PV Module Reliability Scorecard Report 2016

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Table of contents

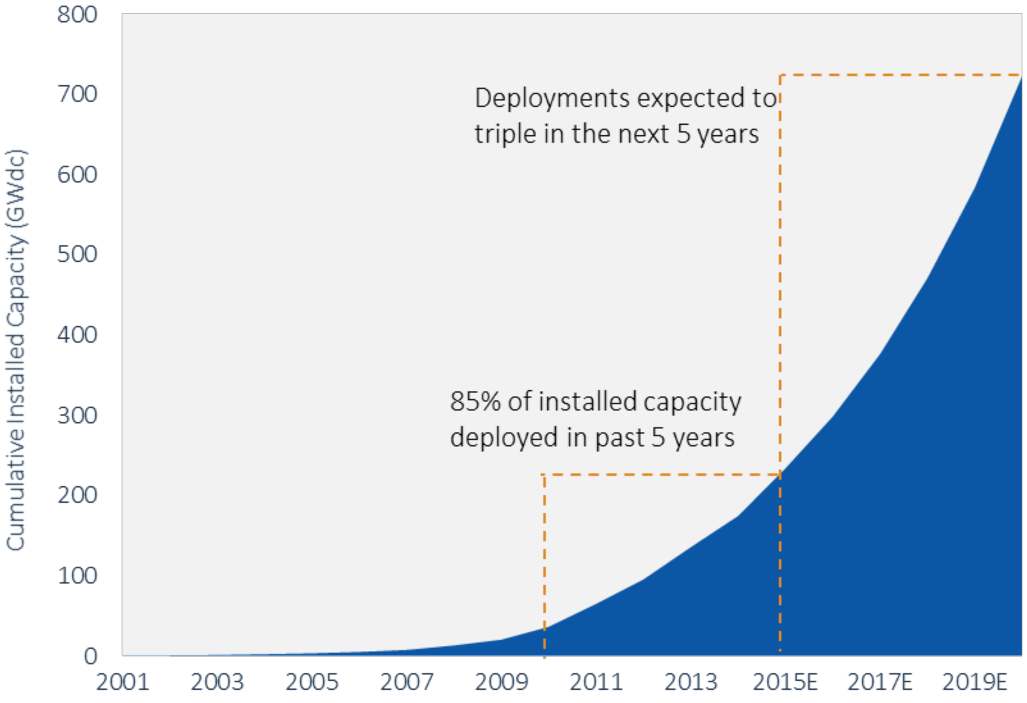
1 INTRODUCTION

In the spring of 1997, Siemens Solar Industries announced the extension of its module warranty expanding it from 10 years to 25 years. This announcement marked the beginning of an industry standard, setting the 25-year warranty as a basic requirement 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 fairly unclear. Publicly available and high quality field data on long term operating performance of PV systems is limited. Additionally, field data takes many years and by that time the technology has evolved. Because of this, over the past few years high quality and independent lab data has established a critical role in evaluating PV module quality and long term reliability.

85% of the 234 GW of installed global PV capacity has been in the field for less than five 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, industry concerns over cost reduction at the expense of module quality have persisted even as module pricing has stabilized. The import tariff (AD/CVD) policy in the U.S. has driven many manufacturers to contract manufacture or build new factories in tariff-free countries such as Malaysia, Vietnam, Thailand, India, etc. Reacting to intense pricing pressures and dynamic supply chain behavior may be at the expense of quality. Yet neither price nor top-tier ranking have been proven to indicate module quality or performance.

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?

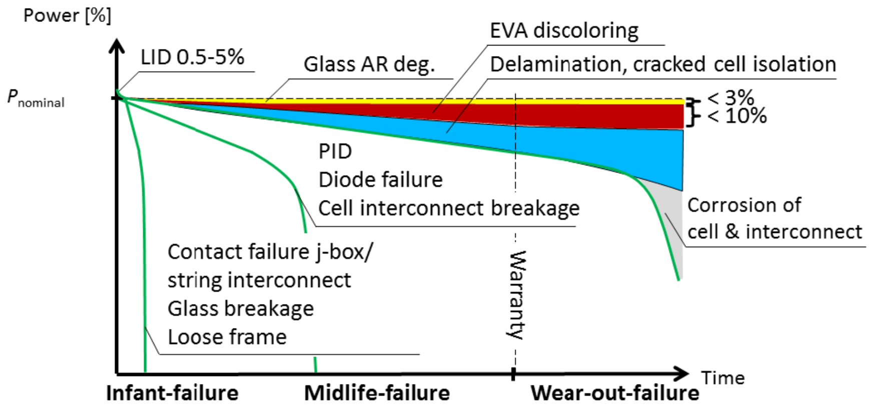
The PVEL-GTM PV Module Reliability Scorecard aims to address this critical problem. With its supplier-specific performance analysis, the Scorecard can help investors and developers generate quality-backed procurement strategies to ensure long-term project viability.

