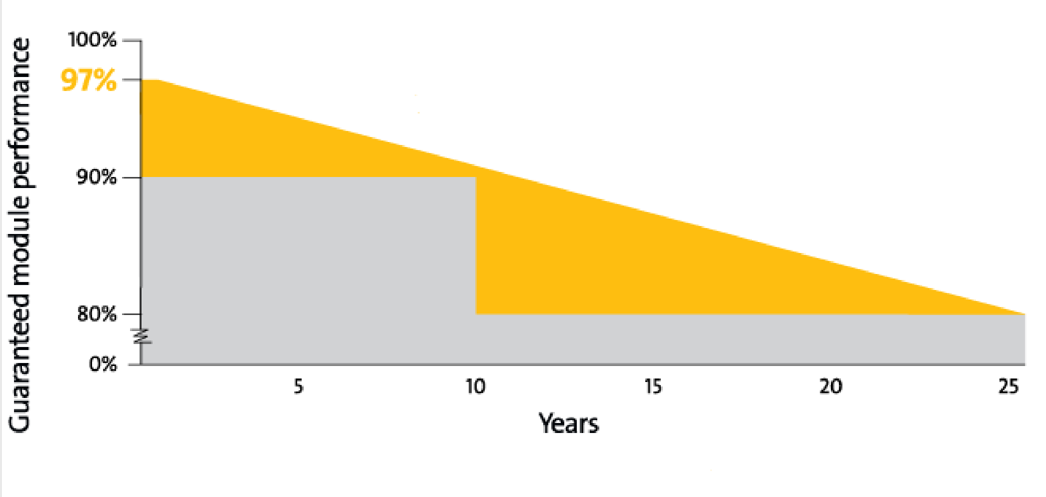


Source: Fraunhofer USA

2.3. Degradation Versus Failure

Power degradation over time is built into project expectations by means of warranty guarantees. The current standard 25-year warranty provides protection if modules degrade more than 3% within the first year and at a linear rate in the following years, with performance rates of 80% or more of its initial nominal operating power guaranteed in year 25.

Figure 2.3 Linear Warranty Versus Step Function Warranty



Source: SolarWorld

A module fails if it is unable to meet guaranteed power performance in a given year. Even if degradation levels exceed the manufacturer's guarantees for the given year, there is no evidence to support the notion that degradation levels will decline at linear rates in the years following. In fact, module defects such as hot spots can often increase the overall rate of module degradation. The year-over-year rate of degradation often looks more like a negative exponential chart rather than the linear chart shown in the module guarantee.

2.4. Reversible Versus Permanent Degradation

The Scorecard defines module failure as permanent, non-reversible degradation beyond the guaranteed performance level. However, to a certain magnitude and for specific tests, power degradation can be reversed.

Crystalline silicon modules typically do not exhibit reversible degradation. However, static charge buildup on the front surface of the crystalline silicon solar cell caused by potential induced degradation can lead to reversible degradation. In contrast, thin-film modules typically do exhibit reversible degradation or meta-stable behavior for degradation due to initial light exposure. The methods used to reverse and stabilize the effect vary by thin film technology.

3. The Reliability Testing Regimen

3.1. Test Design and Philosophy

There are three ways to extend environmental testing beyond the IEC 61215's infant mortality scope: increasing the test duration (by number or cycles or time period), using higher stress levels (e.g., increasing voltage), or combining stress tests.

However, there are numerous factors that constrain the extension of the tests to emulate the full 25-year guarantee. In some cases, current testing equipment may not have the capability to handle extensions beyond a certain level. Additionally, excessive stress can cause failure modes not seen in real-world conditions, therefore diminishing the value of test results. The Scorecard's test regimens are designed to maximize the number of years simulated in the face of the aforementioned limiting factors.

To rank and compare vendor results for each test, suppliers were divided into three categories: Performance Leaders, Class 2 Performers and Class 3 Performers. The results were divided to maintain the smallest standard deviation possible within each group.

3.2. Module Selection and Sampling Process

The Scorecard evaluates a minimum of ten companies for each testing regimen. Each participating manufacturer submitted 100+ serial numbers to PV Evolution Labs. To prevent module cherry-picking, twelve random samples were selected from the batch of serial numbers. Note that participating companies disclosed their identities at their own discretion, with some choosing to remain anonymous, and not all module manufacturers participated in every test. Additionally, all modules have fulfilled the standard IEC and UL certification requirements, which means they are free of defects that would likely cause early-life failure. Finally, it should be noted that the PVEL Scorecard program is voluntary. As such, participants are likely in the higher quality range, as poor performers would have been less likely to volunteer to participate.

3.3. Initial Module Preparation and Characterization

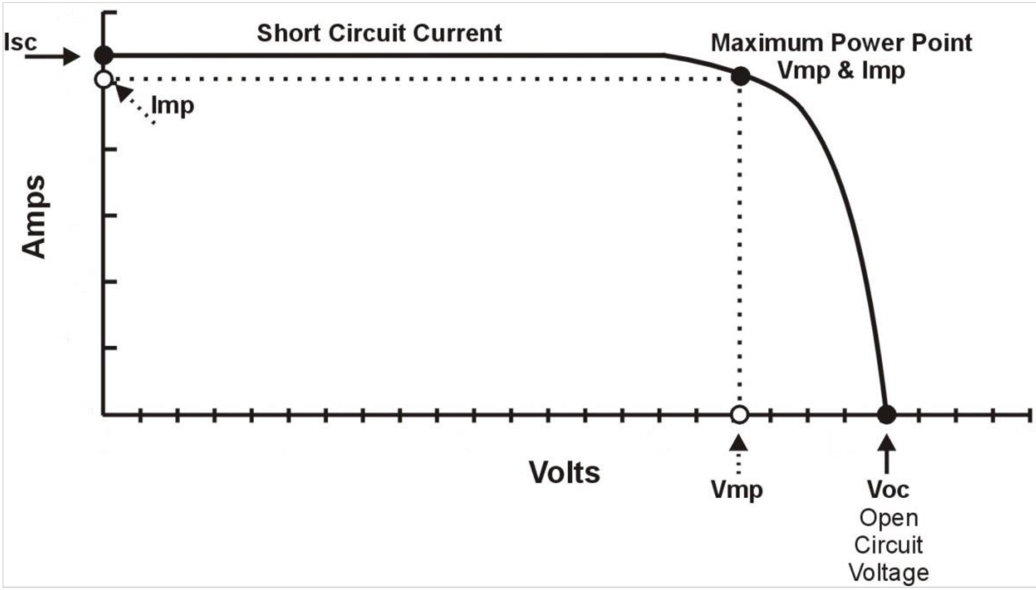
Figure 3.1 Initial Module Preparation and Characterization

Source: PV Evolution Labs

The processes of module preparation and characterization allow access to the performance metrics necessary to accurately measure and compare module reliability. Characterization is performed multiple times in each testing regimen, since the performance metrics are subject to change as power degradation occurs. Described in greater detail in the following subsections, this preparatory procedure was applied to all modules tested.

3.3.1. Flash Testing

Figure 3.2 I-V Curve



Source: Hong Kong Electrical and Mechanical Services Department

The most important parameters for characterizing module performance are found by creating current-voltage (I-V) curves. As previously noted, the values of these metrics are subject to change as modules degrade. By creating I-V curves before and after the testing regimens, the Scorecard can track a module's power degradation. To produce this chart and obtain the performance metrics listed below, the Scorecard uses the IEC's 60904 flash testing procedure.

Figure 3.3 Fundamental Performance Metrics

Performance Metric		Description
Short-Circuit Current	I_{SC}	The short-circuit current is the theoretical maximum current. On an I-V curve, I_{SC} is the maximum Y-axis value.
Open-Circuit Voltage	V_{OC}	The open-circuit voltage is the theoretical maximum current. On an I-V curve, V_{OC} is the maximum X-axis value.
Fill Factor	FF	The fill factor characterizes how far actual maximum power performance differs from ideal conditions. It is measured by dividing actual maximum power and the theoretical maximum power (I_{SC}*V_{OC}).
Maximum Power	P_{MAX}	Under standard testing conditions, maximum power is dictated by module material composition and the value of a module's theoretical maximum power.

Performance Metric		Description
Conversion Efficiency	η	Conversion efficiency is the ratio of maximum power to optical incident power.

Source: GTM Research

The procedure begins by exposing the modules to a short (10 msec.), uniform flash of xenon light (1 kW/m^2), a spectrum that mocks the sun at noon (Air Mass 1.5). The full I-V curve is obtained by sweeping the voltage during the light flash, from zero volts to open-circuit voltage (V_{OC}) or vice versa. The data is collected, graphed and assessed by a computer. To ensure consistency in data output, the module is tested under standard testing condition (STC) temperature, which is 25°C (77°F), and at zero angle of incidence.

3.3.2. Light-Induced Degradation

In response to their first extended exposure to light, modules experience a certain degree of power degradation in the first few weeks of installation. The phenomenon is called “light-induced degradation.” On average, LID for crystalline silicon modules ranges from 0.5% to 3%, with some modules exhibiting a loss of up to 5%. Manufacturers take this deterioration into account by factoring in a 3% power loss during the first year of the module warranty.

