PV Module Reliability Scorecard Report 2017

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Manufacturers Named as Top Performers (alphabetical order)

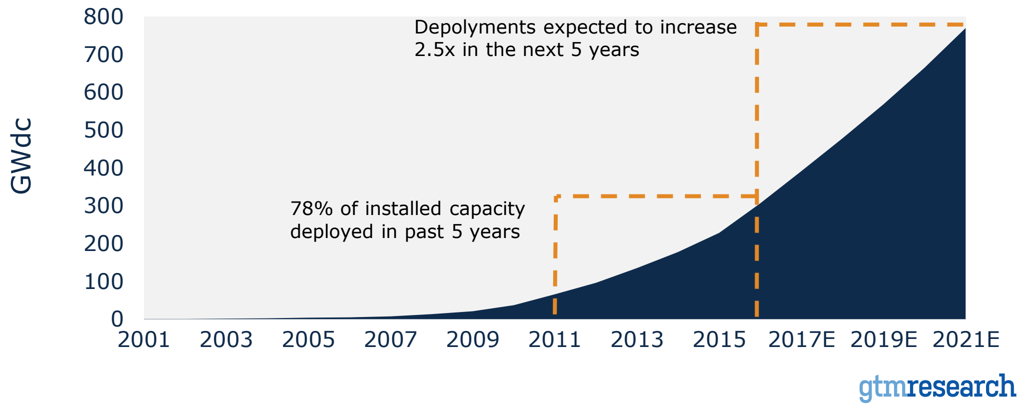
Astronergy	Jinko Solar	Seraphim	Talesun
BYD	Kyocera	Silfab	Trina Solar
Flextronics	LONGi	Solaria	Vikram
GCL	NSP	SolarWorld	Yingli
Hanwha Q CELLS	REC	SunPower	
Hyundai	S-Energy	SunSpark	

1 INTRODUCTION

The modern solar cell was invented in 1954. In the spring of 1997, Siemens Solar Industries announced the extension of its PV 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 photovoltaic (PV) systems is limited. Additionally, field data take many years to generate and by that time the technology has evolved. Because of this, over the past few years, high quality and independent laboratory data have established a critical role in evaluating PV module quality and long-term reliability.

Of the more than 300 GW of installed global PV capacity, 78% has been in the field for less than five years. It will be more than 20 years from now before actual lifetime field data for the majority of today's capacity can be gathered.



Source: GTM Research

Figure 1-1 Cumulative installed global PV capacity

Additionally, while the roughly 80% drop in module prices from 2010 to 2016 and the roughly 35-50% drop just from early-2016 to mid-2017 helped accelerate industry growth, concerns over cost reduction at the expense of module quality continue to persist. The import tariff and minimum price policies in the United States (U.S.) and Europe respectively have driven many manufacturers to outsource manufacturing 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.