2 PV MODULE AGING MECHANISMS

As the solar industry matures long term performance and reliability of PV modules and other system components (i.e. inverters) have received increased focus from the investment community. Reduced cost of capital has resulted in the out years having real value in discounted cash flow analysis. The objective of any component quality management strategy is to avoid procuring equipment that exhibits early lifetime failure and to select equipment that performs successfully over the long term. There are well over one hundred PV module manufacturers globally active today - often with multiple factories each, sometimes producing in multiple continents. These manufacturers utilize a broad range of materials, manufacturing techniques and quality control practices. This results in a wide range of product quality and reliability. To properly address the risk of early failure of today's products, it is helpful to have a clear understanding of common PV module failures seen in operating PV power plants. Developing an understanding of how modules age in the field will highlight technology risks and enable the implementation of an effective procurement quality assurance strategy.

Aging and failure mechanisms seen over the past several decades have been documented over a wide range of power plant locations and material sets. Field failures of PV equipment can stem from materials, fundamental product design flaws or failures in quality control during manufacturing. Figure 2-1 below indicates leading PV module aging and failure mechanisms that occur as infant mortalities, mid-life failures, and wear out.

Figure 2-1 Aging mechanisms leading to PV module degradation

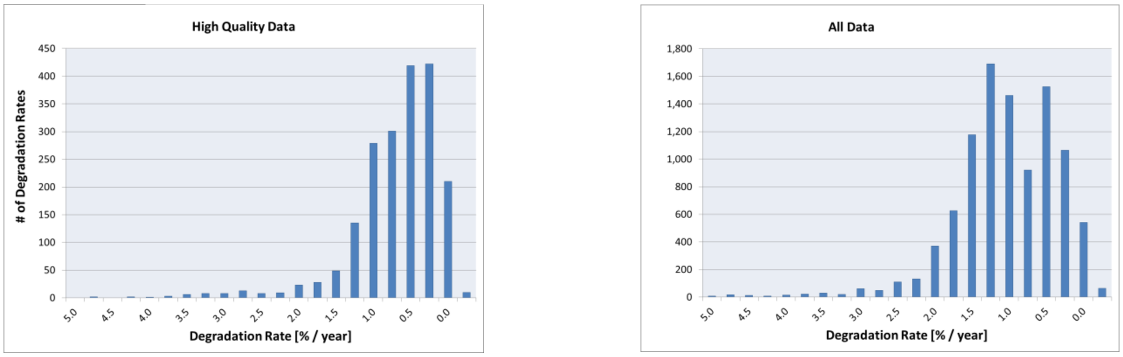


Source: IEA PVPS 2014

2.1 Field studies of PV performance

The solar industry generally lacks comprehensive public datasets of PV equipment performance in the field however several large studies have been performed. Dirk Jordan and Sarah Kurtz from NREL have performed a comprehensive literature survey on published PV module and system degradation rates. In this study they identified almost 10,000 PV module degradation rates from almost 200 studies in 40 countries. Accurate measurement of field performance is very sensitive to several sources of error that could skew the results. Soiling, maintaining calibration and cleanliness of irradiance sensors, module baseline data (nameplate vs. flash test), and not appropriately accounting for LID are just a few major sources of data errors. To account for this the authors segregated data from higher quality studies as defined by: multiple measurements taken for increased confidence; the measurement methods and calibrations were clearly described and were generally similar at each measurement point; details on the installation (disregarding proprietary considerations) are provided. The results of the NREL study shown in Figure 2-2 and Figure 2-3 indicate a mean degradation of about half a percent per year (for the high quality dataset) which is generally in line with expectations. However, there is a long tail with degradation beyond one percent annually. This long tail is likely driven by equipment issues caused by poor quality manufacturing, materials, or product design.