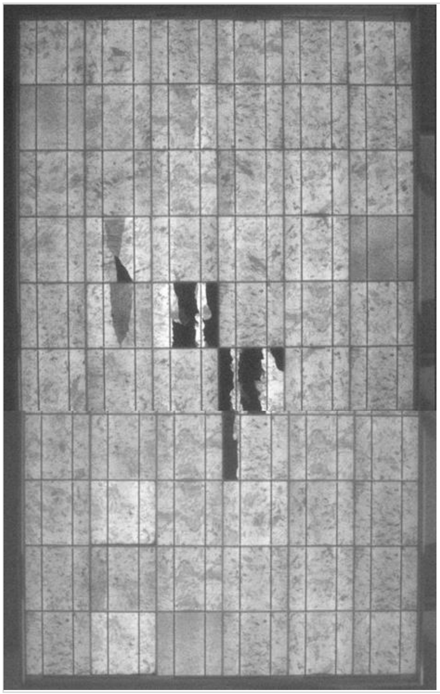
To mock this outdoor exposure effect, the Scorecard subjects the modules to an irradiance > 20kWh/m^2 until modules have reached a stable performance level or when $\frac{P_{MAX}-P_{MIN}}{P_{MEAN}} < 1\%$, where P represents respective power measurements.

3.3.3. Electroluminescence Imaging

Electroluminescence (EL) imaging is a diagnostic test procedure. Poor assembly processes, damage from shipping and physical stress during use can negatively impact a module’s power output. Some of these changes cannot be detected by the naked eye. EL testing uses near-infrared imaging to diagnose these defects in a non-destructive way.

To perform the test, an external voltage is applied to the module. The charge produces a release of photons, which glow in the near-infrared spectrum. Infrared cameras take a snapshot of near-infrared light emitted by the cells, showing where current flow has been disrupted and highlighting cell cracks or other defects. As shown in the following graphic, electrically inactive areas show as dark spots in the EL image.

Figure 3.4 Electroluminescence Imaging



Source: PV Evolution Labs

3.3.4. Wet Dielectric Test

During wet operating conditions such as rain, fog, dew and melting snow, encapsulating material (glass, EVA, backsheet, cable glands, and silicon sealants) provides an insulating layer between the electrically active cells and outside metal frames, structures and enclosures. If adhesion between the junction box and backsheet fail, or if the backsheet and EVA have cracks or pinholes, an electric shock hazard exists. The wet dielectric test (also known as the hipot test, short for "high potential") is a safety test designed to assess module insulation, which protects against electric shock hazard.

During the test procedure, the module is submersed in a tank so all surfaces except the cable entries of the junction box are underwater. For two minutes, a 1 kV test voltage is applied between the output connectors and the water. A high insulation resistance, or the ratio of applied voltage and the leakage current, indicates a well-insulated module. For modules with an area larger than 0.1 m^2, insulation resistance should not fall below 40 mΩ for every square meter.

3.3.5. Visual Inspection

Visual inspection is used to detect any major visual defects in a well-illuminated area (1,000 lux). Typical defects identified in this process include:

- Broken, cracked or torn external surfaces, including superstrates, substrates and junction boxes
- Bent or misaligned external surfaces, including superstrates, substrates, frames and junction boxes to the extent that the installation and/or operation of the module would be impaired
- Cracks in cells which could remove more than 10% of the cell's area from the electrical circuit of the module
- Voids in or visible corrosion of any of the active circuitry of the module that extends through more than 10% of the cell
- Bubbles or delamination forming a continuous path between any part of the electrical circuit and the edge of the module
- Loss of mechanical integrity, to the extent that the installation and/or operation of the module would be impaired
- Module markings (label) are no longer attached or the information is unreadable

3.4. Recurring Procedures

When applicable, the following test procedures were used in select Scorecard test regimens.

3.4.1. The Hot Spot Test

Hot spots are the result of heat localization due to factors such as cell mismatch, interconnection failures, partial shadowing (by trees and buildings) or module soiling (by dirt or bird excrement). At extremes, this focused release of heat burns through module layers, and in some cases, cracks or breaks the module's glass. Multiple field studies have shown that modules with hot spots show higher power degradation rates than non-hot-spot modules.

Figure 3.5 Module Failure Mode: Hot Spot

Source: LG Energy

When a cell's operating current exceeds the short-circuit current (the current under zero load conditions) of the faulty or shadowed cells, the cells are forced to go from forward bias to reverse bias. This means voltage polarity flips from positive to negative and the cell must dissipate power (power = current * voltage). Bypass diodes are installed in parallel to a series cell string to limit power loss from partially shaded cell strings and to reduce risk of extreme heat localization.

3.4.2. Bypass Diode Test

In ideal conditions, modules receive an uninterrupted, uniform flow of sunlight. In reality, partial shading from soiling, cloud coverage, adjacent buildings or trees can disrupt uniform module illumination, causing some parts of the module to be more electrically active than other parts. Inside the module, this disruption causes the current for less active cell strings to go through the bypass diodes, an event which can lead to hot spots and reduced power output. Bypass diodes are added in parallel to cell strings (~12 to 24 cells) to electrically remove underperforming cell strings from the module circuit. In cases where module temperature and current conditions are both high, bypass diodes undergo thermal stress. This can cause the bypass diodes to fail and allow current mismatch to ensue.

The Scorecard tests diode functionality at the end of each stress test leg to ensure all diodes are still fully functional.

4. PV Reliability Scorecard Tests and Results

4.1. Results Summary

Overall, participating module vendors performed well, with relatively few incidents of outright failure as defined by performance degradation of greater than 20% (thereby potentially violating 25-year module performance warranties). In particular, the modules tested were relatively well suited to testing involving damp heat, humidity-freeze, dynamic mechanical load, and potential induced degradation (PID), with a handful of manufacturers exhibiting little or no appreciable degradation over the testing lifetime.

Furthermore, although some tests revealed some relatively poor performers, overall results indicated the sampled population performed well. For example, although one supplier exhibited 10.7% degradation after the damp heat test, while all other manufacturers showed degradation results under 3%.

Finally, judicious interpretation of the results is required. For example, many modules failed the negatively biased PID test, the PID- regimen, with one manufacturer exhibiting total failure. However, the PID- test is only valid for systems where the cells are biased at a lower voltage than the frame, which is common in ungrounded (floating) and positive-grounded systems. However, these degradation mechanisms are not relevant in a negative-grounded system, which is the most common configuration in the U.S.

Figure 4.1 PV Reliability Scorecard Test Results Summary

Reliability Test	Top Result	Bottom Result	Mean Result	Median Result	Std. Dev.
Thermal Cycling	-1.0%	-6.4%	-3.1%	-3.2%	1.7%
Damp Heat	0.0%	-10.7%	-1.7%	-0.9%	2.7%
Humidity-Freeze	0.0%	-4.2%	-1.1%	-1.3%	1.2%
Dynamic Mech. Load	0.0%	-6.3%	-1.1%	-0.5%	1.5%
PID+	0.0%	-2.7%	-1.3%	-1.1%	0.8%
PID-	0.0%	-100.0%	-34.4%	-18.4%	35.6%

Source: GTM Research, PVEL

4.2. Thermal Cycling

Solar modules are constructed from various materials, each independently characterized by a coefficient of thermal expansion (CTE). As ambient temperature fluctuates, materials react in accordance with their coefficients. In cases where adjacent materials have mismatched CTEs and there is a significant fluctuation in temperature, materials can undergo interfacial stress which can trigger the failure modes listed in the following table.

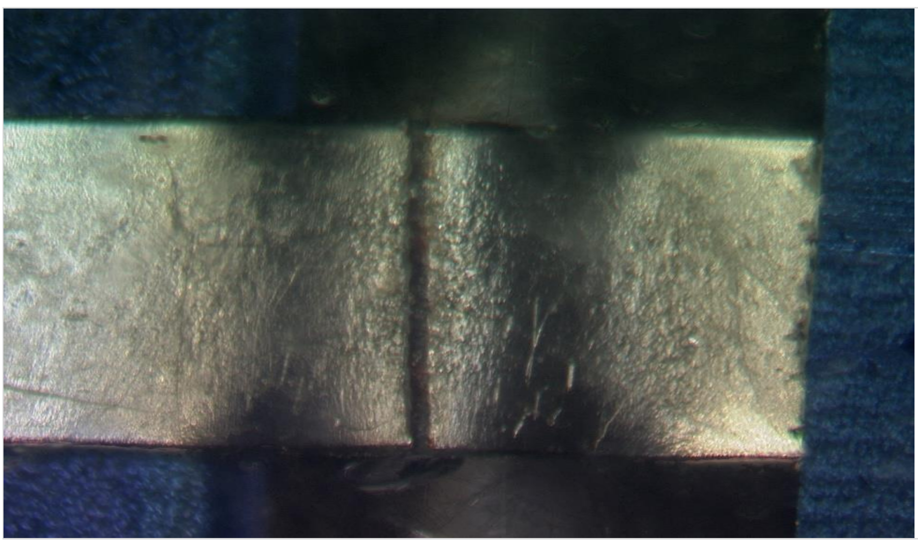
Figure 4.2 Thermal Cycling Failure Modes

Thermal Cycling Failure Modes	
	Broken interconnects
	Broken cells
	Solder bond failures
	Junction box adhesion

Source: PV Evolution Labs

The thermal cycle test mimics climates with extensive, cyclical temperature fluctuations capable of inducing such failure modes. Real-world environments include dry deserts such as interior deserts in North America, the Middle East, Australia and Chile, where the average temperature variation over the year is 20°C to 25°C (68°F to 77°F), with maximum temperatures reaching 43.5°C to 49°C (110°F to 171°F) and minimum temperatures that can reach -18°C. By increasing the tested temperature range, as well as the rate at which modules are cycled through temperature shifts, the thermal cycle test accelerates years of real-world conditions in a shorter testing period.