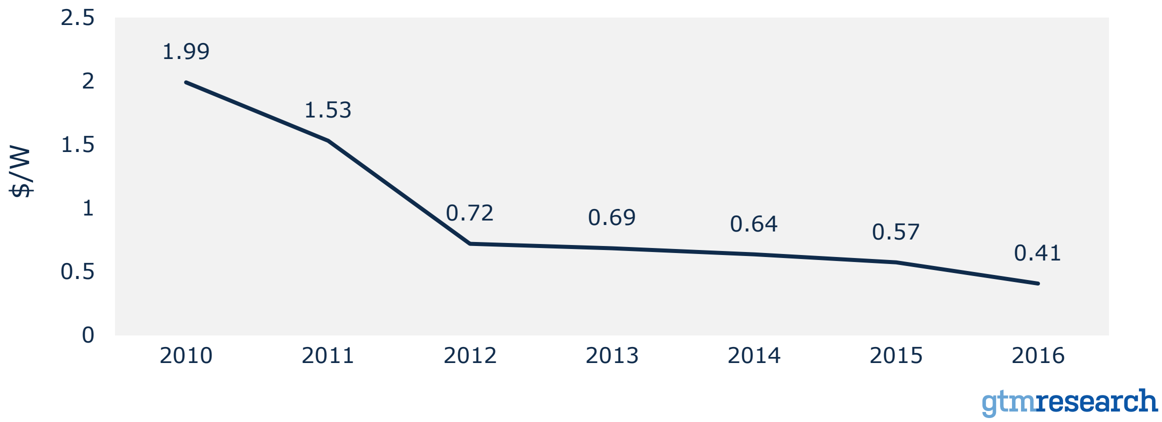


Figure 1-2 Global blended module price

Furthermore, in addition to the relentless competition on price there is also a race for higher efficiencies. On the bright side, after decades of optimizing the standard "H-pattern Aluminum-BSF" technology, the PV industry is finally bringing innovation into the production line: PERC (passivated emitter rear contact), PERT (passivated emitter rear totally diffused), and PERL (passivated emitter rear locally diffused), bifacial modules, shingling technology (also known as "High-Density Modules"), multi-wire, half-cut cells, etc. are all gaining momentum and market share. However, with novel technology comes a new set of challenges, risks, and uncertainties.

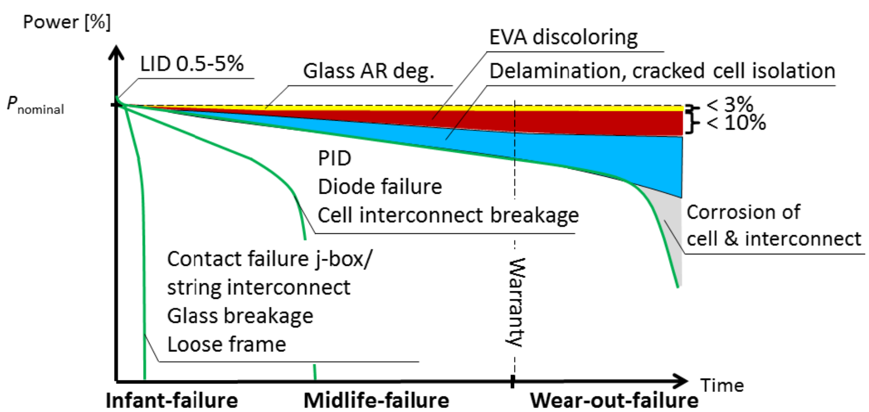
With full-life field performance data more than 20 years away and without access to publicly available data comparing long-term module reliability by vendor, how can buyers and investors factor quality into their procurement discussions?

The DNV GL PV Module Reliability Scorecard aims to address this critical challenge. 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, such as inverters, have received increased focus from the investment community. Reduced cost of capital has resulted in the later years of project life having considerable 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 on 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 failure of today's products, it is helpful to have a clear understanding of common PV module failure modes seen in operating PV power plants. Developing an understanding of how modules age in the field highlights technology risks and enables the implementation of an effective procurement quality assurance strategy.

PV Module 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 material issues, fundamental product design flaws, or failures in quality control during the manufacturing process. Figure 2-1 below indicates leading PV module aging and failure mechanisms that occur as infant mortalities, mid-life failures, and wear-out failure.