Figure 2-2 Results of Kurtz-Jordan NREL study of PV degradation


High Quality Data

All Data

Source: “Compendium of Photovoltaic Degradation Rates”, D.C. Jordan, et al, NREL, 2015

Figure 2-3 Results of Kurtz-Jordan NREL study on PV degradation

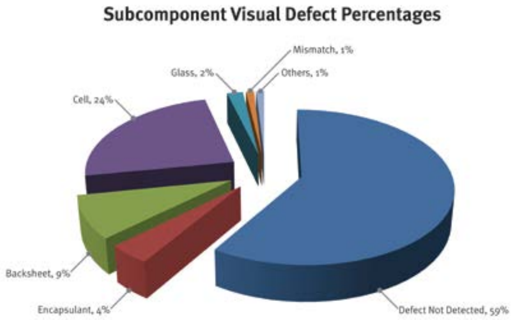
Dataset	# of modules surveyed	Mean Degradation Rate	Median Degradation Rate	P90 Degradation Rate
High Quality	1,936	0.5 – 0.6 % / year	0.4 – 0.5 % / year	1.2 % / year
All Module Data	9,977	0.9 – 1.0 % / year	0.9 – 1 % / year	1.7% / year

Source: “Compendium of Photovoltaic Degradation Rates”, D.C. Jordan, et al, NREL, 2015

In another large study, DuPont performed extensive field inspections (visual inspection and thermal imaging) of 60 global sites totaling 1.5 million PV modules from 45 manufacturers to evaluate aging behaviors in the real world. System ages ranged from 0 to 30 years. Their findings are outlined in Figure 2-4, issues were identified on 41% of the modules surveyed.

Figure 2-4 DuPont inspection of field PV modules

Failure Categorizations	
Glass / Superstrate	Broken, etched, hazed glass
Encapsulant	Discoloration or delamination
Cell / Interconnect	Corrosion, hot spot, broken interconnect, snail trails, cracks, burn marks
Backsheet	Cracking, yellowing, delamination



Source: courtesy of DuPont Photovoltaic Solutions, “Quantifying PV Module Defects in the Service Environment”, Alex Bradley, et al,

2.2 The objective of laboratory testing

The most accurate way to determine if a product can last 20 years in the field is to instrument it and deploy it for 20 years. This level of testing is obviously prohibitive. Laboratory testing should be leveraged to understand PV equipment aging behavior in a commercially reasonable timeframe. Quite a bit can be learned about PV modules in only a few months in the laboratory. Unfortunately, extrapolating lab results to precisely predict field degradation rate is not possible today. However, relative performance in the laboratory is expected to translate to the field. For example, if module A outperforms module B in Thermal Cycling in the lab it will very likely outperform in the field as well for the aging mechanisms captured by this test. In addition to degradation analysis the stress tests available today are very effective at screening for PV module defects that cause severe degradation or safety issues such as bad solder joints or a poorly adhered junction box. Figure 2-5 outlines failure modes targeted by each laboratory stress test as published by NREL.

Figure 2-5 PV module failure modes per laboratory test

Accelerated Stress	Failure Mode
Thermal Cycling	Broken Interconnect Broken Cell Solder Bond Failures Junction Box Adhesion Module Connection Open Circuits Open Circuits leading to Arcing
Damp Heat	Corrosion Delamination of Encapsulant Encapsulant loss of adhesion & elasticity Junction Box Adhesion Electrochemical corrosion of TCO Inadequate edge deletion
Humidity Freeze	Delamination of Encapsulant Junction Box Adhesion Inadequate edge deletion
UV Exposure	Delamination of Encapsulant Encapsulant loss of adhesion & elasticity Encapsulant Discoloration Ground Fault due to backsheet degradation