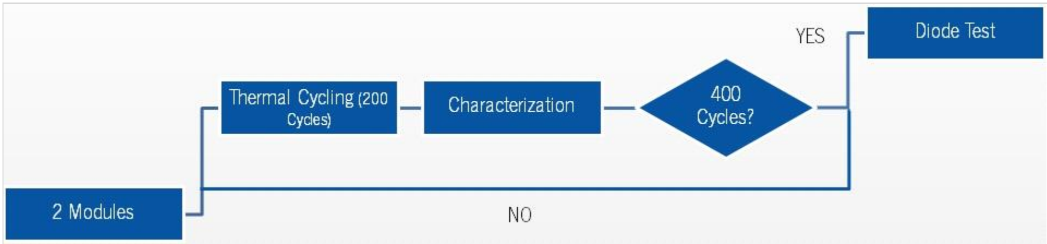
Figure 4.3 Broken Interconnect



Source: PV Evolution Labs

The Thermal Cycling Test Procedure

Figure 4.4 Thermal Cycling Test Procedure



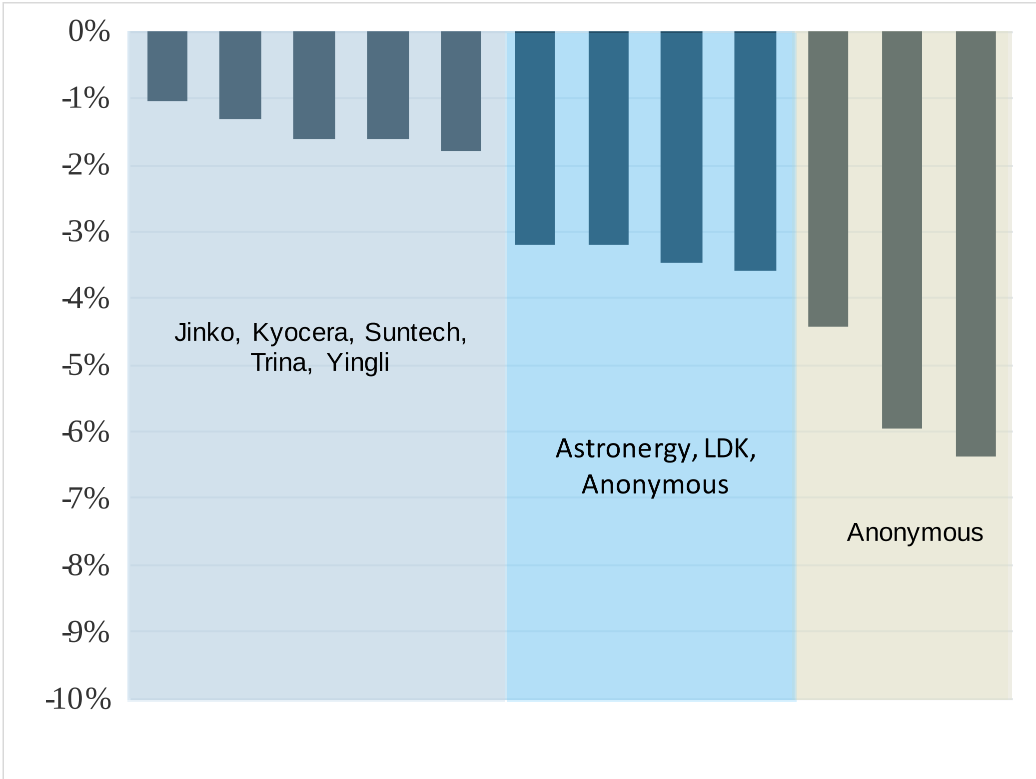
Source: PV Evolution Labs

Following preparation and characterization, two modules are cycled from -40°C (±2°C) to 85°C (±2°C) (104°F to 185°F). When the temperature rises above 25°C, the maximum power current is sourced into the modules, allowing heat localization. IEC 61215 requires only 200 cycles, which, via existing field and weather modeling data, is estimated to represent several years of field exposure. The Scorecard procedure extends the test to 400 cycles, characterizing the modules every 200 cycles. This simulates an estimated fifteen years of field performance. It should be noted that the test procedure does not combine all conditions that modules experience in desert environments. High-intensity light exposure is also present in arid desert environments and can lead to failure modes such as encapsulant browning.

Thermal Cycling Test Results

Twelve companies participated in the thermal cycle test with degradation rates varying from -1.0% to -6.4%. As shown in the graph below, four out of five of the top-performing modules were Chinese-produced; the one exception was a module from Kyocera, a Japanese company.

Figure 4.5 Thermal Cycling Test Results



Source: PV Evolution Labs

Historic data has shown thermal cycling to be one of the toughest tests for modules. Compared to every other Scorecard test, thermal cycling is the only regimen where all modules in the Performance Leaders group showed some measure of power degradation. In other words, no module was immune to degradation during the thermal cycling test.

Since the Scorecard's thermal cycle test simulates approximately fifteen years of field conditions, degradation shouldn't exceed 13.5% with a standard linear warranty (−0%/+3% power rating, -0.7%/Y degradation following the first year). Under those conditions, all modules put through the thermal cycle test "passed" based on their warranty terms. In real-life conditions, thermal cycle conditions are coupled with other environmental conditions, like UV exposure, which would likely increase module degradation rates.

4.3. Dynamic Mechanical Load

The dynamic mechanical load (DML) test determines a module's ability to handle large pressure loads; synonymous real-life conditions include regions with wind, snow or ice loads, as well as seismically active regions. Significant or repetitive pressure can create deflections on a module, resulting in the failure modes listed in the following table.

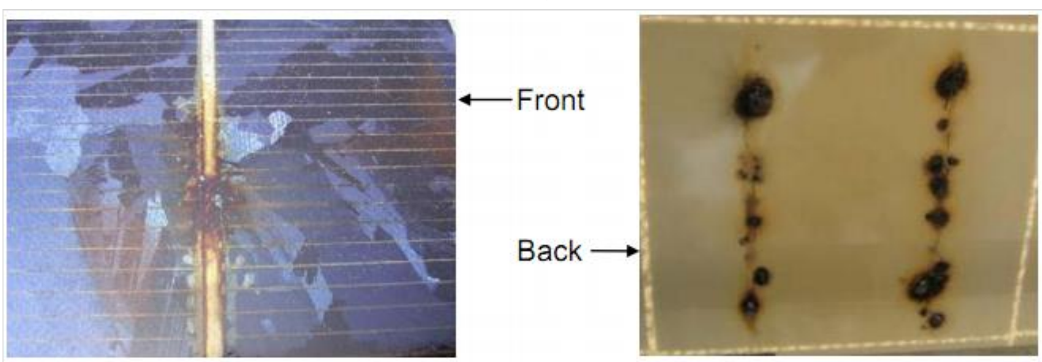
Figure 4.6 Dynamic Mechanical Load Failure Modes

Dynamic Mechanical Load Failure Modes	
	Glass fracture
	Cracked cell
	Solder joint degradation
	Frame tape or frame adhesive failure
	Frame fatigue

Source: PV Evolution Labs

Various aspects of the processing steps (such as soldering and cell etching), as well as the selection of glass, EVA and backsheet material, protect modules from the physical damage that pressure loads may cause. It should also be noted that in real-life conditions, large pressure loads are often coupled with and exacerbated by other environmental conditions such as cold, wet environments. Therefore, in order to form a complete understanding of pressure-induced failures, the Scorecard's procedure combines high-pressure loads with other testing regimens, thermal cycling and humidity freeze. This test procedure is known as the dynamic mechanical load regimen.