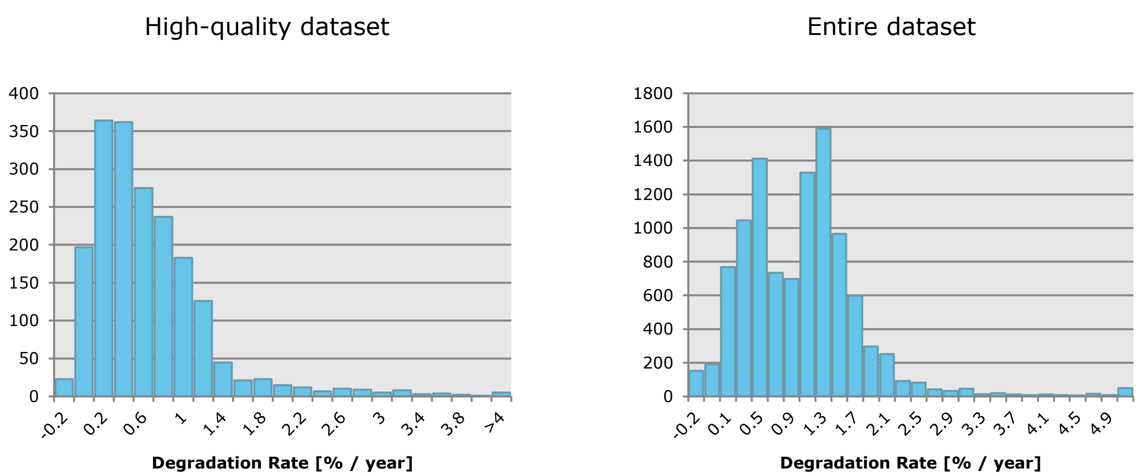


Source: IEA PVPS 2014

Figure 2-1 Aging mechanisms leading to PV module degradation

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 the National Renewable Energy Laboratory (NREL) have performed a comprehensive literature survey[1] 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 versus flash test), and not appropriately accounting for light-induced degradation (LID) are just a few major sources of potential 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 are shown in Figure 2-2 and Figure 2-3. Note that 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.



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

Figure 2-2 Results of Kurtz-Jordan NREL study of PV degradation in the Field

[1] Compendium of Photovoltaic Degradation Rates", D.C. Jordan, et al, NREL, 2015. Report updated in 2016 with support from DNV GL.

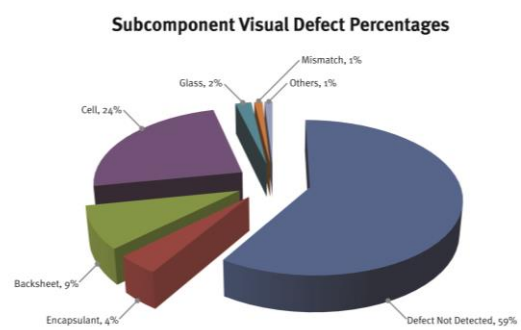
Data set	No. of modules surveyed	Mean degradation rate	Median degradation rate	P90 degradation rate
High Quality	1,936	0.5 – 0.6 % / year	0.4 – 0.5 % / year	1.2 % / year
All Module Data	9,977	0.9 – 1.0 % / year	0.9 – 1 % / year	1.7% / year

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

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

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.

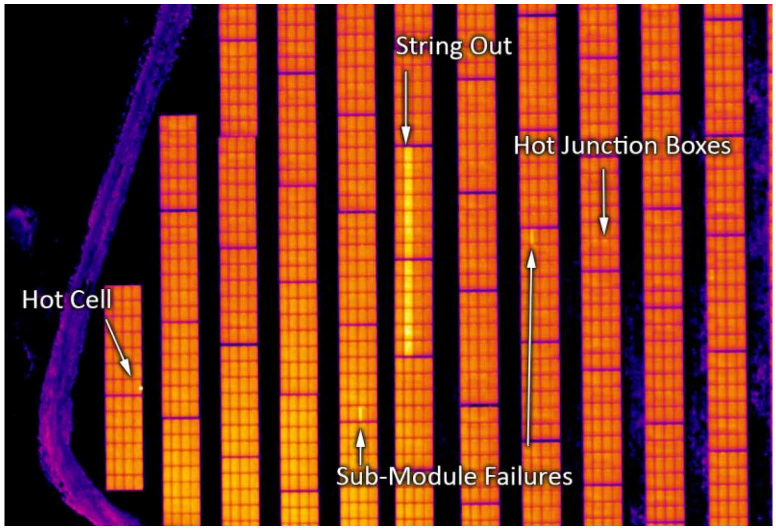
Failure categorizations	
Glass / Superstrate	Broken, etched, hazed glass
Encapsulant	Discoloration or delamination
Cell / Interconnect	Corrosion, hot spot, broken interconnect, snail trails, cracks, burn marks
Backsheet	Cracking, yellowing, delamination