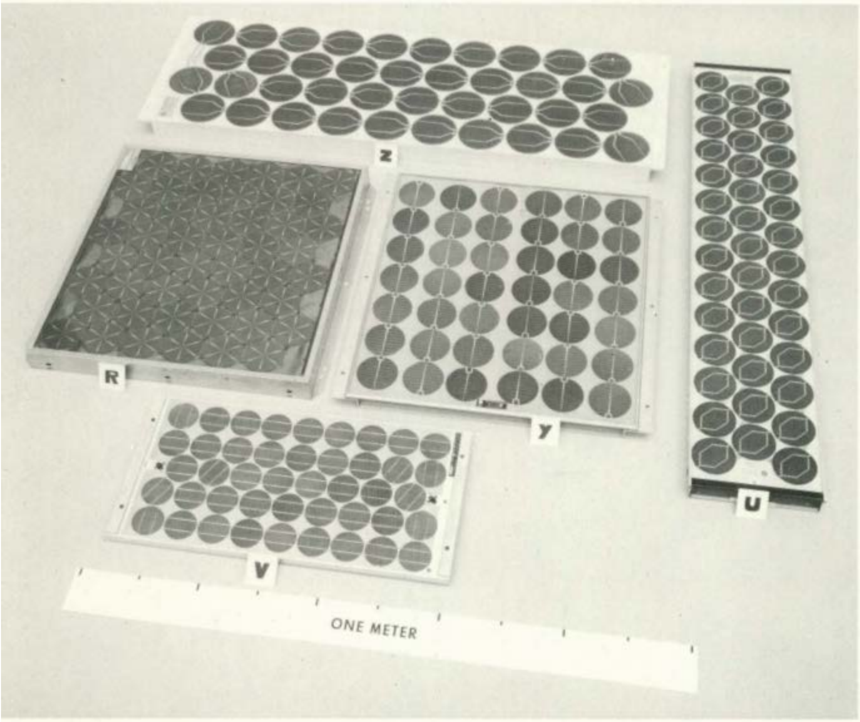
Source: “Reliability Testing Beyond Qualification as a Key Component in Photovoltaic’s Progress Toward Grid Parity”, Wohlgemuth, et al, NREL, 2011

3 MODULE RELIABILITY AND TESTING

3.1 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 3-1 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 freeze and 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 (IEC) 61215, and safety test, the Underwriters Laboratories (UL) 1703.

3.2 The limitations of existing certification standards

Though most projects require UL and/or IEC certification to ensure a minimum bar of module robustness, it is widely accepted that these certification standards are not sufficient to demonstrate PV module reliability nor consistency.

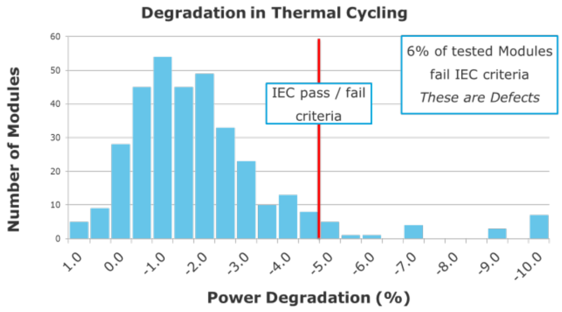
First, it should be noted that UL 1703 is purely a safety test. The goal of the test is to ensure that the module does not pose a hazard during operation.

The IEC 61215 standard is the minimum baseline industry-accepted module assessment program, 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 and leaves aside a number of common potential causes of failure. For instance, resilience to PID is not tested at all (more on that later). This means that the IEC 61215 tests are only well suited to weed out modules that would be likely to fail within the first years in the field (screening for defects).

Certification testing is performed on only on a small number of samples and isn't necessarily representative of high volume commercial production over time. Besides, the manufacturer is free to select the physical modules sent for testing and no random selection out of the production line is necessary. Furthermore, maintaining certification does not require periodic re-testing unless materials or designs change. Applying these IEC tests for PV module defect screening is becoming a common and effective Batch Acceptance test, screening for serial defects for PV module procurement in large residential or commercial procurements or utility scale projects, but it is not sufficient to start to quantify long-term reliability of the module construction. Based on DNV GL's experience at least 6% of commercial PV modules do not pass the IEC 61215 Thermal Cycling test – see Figure 3-2 below.

Additionally, the IEC certification only functions as a pass/fail set of tests. It does not report the actual magnitude of degradation after the tests, nor does it seek to discern the root cause of performance loss.

Figure 3-2 DNV GL's historical Thermal Cycling degradation results



IEC pass / fail criteria

6% of tested Modules fail IEC criteria

These are Defects

Source: DNV GL Laboratory Services Group

3.3 Degradation versus failure

Power degradation over time is built into project expectations and is warranted by the manufacturers. The current standard 25-year warranty is typically triggered if modules degrade more than 3% within the first year and at a linear rate down to 80% of its initial nameplate power in year 25. Small levels of power degradation in the field are difficult to accurately measure due to the uncertainty of measurement tools. Warranty claims are therefore typically only executed for gross underperformance or complete failure. Prior to module purchase measurement of the resilience of modules to the most common degradation mechanisms is therefore of essential importance.