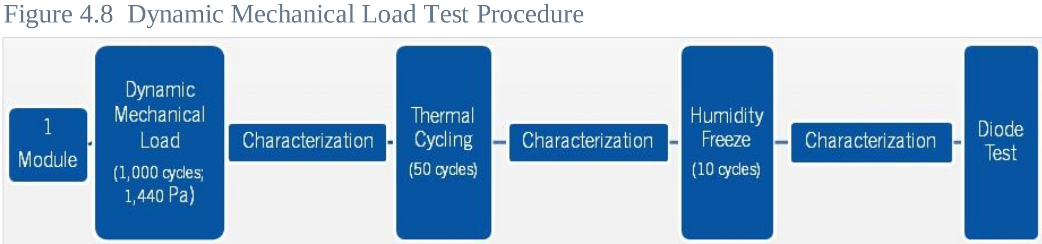
Figure 4.7 Module Failure Mode: Solder Joint Degradation



Source: PV Evolutions Labs

The Dynamic Mechanical Load Test Procedure

Figure 4.8 Dynamic Mechanical Load Test Procedure



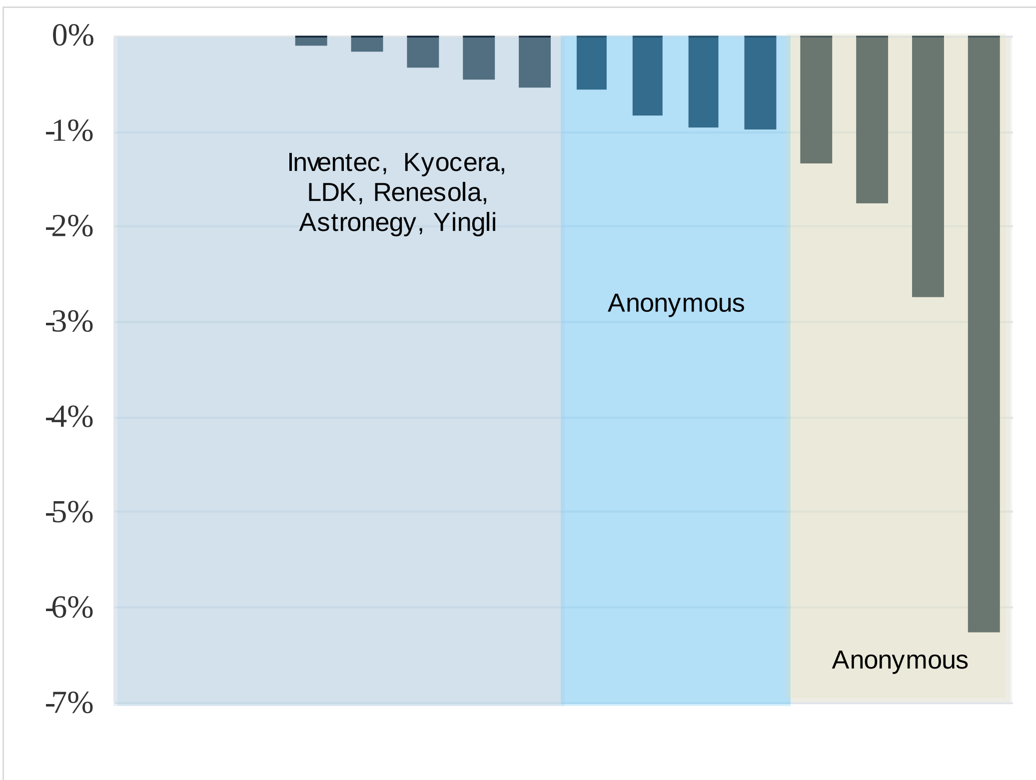
Source: PV Evolution Labs

In order to test real-world performance, the tested module is mounted per the manufacturer's specifications. The standard IEC 61215 test calls for applying three cycles of uniform loads (2,400 Pa) to the front and back surfaces of the module for one hour. PVEL extends the test by first exposing the module to 1,000 mechanical deflections at 1,440 Pa. Following these deflections, modules go through a series of temperature- and moisture-focused environmental tests. The initial cyclic mechanical deflection causes micro-cracks to form, while the combined environmental stresses cause the micro-cracks to propagate.

Dynamic Mechanical Load Test Results

Sixteen companies participated in the dynamic mechanical load test with degradation rates varying from 0% to -6.3%. Four out of six of the top-performing modules were Chinese-produced. Another two were non-Chinese: Japanese manufacturer Kyocera and a Taiwanese manufacturer, Inventec. The manufacturer of one of the top-performing modules chose not to disclose its name.

Figure 4.9 Dynamic Mechanical Load Test Results



Source: PV Evolution Labs

Comparing variance among the top ten performers for each Scorecard test shows that the DML regimen had the smallest variance in terms of performance degradation. Additionally, high pressure load conditions for the Scorecard's leading performers resulted in insignificant power degradation. All modules in DML's Performance Leader group and the Class-2 performance group showed minimal to no power degradation.

In the Class-3 performance group, the performance of one supplier caused a comparatively wider variance in degradation rates. The gap in performance provides some context to current material quality and processing variability among small subsets of suppliers.

4.4. Humidity-Freeze

In the continental interior of regions of the Northern Hemisphere, between 40° and 70° latitude, humidity and large seasonal temperature variations cause a variety of environmental stressors on modules.

Figure 4.10 Module Failure Mode: Corrosion

Source: PV Evolution Labs

Specifically, in the Northeastern regions of North America, Europe and Asia, where temperatures are subject to quick shifts to below-freezing conditions, this can cause in-situ freezing, bringing about ice crystals that exert physical stress on module packaging. The humidity-freeze test mimics environmental conditions where ambient moisture and freezing temperatures coexist.

Figure 4.11 Humidity-Freeze Failure Modes

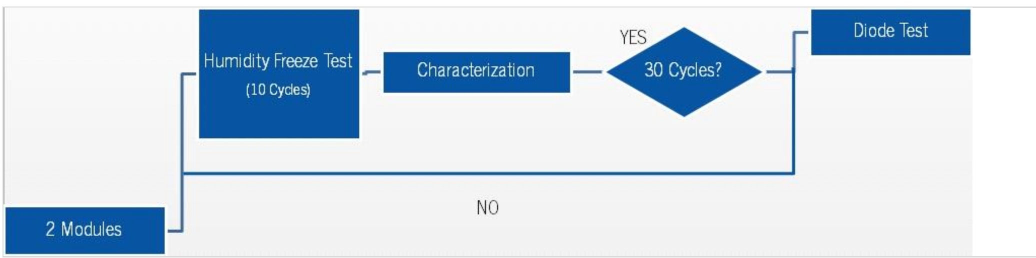
	Corrosion of cell metallization
	Junction box failure

Humidity-Freeze Failure Modes	
	Cracked cell
	Delamination
	Junction box detach
	Quick connector embrittlement
	Frame tape or frame adhesive failure
	Outgassing of in-laminate materials
	Backsheet embrittlement
	Discoloration of frame, junction box or polymeric materials
	Backsheet stack layer delamination

Source: PV Evolution Labs

The Humidity-Freeze Test Procedure

Figure 4.12 Humidity-Freeze Test Procedure



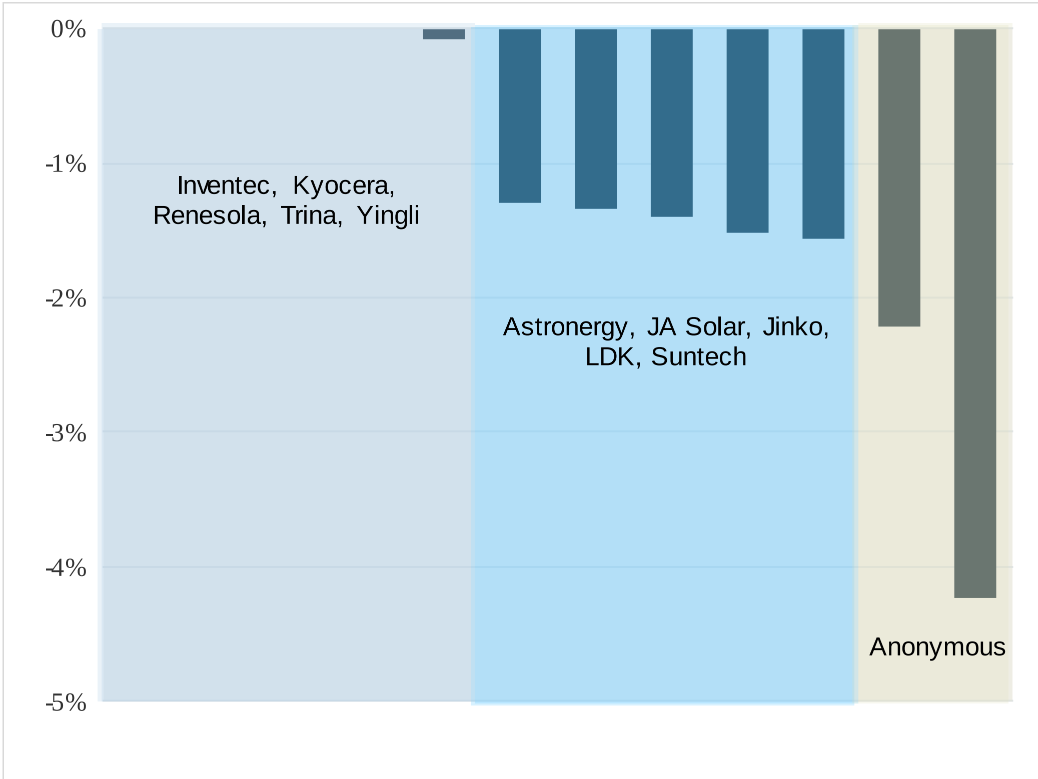
Source: PV Evolution Labs

In the standard IEC 61215 test, modules are exposed to temperatures of 85°C±5°C (185°F±9°F) and a relative humidity of 85% (±5%) for a minimum of 20 hours. This step ensures the modules are saturated with water. The temperature is then rapidly dropped to -40°C±5°C (-40°F±9°F) for a minimum of a half-hour (maximum 4 hours), freezing any moisture within the module. This cycle is completed a total of 10 times in the IEC's test procedure. PVEL extends the test by cycling a total of 30 times.