Source: Courtesy of DuPont Photovoltaic Solutions, "Quantifying PV Module Defects in the Service Environment", Alex Bradley, et al., 2017

Figure 2-4 DuPont inspection of field PV modules

Aerial inspections (from drone or airplane) of PV power plants is becoming more common as a means of screening for defective or underperforming modules and strings, and were recently included in the NREL operations and maintenance best practices guide. These techniques are able to detect module-level defects which cause temperature differences in the module such as diode faults, cell hot-spots, junction box heating and major differences in module efficiency, some of which are shown in Figure 2-5. An example of this is Heliolytics, which offers plant level thermography from an airplane and can be used to more precisely identify fielded module faults for further laboratory testing.



Source: Heliolytics, "Summary of DC Losses Observed using Aerial Infra-Red Inspection Across >1.6 GW", Rob Andrews and Kristine Sinclair, 2017

Figure 2-5 Heliolytics thermal scan of PV plant

2.2 The objective of laboratory testing

The most accurate way to determine if a product can last 25 years in the field is to instrument it and deploy it for 25 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 rates 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 defective solder joints or a poorly adhered junction box. Table 2-1 outlines failure modes targeted by each laboratory stress test as published by NREL.

Table 2-1 PV module failure modes per laboratory test

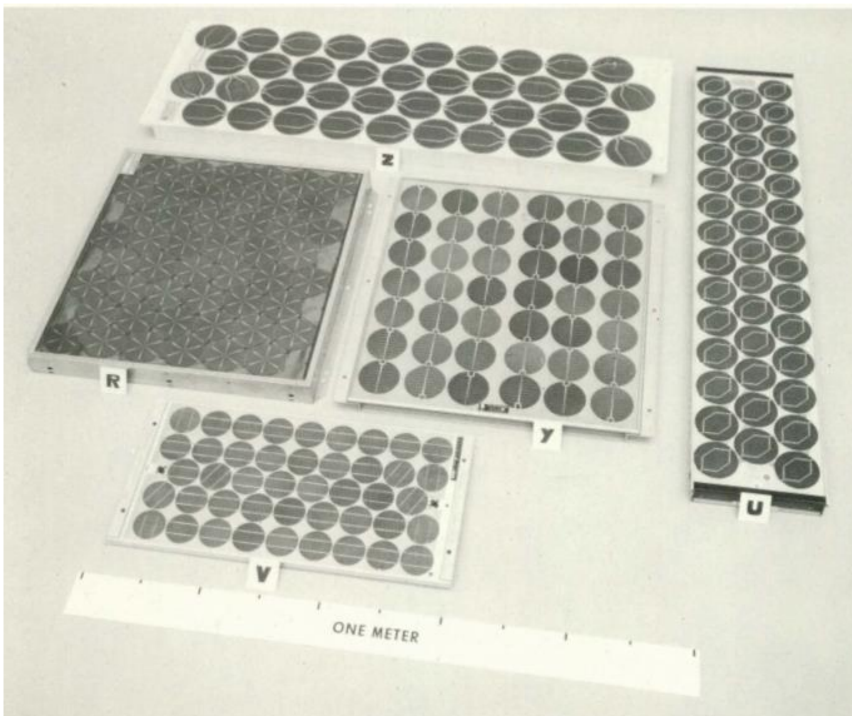
Accelerated stress	Failure mode
Thermal cycling	Broken interconnect Broken cell Solder bond failures Junction box adhesion Module connection open circuits Open circuits leading to arcing
Damp heat	Corrosion Delamination of encapsulant Encapsulant loss of adhesion and elasticity Junction box adhesion 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 and 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[2] (see Figure 3-1) and the Joint Research Center's European Solar Test Installation[3].