4 THE PRODUCT QUALIFICATION PROGRAM

DNV GL (formerly PV Evolution Labs a.k.a. PVEL) developed the Product Qualification Program to support the downstream solar community back in 2013. The objectives of the program are twofold. First, it provides PV equipment buyers and PV power plant investors with independent and consistent reliability and performance data to help implement effective supplier management process (such as an Approved Product or Vendor List). Additionally, it provides module manufacturers focused on the reliability of their products the visibility they need to be successful in this competitive market. The Product Qualification Program provides DNV GL's downstream partners with 3rd party performance data (PAN files, IAM, NOCT, and LID) as well as reliability data as outlined in the table below. Data in the PV Module Reliability Scorecard is pulled from this Product Qualification Program. In the past 2 years DNV GL has executed 40 Qualification Programs across 30 manufacturers.

Figure 4-1 DNV GL's Product Qualification Program compared to IEC 61215

Test	Thermal Cycling	Damp Heat	Humidity Freeze	Mechanical Load	PID
Product Qualification Program	800 TC cycles	3,000 DH hours	30 HF cycles	Dynamic Load	600 hours
IEC 61215 Standard	200 TC cycles	1,000 DH hours	10 HF Cycles	Static mechanical load	None

Source: DNV GL Laboratory Services Group

4.1 Module selection and sampling process

Independent PV module sampling is a critical step in testing and qualification. This step builds confidence that the production process and Bill of Materials (BOM) are representative of commercial production. DNV GL works with independent inspectors from SolarBuyer and CEA for all modules tested in the PV Module Reliability Scorecard. This is a standard part of the Product Qualification Program.

4.2 Light-induced degradation

Upon initial exposure to light, modules experience a permanent reduction in power output. The phenomenon is called light induced degradation or LID. On average, LID for crystalline silicon modules ranges from 0.5% to 3%, with some modules exhibiting a loss of up to 5%. Manufacturers using n-type silicon cells such as SunPower exhibit no LID loss. Manufacturers take this into account by factoring in a 3% power loss (typically) during the first year of the module warranty.

To ensure that light-induced degradation does not jeopardize the conclusions of the chamber testing, all PV modules in the PV Module Reliability Scorecard were light soaked for at least 40 kWh / m^2 before entering the testing chambers.

5 PV MODULE RELIABILITY SCORECARD RESULTS

5.1 Results summary

Overall, most participating PV module manufacturers performed well, with relatively few incidents of outright failure. The mere participation in the PVEL Product Qualification Program indicates already the importance that the participating manufacturers place on the reliability of their products. Because of this the average and median results presented here may be better than the average and median results of the industry taken as a whole. Results indicate average values of multiple individual PV modules from each manufacturer. The factory locations are listed in the table below. All PV modules are standard 60 or 72-cell crystalline silicon modules. A different number of manufacturers participated in each test. The vertical axis in each chart indicates the power degradation caused by stress testing in percent relative to pre-stress output (after light soaking). Top performers are defined as those to the left of the red vertical line indicated on the results charts.

Figure 5-1 PV Module reliability scorecard test results summary

Reliability Test	Top Result	Bottom Result	Median Result	Std. Dev.
Thermal Cycling	-1.07%	-34.59%	-4.68%	7.29%
Damp Heat	-0.57%	-58.77%	-3.59%	14.86%
Humidity-Freeze	-0.13%	-4.10%	-2.30%	1.11%
Dynamic Mechanical Load	-0.18%	-7.28%	-1.55%	1.98%
PID (-1kV)	0.47%	-58.27%	-2.69%	18.60%

Source: DNV GL Laboratory Services Group

Figure 5-2 Manufacturer factory locations

Manufacturer	Factory Location
CSUN	Tuzla/Istanbul, Turkey
Hanwha	Qidong, Jiangsu, China
JA Solar	Hefei, Anhui, China
Jinko	Shangrao, Jiangxi, China
Kyocera	Tijuana, Mexico
Phono Solar	Nanjing, Jiangsu, China