Humidity-Freeze Test Results

Twelve companies participated in the humidity-freeze test, with degradation rates varying from 0% to -4.2%. Three out of five of the top-performing modules were Chinese-produced. The other two top companies included Japanese manufacturer Kyocera and Taiwanese manufacturer, Inventec.

Figure 4.13 Humidity-Freeze Test Results



Source: PV Evolution Labs

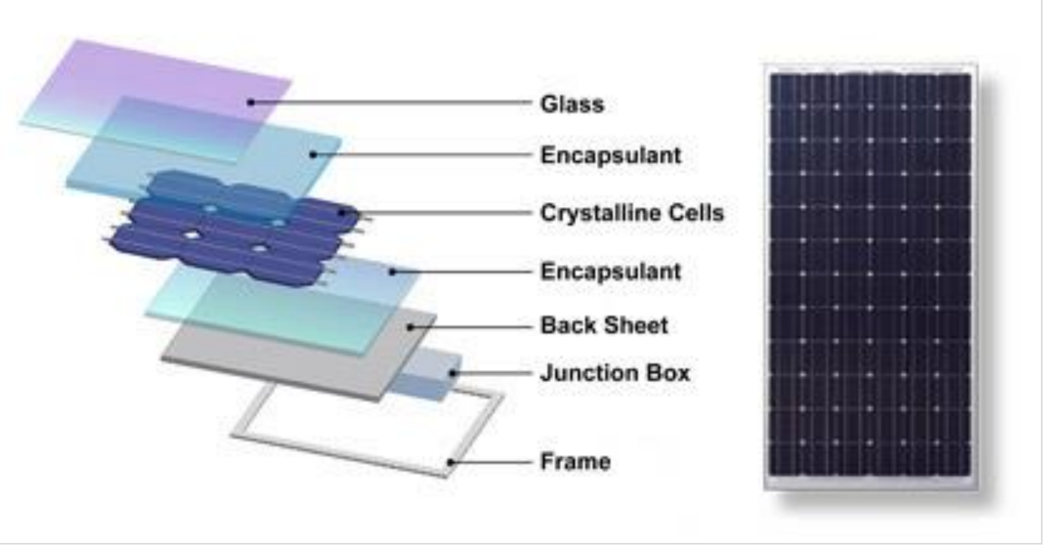
Degradation rates for vendors in the Performance Leaders group were negligible for the humidity-freeze regimen. In fact, since four out of the five vendors showed zero degradation, more producers posted no power loss after the humidity-freeze testing regimen than in any other Scorecard test.

Degradation rates in the Class 2 and Class 3 performance groups were comparatively more significant. However, the magnitudes of degradation observed in these two performance groups do not indicate module failure.

Minimal power degradation during the humidity-freeze regimen may speak to the quality of the suppliers tested, or, more generally, the mild stress that such conditions place on modules. Regardless, results show a clear difference between vendors that tested into the Performance Leaders group and all others.

4.5. Damp Heat

Figure 4.14 Layers of a PV Module



Source: Dow Corning

Solar cells are encapsulated and connected to multiple materials. On the outside, the glass is laminated to a polymer backsheet. Inside this shell, materials such as ethyl-vinyl acetate (EVA) are used to create an optically transparent environmental seal. Depending on the material properties of these layers and sealants, moisture can diffuse into the interfaces and insulating materials.

Figure 4.15 Damp Heat Failure Modes

Damp Heat Failure Modes	
	Corrosion of cell metallization
	Bypass diode failure
	Delamination
	Junction box detach
	Quick connector embrittlement
	Outgassing of in-laminate materials
	Backsheet embrittlement leading to cracks
	Discoloration of frame, junction box or polymeric materials
	Backsheet stack layer delamination

Source: PV Evolution Labs

Long seasons of high-temperature weather and moist conditions along the coastal regions of the U.S. and in parts of EU and Asia (e.g., Romania, Turkey, India, and Thailand), as well as some subtropical regions in South America (Brazil), result in conditions that are likely to bring about the failure modes listed in Figure 4.15. To test for these conditions, the Scorecard uses a damp heat test regimen.

Figure 4.16 Module Failure Mode: Laminate Outgassing

Source: PV Evolution Labs

The Test Procedure

Figure 4.17 Damp Heat Test Procedure

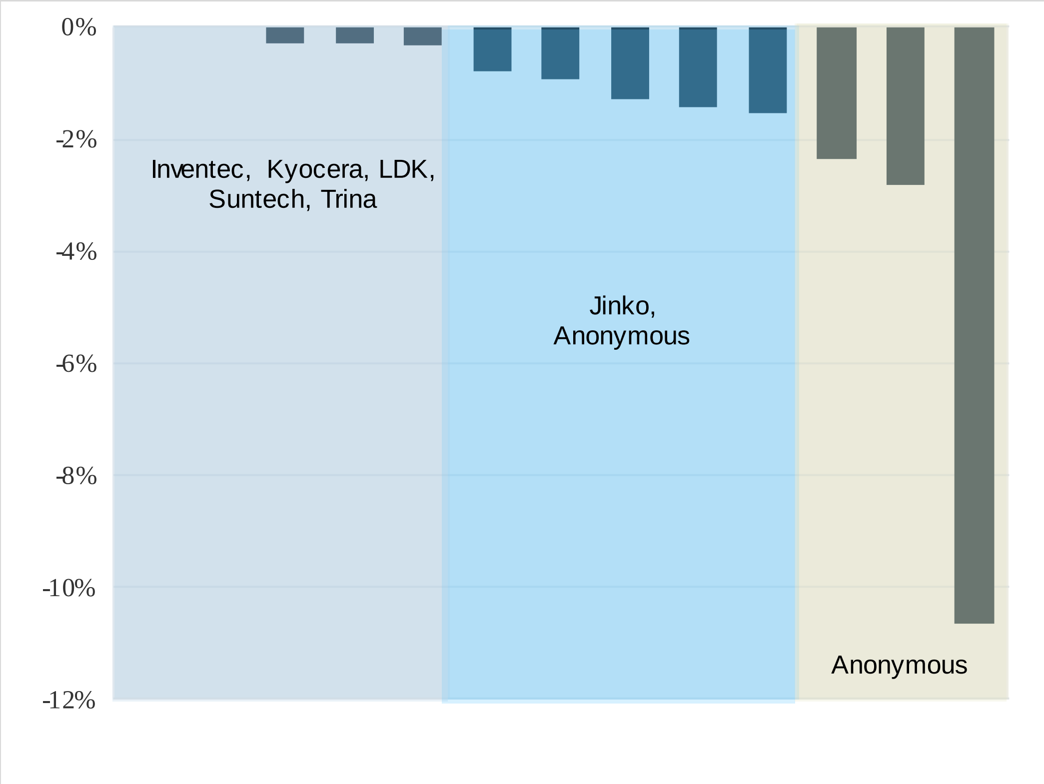
Source: PV Evolution Labs

In the IEC 61215 test procedure, two modules are held at a constant temperature of 85°C±5°C (185°F±9°F) and a relative humidity of 85% (±5%) for a minimum of 1,000 hours. This allows modules to become completely saturated with moisture. According to PV Evolution Labs, several modules that pass this certification test will fail if the test is extended an additional 250 hours. The Scorecard extends the test procedure to 2,000 hours.

Damp Heat Test Results

Thirteen companies participated in the damp heat test, with degradation rates varying from 0% to -10.7%. Three out of five of the top performing modules were Chinese-produced. The other three top companies include Japanese manufacturer Kyocera and Taiwanese manufacturer Inventec.

Figure 4.18 Damp Heat Test Results



Source: PV Evolution Labs

Two out of five producers in the Performance Leaders group showed no degradation after the Scorecard's damp heat test regimen. The Class 3 group showed the most significant degradation rates, with results varying from -2.3% to -10.7%, but this large variance can be explained by the particularly poor performance of one vendor.

It is important to note that though it is a common outcome of the damp heat test, glass corrosion is an artifact of the test rather than a prediction of real-world performance. Because high heat and humidity are maintained at a steady rate, sodium ions leach out of the glass to the front surface. This causes microscopic pitting in the glass, which comes to function as an anti-reflective coating, causing the performance to improve by up to 1% to 2%. The only time the glass corrosion effect has been reported in the field is at a PV installation in front of a fountain.

4.6. PID+ and PID- Test

During operation, cells experience a voltage bias relative to their frame. Increasing string voltage (which increases this voltage bias for large commercial and utility-scale plants) is thought to be a means to reduce system costs, but when the voltage bias increases beyond ± 600 V in high-temperature and humid conditions, leakage current increases. This causes negatively charged ions to diffuse toward either the cell or frame and positive ions to move in the opposite direction (frame or cell), an effect which can disrupt the normal electrical function in solar cells and can result in a large power-output reduction. This effect is commonly known as potential induced degradation or PID. In ungrounded or floating systems, sodium ions from the glass are commonly thought to penetrate the cell's silicon nitride (SiN) antireflection coating through small pinholes and damage the PN junction.