Q-Cells	Kwidzyn, Poland
REC	Singapore
RECOM	Taoyuan, Taiwan
Tenksolar	Shanghai, China
Trina	Changzhou, China
Yingli	Baoding, China and Hengshui, China
ZNShine	Jintan, Jiangsu, China

Source: DNV GL Laboratory Services Group

5.2 Thermal Cycling

PV modules are constructed from several materials, each with varying coefficients of thermal expansion (CTE). As ambient temperature and irradiance fluctuates, materials expand or contract. When adjacent materials have mismatched CTEs (for example silicon solar cells and metal busbar ribbons), the interface experiences stress which causes aging such as solder joint fatigue.

Following preparation and characterization, modules were cycled from -40°C to 85°C. When the temperature rises above 25°C, the maximum power current is injected into the modules, causing localized heating if solder joints are degrading. IEC 61215 requires only 200 cycles which may be estimated to represent a few years of field exposure. The PV Module Reliability Scorecard procedure extends the test to 800 cycles. This simulates an estimated 25+ years of field exposure. It should be noted that the test procedure does not combine all conditions that modules may experience in very harsh environments. High-intensity and/or high-photon-energy light exposure is for instance present in arid desert environments and may expose the modules to additional failure modes such as encapsulant browning.

5.2.1 Thermal Cycling Test Results

Nineteen companies participated in the thermal cycling test with degradation rates varying from -1% to -35%. As shown in the graph below, four of seven of the top-performing modules were Chinese-produced. Phono Solar (produced in Nanjing, China) and Kyocera (produced in Tijuana, Mexico) were the top performing manufacturers with less than 1.5% degradation. Other modules were produced in Taiwan.

Figure 5-3 Thermal Cycling results

Source: DNV GL Laboratory Services Group

5.3 Dynamic Mechanical Load

The dynamic mechanical load (DML) test determines a module's ability to handle cyclic pressure loads often caused by wind or snow. Significant or repetitive pressure will cause deflection of the glass and can result in cell cracks or solder joint degradation.

Various aspects of the processing steps such as cell soldering and cell etching, as well as the selection of glass, EVA and backsheet material, impact a module's sensitivity to physical damage from mechanical loads. It should also be noted that in real-life conditions, large pressure loads can also be combined with other environmental conditions such as cold and wet environments.

The PV Module Reliability Scorecard utilizes a test sequence of mechanical stress to cause cell cracks (1,000 cycles at 1,440 Pa) followed by thermal stress (50 cycles of Thermal Cycling) to cause crack propagation followed by freezing moisture stress (10 cycles of Humidity Freeze) which causes cell cracks to impact power output. This test sequence therefore also probes the ability of modules to sustain high performance despite presence of cracks or microcracks, for instance originated by rough transportation or installation.

In order to test real-world performance, the tested module is mounted per the manufacturer's specifications.

5.3.1 Dynamic Mechanical Load Test Results

Seventeen companies participated in the dynamic mechanical load test with degradation rates varying from -0.2% to -7.3%. Seven of the eleven top-performing modules were Chinese-produced. Other top performing modules were produced in Taiwan, Mexico and Poland. The top four performers which all degraded less than 0.5% were Tenksolar, RECOM, Kyocera, and Phono Solar.

Figure 5-4 Mechanical Load test results

Source: DNV GL Laboratory Services Group

5.4 Humidity-Freeze

Several materials used in PV modules such as junction box and frame adhesives, backsheets, and encapsulants can absorb moisture. In Northern regions of North America, Europe and Asia, where temperatures often drop below freezing conditions, this moisture can freeze inside the module package. The expansion of moisture during this freezing process can be very detrimental to the module integrity. Ice crystals can cause failure of adhered interfaces resulting in delamination or other mechanical failure. Corrosion of the cell metallization can also be caused by this environmental test. The humidity-freeze test mimics environmental conditions where ambient moisture and freezing temperatures coexist.

In the standard IEC 61215 test, modules are exposed to temperatures of 85°C and a relative humidity of 85% for a minimum of 20 hours. This step ensures the modules are saturated with water. The temperature is then rapidly dropped to -40°C 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 standard's test procedure. The PV Module Reliability Scorecard extends the test to 30 cycles.

5.4.1 Humidity-Freeze Test Results

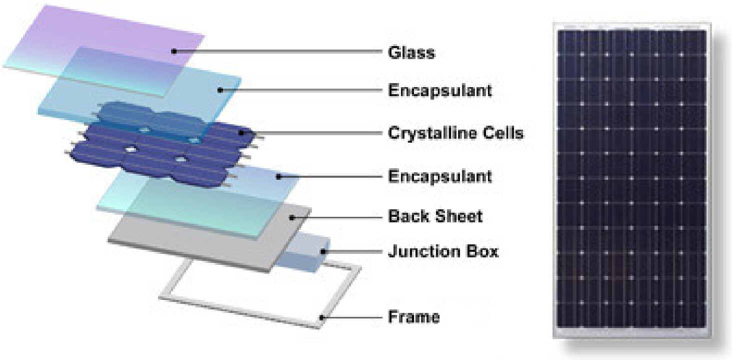
Eighteen companies participated in the humidity-freeze test, with degradation rates varying from -0.1% to -4.1%. Four out of seven of the top-performing modules were Chinese-produced. The other top modules were produced in Mexico and Poland.

Figure 5-5 Humidity Freeze results

Source: DNV GL Laboratory Services Group

5.5 Damp Heat

Figure 5-6 Layers of a PV module



Source: Dow Corning

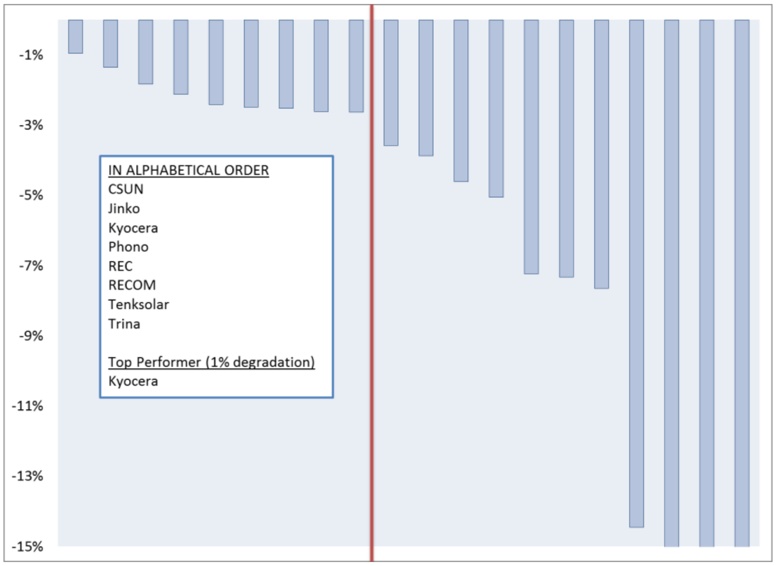
High ambient temperature and humidity such as those in some parts of Southern U.S. (e.g. Florida) and in parts of EU and Asia (e.g. Romania, Turkey, India, and Thailand), as well as some subtropical regions in Central and South America (e.g. Panama, Brazil), result in conditions that are likely to bring about aging stimulated by this test, the PV Module Reliability Scorecard uses the Damp Heat test profile outlined in the IEC standard.

In the IEC 61215 test procedure, modules are held at a constant temperature of 85°C and a relative humidity of 85% for 1,000 hours (~42 days). This allows modules to become completely saturated with moisture which is stressful on adhered interfaces. As outlined in the literature occasionally modules that pass this certification test may fail if the test is extended by only a few additional hundred hours. The PV Module Reliability Scorecard extends the test procedure to 3,000 hours. It is important to note that 2,000 hours is widely considered to be sufficient for long term PV Module qualification testing for regions that exhibit less extreme humidity levels.

5.5.1 Damp Heat Test Results

Twenty one companies participated in the damp heat test, with degradation rates varying from -0.6% to -58.8%. Six out of ten of the top performing modules were Chinese-produced. The other top modules were produced in Mexico, Taiwan and Singapore.

Figure 5-7 Damp Heat results



Source: DNV GL Laboratory Services Group

5.6 PID test

During operation, because the modules are connected in series, and because the frames are all connected together, cells experience a voltage bias relative to the module frame. Several system design decisions impact the voltage between the cells and frame such as system grounding configuration (negative vs. bi-polar vs. floating) and string voltage (600 vs. 1kV vs. 1.5kV). The electric field between the solar cell and module frame causes sodium ions contained in the glass to diffuse either toward the cell or toward the frame (i.e. away from the cell) depending on the polarity of the voltage drop. This effect can damage cell properties and can result in a large reduction in power output. This effect is commonly known as potential induced degradation or PID.