Figure 4.19 Failure Mode: PID

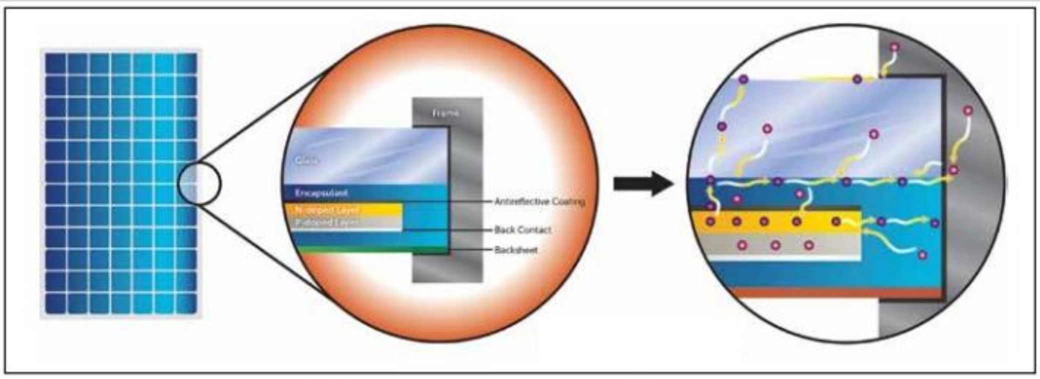


Figure 1 - Leakage current and voltage potential (negative potential shown) cause negative (-) (purple) ions to migrate away from the semiconductor, as positive (+) (pink) ions migrate toward the semiconductor from the glass and package, and the module's external environment.

Source: Advanced Energy

Figure 4.20 PID Failure Modes

PID Failure Modes	
	Electrochemical corrosion of busbars or cell metallization
	Ion migration / polarization / potential induced degradation

Source: PV Evolution Labs

The risks associated with PID have only recently been discovered and are still not well understood, though the selection of various types of module glass, encapsulation materials and anti-reflective coatings has been shown to have an impact on performance in PID conditions. At the current juncture, it is postulated that along with relevant environmental conditions (high temperature and humidity), the magnitude and polarity of the voltage bias are directly related to the severity of the effect. Europe is the focus of the majority of PID degradation conversations because of the typical grounding configurations used in that region. Solar installations in the U.S. have largely been protected from these effects because most systems in the country are negatively grounded.

It should be noted that there are reversible and non-reversible PID mechanisms. Electrochemical corrosion and sodium damage to the PN junction is irreversible, while PID due to the accumulation of static charge on the surface of cells, also known as polarization, can be countered by equalizing the charge with a reverse voltage at nighttime.

The PID Test Procedure

Figure 4.21 PID Test Procedure

Source: PV Evolution Labs

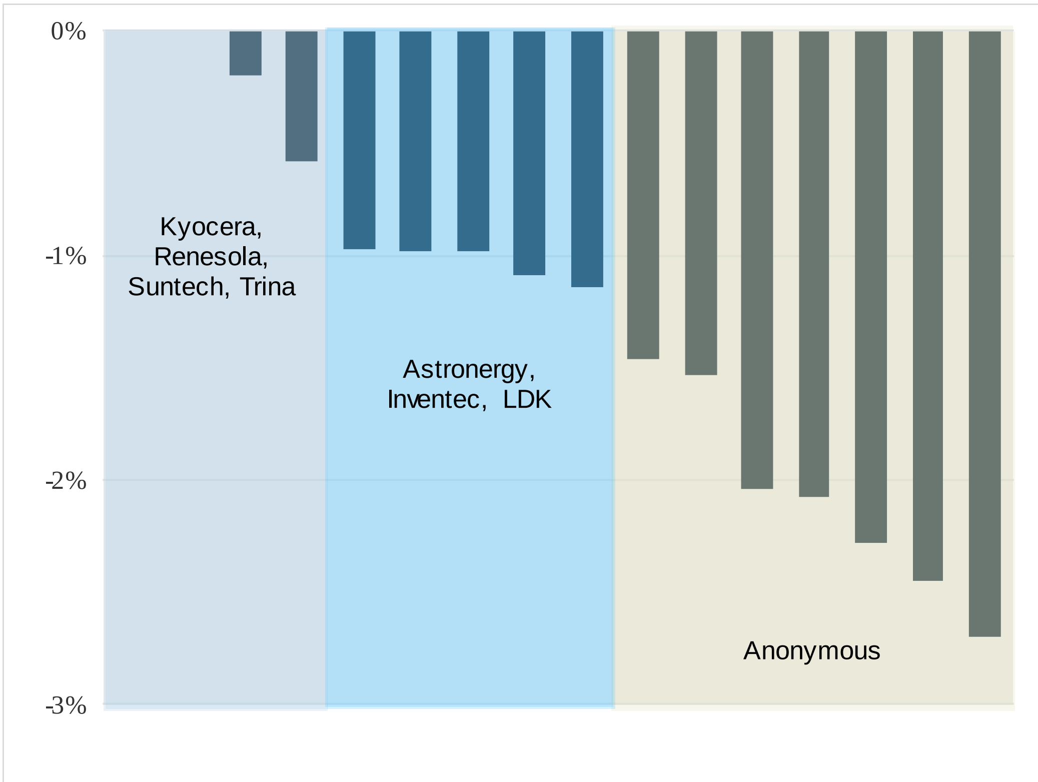
During the test, a positive 1 kV (PID+) or negative 1kV (PID-) voltage bias is applied in damp heat testing conditions (T= 85°C±5°C (185°F±9°F), RH= 85% [±5%]). This provides the temperature and moisture conditions necessary to stimulate increased leakage currents. In field conditions, the PID polarity will depend on the inverter and electrical grounding configuration. For negatively grounded systems, PID+ is the only relevant test, and for positive-grounded systems, PID- is the only relevant test. In cases where the system is bipolar or ungrounded (or floating), both tests are necessary.

The 600-hour test duration was determined to be the roughly equivalent time in damp heat conditions necessary to achieve a similar total charge transfer (mAhs or milliamp-hours) as two decades in hot, humid conditions.

PID+ Test Results

Sixteen companies participated in the PID+ test, with degradation rates varying from 0% to -2.7%. Three out of four of the top performing modules were Chinese-produced. The one exception was Kyocera, a Japanese manufacturer.

Figure 4.22 PID+ Test Results



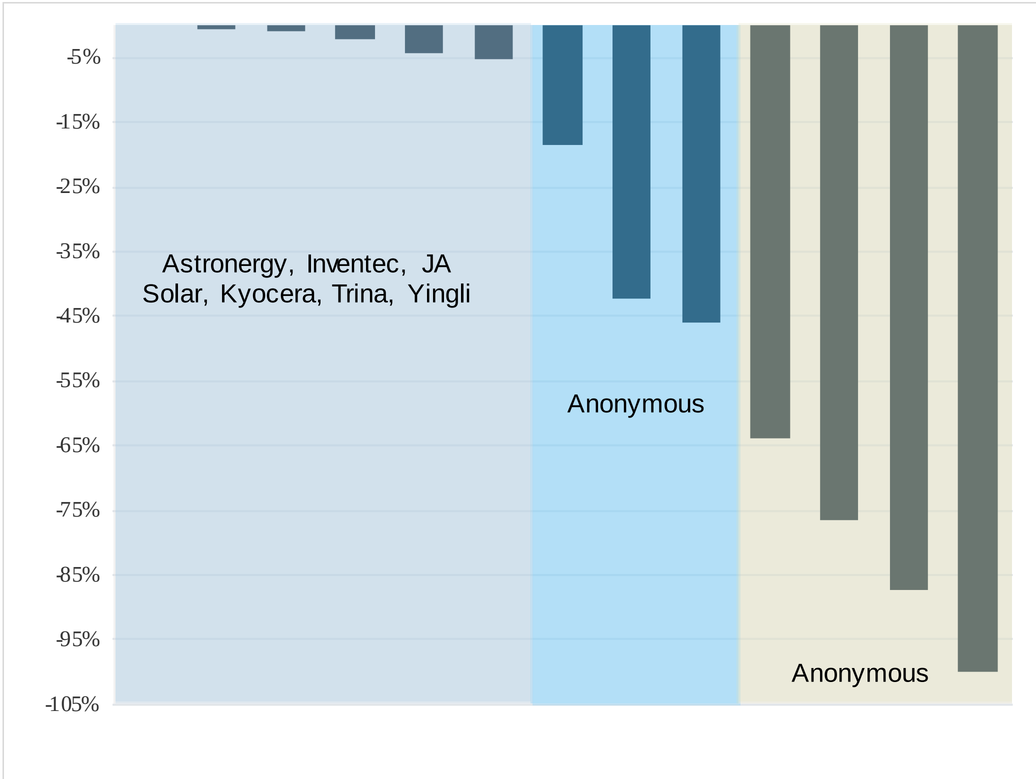
Source: PV Evolution Labs

For the PID+ regimen, degradation rates for the Performance Leaders group varied from 0% to -0.6%, with two out of four producers showing no degradation. In fact, the whole testing sample (fifteen producers) showed minimal power degradation. In the PID+ test regimen, the differential factor between vendors was the ability to eliminate the effect.