It should be noted that there are reversible and non-reversible PID mechanisms. Electrochemical corrosion and sodium ion damage to the PN junction are likely 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. This laboratory test captures both irreversible and reversible mechanisms.

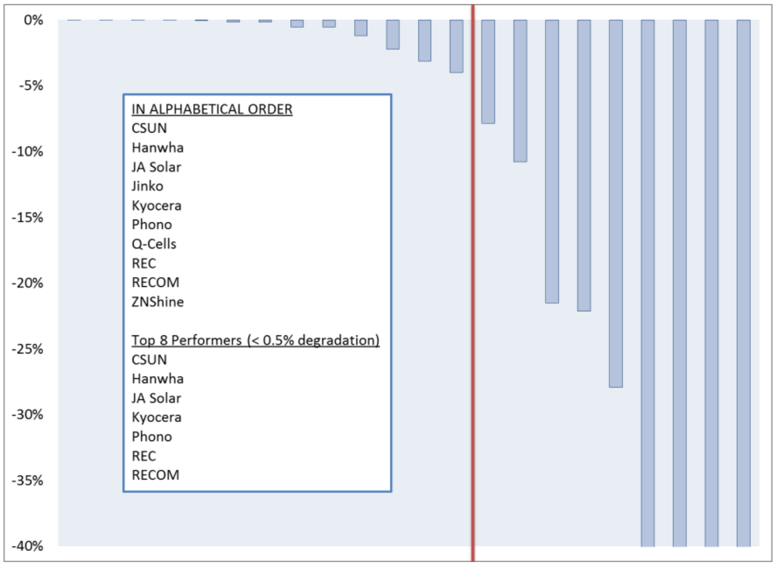
5.6.1 The PID Test Procedure

During the test, a -1kV voltage bias is applied in damp heat testing conditions (T= 85°C, RH= 85%) for 100 hours. This provides the temperature and moisture conditions necessary to stimulate increased leakage currents.

5.6.2 PID Test Results

Twenty two companies participated in the PID test, with degradation rates varying from 0% to -58.3%. Seven of the thirteen top performing modules were Chinese-produced. The remaining top performing modules were produced in Mexico, Taiwan, Singapore and Poland.

Figure 5-8 PID results



Source: DNV GL Laboratory Services Group

6 CONCLUSIONS: INTERPRETATION OF RESULTS

6.1 Use of laboratory data

There is no truer test of a module's reliability than real-world experience. PV power plants experience a myriad of conditions that cannot be perfectly replicated by accelerated testing. Modules experience all stresses in the field at the same time to varying degrees. Laboratory testing is well controlled and typically limited to a single stress type at a time. Laboratory observations should be utilized to accurately assess how a specific set of aging mechanisms impact module output over the duration of the test. Laboratory data should be leveraged to effectively manage your Approved Vendor List by setting degradation thresholds (e.g. 5%). Additionally, Accelerated Testing should be used to screen for PV module defects in large procurements.

Degradation levels identified by the PV Module Reliability Scorecard testing program should not be used as a direct forecast of yearly degradation rates for fielded modules. It should be used as a mechanism to Qualify PV modules and associated Bill of Materials and factory locations, and as a tool to compare module expected reliability and long-term performance qualitatively.

These tests provide a comparison of how vendors, modules, bill-of-materials and factories compare with one another on a given set of controlled environmental conditions, stimulating a given set of failure mechanisms encountered in the field.

By choosing vendors with lower degradation levels the likelihood of technical and financial success for your project is increased.

6.2 Conclusions

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

- Overall, many module vendors performed well across all tests. For example, 8 manufacturers degraded less than 3% after 4 times the IEC duration in Thermal Cycling (the IEC pass/fail criteria for 200 cycles is 5% degradation).
- Two manufacturers performed in the top group on every test: Kyocera and Phono Solar.
- Roughly 55 – 60% of top group modules were manufactured in China. This is roughly equivalent to the ratio of Chinese module participation in the full PV Module Reliability Scorecard. This demonstrates that manufacturing location is not a good proxy for reliability.

ABOUT DNV GL