PID- Test Results

Thirteen companies participated in the PID- test, with degradation rates varying from 0% to 100%. Four out of six of the top-performing modules were Chinese-produced. The two exceptions were Kyocera, a Japanese manufacturer and Inventec, a Taiwanese manufacturer.

Figure 4.23 PID- Test Results



Source: PV Evolution Labs

The PID- test had by far the largest spread of degradation rates.

Within the Performance Leaders group, degradation rates varied from 0% to -5.1%. Assuming the Scorecard's test simulated a module's full life (25 years), all modules passed the test. The effect of increasing voltage beyond the Scorecard's 1,000V test conditions opens up the question of whether the degradation rate would exceed acceptable levels.

For the six producers in the Class 2 and Class 3 performance groups, degradation levels exceeded warranty guarantees with rates varying between -18.4% to 100% degradation.

5. Conclusions: Applicability and Interpretation of Results

5.1. Translating Laboratory Data Into Real-World Data

To assess Scorecard results in terms of environmental climate, we categorized the top ten solar PV markets by their Köppen climate classifications, the leading environmental climate classification system. As represented in the following graph, these regions represent between 45% and 89% of annual installation demand for historic installations and 75% to 82% of forecasted annual installation demand. It should be noted that the U.S. was classified on a state-by-state basis due to its large size and range in climate diversity, while other leading markets were categorized under one Köppen classification. In the latter case, regions were either classified by or PV demand is largely centered within one Köppen climate category. This classification is meant to provide a macro outlook on PV installation according to climatic conditions; it cannot substitute for vigilant due diligence on individual projects.

In addition to the tests outlined in the following table, PID- is relevant for any system utilizing ungrounded or positively grounded system configurations. This effect is exacerbated in humid environments.

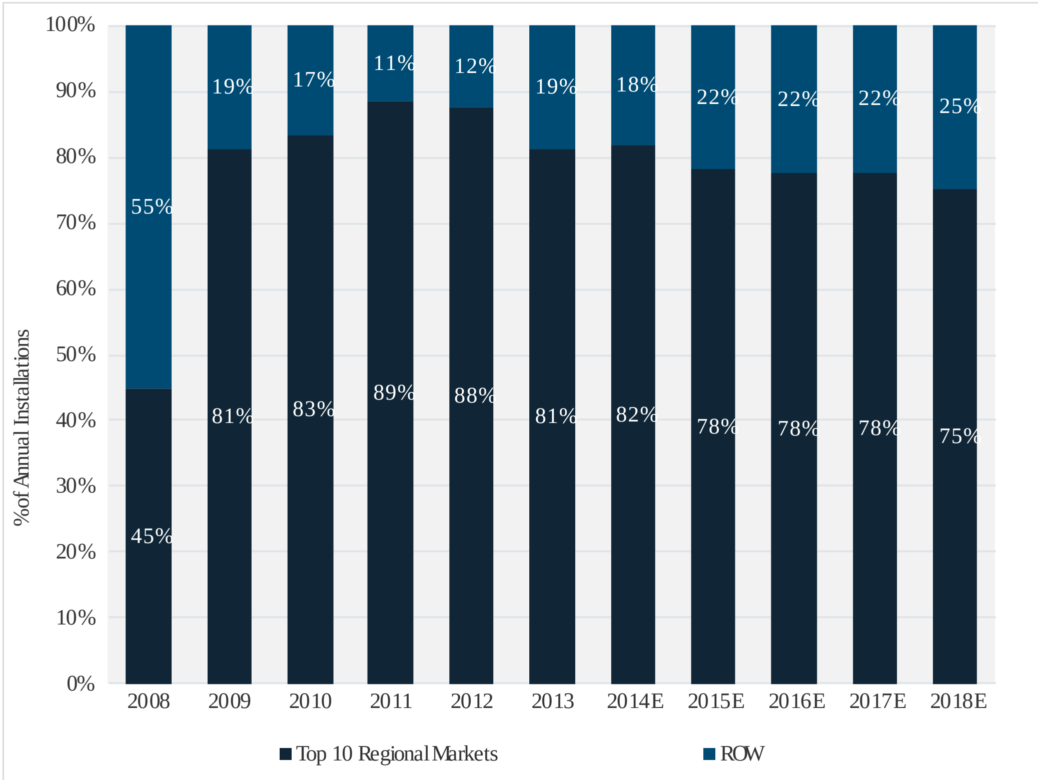
Figure 5.1 The Scorecard Testing Regimens

Primary Climate	Köppen Climate Classification	Characteristics	Primary Test	Secondary Tests	Major Markets
Tropical	Af	Moist; No dry season	Damp Heat	Dynamic Mechanical Load	Parts of Hawaii
	Am	Wet; Short dry season; Monthly mean temperature >18°C	Damp Heat	Dynamic Mechanical Load	Southern tip of India
	Aw	Wet and pronounced (long and severe) dry season	Temperature Cycling	Damp Heat; Dynamic Mechanical Load	Eastern and West Coast of India; Northern Coast of Australia; Venezuela; Taiwan; Thailand; Parts of Hawaii
Dry	Bsh	Dry, hot; Dry season in summer of respective hemisphere; Mean annual temperature > 18 °C	Temperature Cycling	Dynamic Mechanical Load	Central and Northwestern India
	Bsk	Dry, cold; Mean annual temperature < 18 °C	Temperature Cycling	Dynamic Mechanical Load	New Mexico; Western Texas

Primary Climate	Köppen Climate Classification	Characteristics	Primary Test	Secondary Tests	Major Markets
	Bwh	Dry, hot; Dry season in winter of respective hemisphere; Mean annual temperature > 18 °C	Temperature Cycling	Dynamic Mechanical Load	Southeast California; Eastern and Southern Arizona; Nevada; Saudi Arabia; Central Australia
Humid/ Temperate	Cfa	Moist; No dry season; Hot summers; Warmest month > 22 °C	Damp Heat	Dynamic Mechanical Load; Humidity-Freeze	New Jersey; North Carolina; Eastern Texas; Most of China; Japan
	Cfb	Moist; No dry season; Warm summers; Warmest month < 22 °C	Damp Heat	Dynamic Mechanical Load; Humidity-Freeze	U.K.; France; Germany
	Csa	Dry season during the summer of respective hemisphere; Hot summers; Warmest month > 22 °C	Thermal Cycling	Dynamic Mechanical Load; Damp Heat	Italy; California Coast
Continental/ Microthermal	Dfb	High variation in seasonal temperatures; No dry season; Hot summers; Warmest month > 22 °C	Temperature Cycling	Dynamic Mechanical Load; Humidity-Freeze	Northern New York
	Dfa	High variation in seasonal temperatures; No dry season; Warm summers; Warmest month < 22 °C	Temperature Cycling	Dynamic Mechanical Load; Humidity-Freeze	Massachusetts, Southern New York

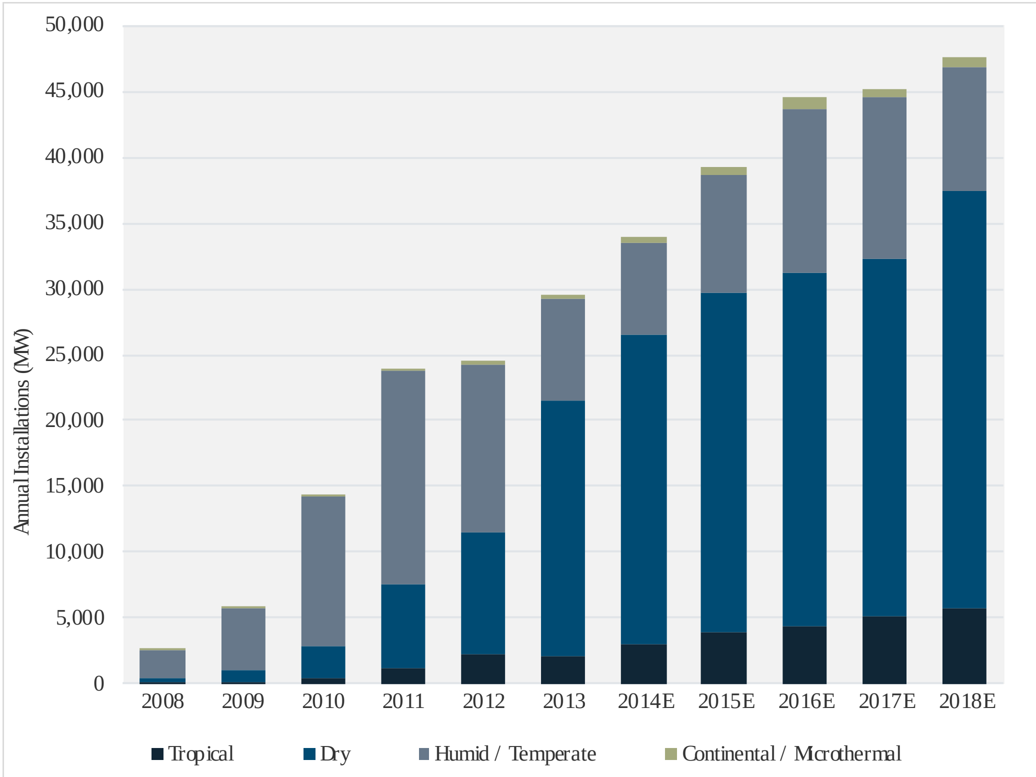
Source: GTM Research

Figure 5.2 Annual Installation Demand: Top 10 Regional Markets vs. Rest of World



Source: GTM Research

Figure 5.3 Annual Installation Forecast by Climate: Top 10 Solar PV Markets



Source: GTM Research

There is no truer test of a module's reliability than real-world experience. Systems go through a myriad of conditions that cannot be replicated by accelerated testing. The applicability of test results is limited by factors such as the extent to which Highly Accelerated Tests (HALT) can replicate full lifetimes, or, as illustrated in the table above, the narrow scope of one test's environmental conditions in comparison to the world's wide range of climatic conditions. Real-world environments comprise multiple HALT-emulated conditions, each to varying degrees. Degradation rates found by the Scorecard testing procedures should not be used as a direct forecast of degradation rates for fielded modules.

What these tests do provide is an understanding of the magnitude of the impact that one set of conditions can have on a module and a comparison of how vendors compete with respect to module quality. By choosing vendors with lower degradation rates for use in environments similar to the conditions simulated in the tests, the likelihood of better module reliability can be increased.

5.2. Conclusions

We find four key takeaways from the Scorecard's test results.

- Overall, module vendors performed relatively well across all metrics, with a few exceptions in certain tests. However, except for the PID- test, top performers exhibited relatively small degradation values.
- Module reliability is not necessarily a consistent quality. With the exception of one vendor, Kyocera, no company consistently ranked within the Performance Leaders group for all test regimens. In fact, results showed that most producers that performed well one test regimen likely performed comparatively poorly in another test. Coupling a module's performance capabilities with suitable install environments can prove valuable for ensuring project long-term viability.
- PID continues be a major concern. Even as vendors release "PID-free" modules, test results show that historical modules are potentially subject to an alarming degree of PID degradation. Results for negatively biased modules were the most severe, with a degradation spectrum that ranged from 0% to 100%. Under standard warranty guarantees (modules should retain 80% of their initial power capabilities), half of these modules failed. While these concerns are somewhat mitigated by the fact that most systems are not positive-grounded, floating and bipolar systems may be susceptible. This is often the case in systems utilizing certain transformerless inverters. As noted in the graph above, from 2015 to 2018, around 35% of demand from the top ten PV markets is projected to come from regions with environmental conditions that could lead to damp-heat failure.
- No module is immune to thermal cycling degradation. By GTM Research's installation forecasts, relevant thermal cycling environments (dry and continental) account for 65% of demand from the top ten PV markets global demand from 2015 to 2018. While the severity level of thermal cycling degradations tended to be low, the test does not account for additional environmental conditions that are present in real-world climates, such as ultraviolet radiation. Thus, the magnitude of degradation rates measure by Scorecard tests is not equivalent to the rates seen in fielded modules. Differentiating between module suppliers that can minimize the ill effects of thermal cycling will be a key factor in determining the reliability of the majority of oncoming solar capacity.

Figure 5.4 PV Module Reliability Scorecard – Summary of Tests and Results

TEMPERATURE CYCLING TEST

Summary

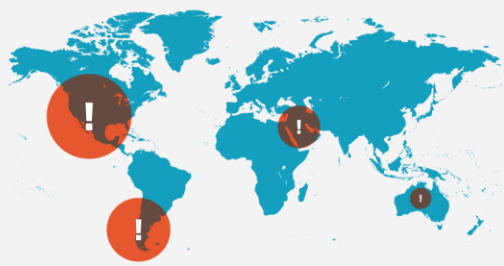
Cycles modules between two temperature extremes to simulated regions with large temperature fluctuations.

Performance Leaders (Alphabetical):

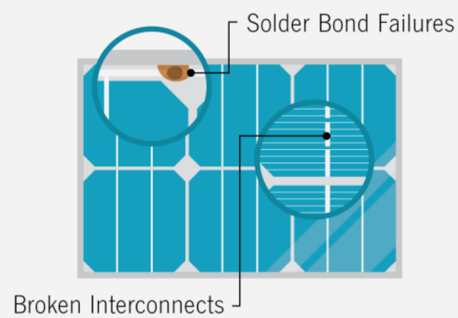
- Kyocera
- Jinko Solar
- Suntech
- Trina Solar
- Yingli Solar

Relevant Climates

Dry arid deserts such as interior deserts in North America, the Middle East, Australia and Chile.



Common Failure Modes



DYNAMIC MECHANICAL LOAD TEST

Summary

Exposes modules to mechanical deflections to simulate pressure loads such as snow and wind as well as seismic motion.

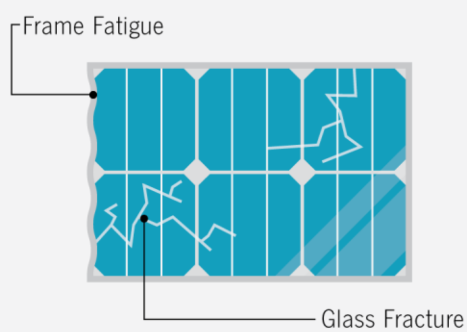
Performance Leaders (Alphabetical):

- Inventec
- Kyocera
- LDK
- ReneSola

Relevant Climates

Snow: Eastern U.S., Canada, UK, Germany
Earthquake Zones: Japan, Western U.S., Chile

Common Failure Modes



HUMIDITY FREEZE TEST

Summary

Immerses modules in damp air and drops temperature to simulate moist, cold environments.

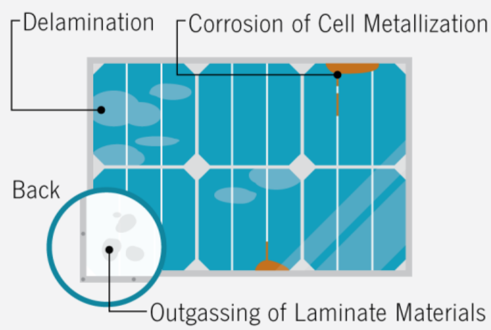
Relevant Climates

Eastern regions of North America, Europe and Asia

Performance Leaders (Alphabetical):

- Inventec
- Kyocera
- ReneSola
- Trina Solar
- Yingli Solar

Common Failure Modes



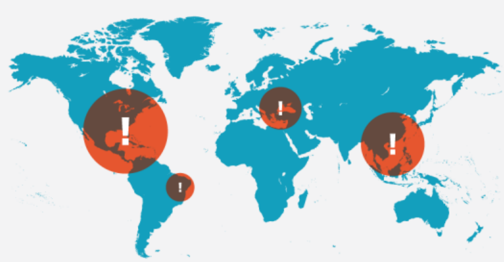
DAMP HEAT TEST

Summary

Immerses modules in damp air and drops temperature to simulate humid, hot environments.

Relevant Climates

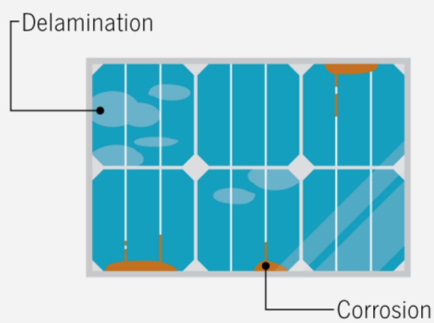
Coasts of U.S., in the parts of EU and Asia (Romania, Turkey, India, and Thailand) as well as some subtropical regions in South America (Brazil)



Performance Leaders (Alphabetical):

- Inventec
- Kyocera
- LDK
- Trina Solar
- Suntech

Common Failure Modes



POTENTIAL INDUCED DEGRADATION (POSITIVE AND NEGATIVE) TEST

Summary

Applies large voltage in a damp, high heat conditions to simulate high bias systems in humid, hot environments.

Relevant Climates

EU and large bias projects in humid regions in the U.S. (Massachusetts, New York)

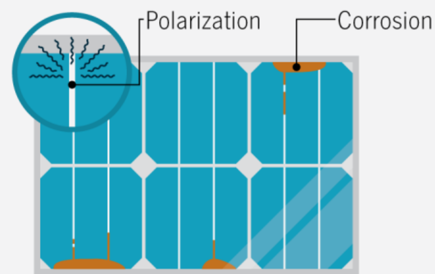
PID+ Performance Leaders (Alphabetical):

- Kyocera
- ReneSola
- Suntech
- Trina Solar

PID- Performance Leaders (Alphabetical):

- Astronergy
- Inventec
- JA Solar
- Kyocera
- Trina Solar
- Yingli Solar

Common Failure Modes



Source: GTM Research

PV RELIABILITY SCORECARD REPORT 2014

July 2014

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