Source: Jet Propulsion Laboratory

Figure 3-1 Jet Propulsion Laboratory's Block Buy modules

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.

[2] https://www2.jpl.nasa.gov/adv_tech/photovol/Pub_blockbuys.htm
[3] https://ec.europa.eu/jrc/sites/jrcsh/files/esti_european_solar_test_installation_en.pdf

These two programs formed a foundation for today's basic module certification test, the International Electrotechnical Commission (IEC) 61215 "Crystalline silicon terrestrial photovoltaic (PV) modules –Design qualification and type approval", and safety test, Underwriters Laboratories (UL) 1703 "Standard for Flat-Plate Photovoltaic Modules and Panels."

3.2 The limitations of existing certification standards

Though most PV projects require UL and/or IEC certification to ensure a minimum level of module robustness and safety, it is widely accepted that these certification standards are not sufficient to demonstrate PV module reliability or 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.

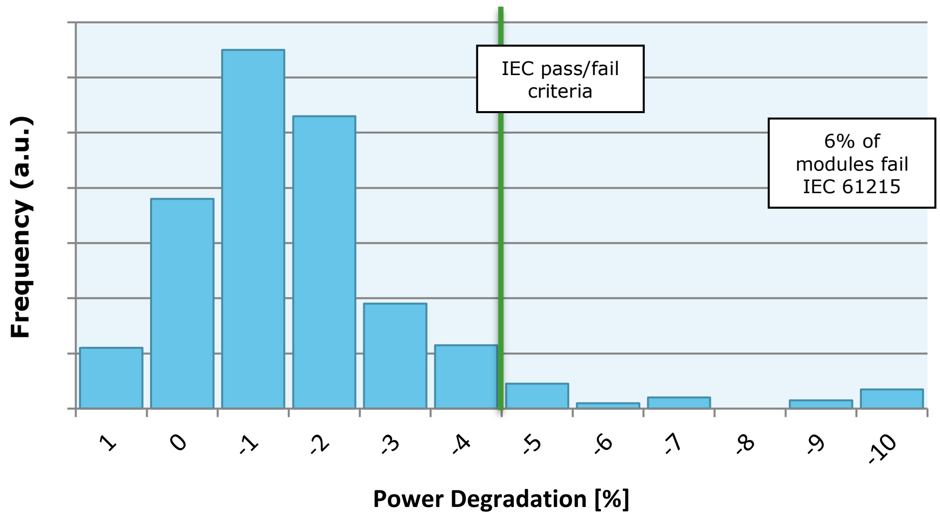
The IEC 61215 standard is the minimum baseline industry-accepted module assessment program, applying environmental stress tests first developed in the JPL Block Buy program. However, the scope of these tests accounts only for so-called infant mortality and leaves aside a number of common potential causes of failure. For instance, resilience to potential induced degradation (PID) is not tested at all. This means that the IEC 61215 tests are only 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 a small number of samples and is not necessarily representative of high volume commercial production over time. The manufacturer is free to select the physical modules sent for testing, meaning no random selection out of the production line is necessary. This allowance may lead to manufacturers selecting only the best of their supply to be tested. Furthermore, maintaining certification does not require periodic re-testing unless materials or designs change.

Applying the same IEC tests for PV module defect screening is becoming a common and effective batch-acceptance approach for screening for serial defects for PV module procurement in large residential or commercial procurements or utility scale projects (see Section 6.1 below). However this method is not sufficient to start to quantify long-term reliability of the module construction.

Based on DNV GL's experience and data, at least 6% of commercial PV modules do not pass the IEC 61215 thermal cycling test – see Figure 3-2 below. This 6% figure has remained constant as the historical dataset has grown from tens to hundreds of modules.

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.



Source: DNV GL Laboratory Services Group

Figure 3-2 DNV GL's historical thermal cycling degradation results (200 cycles)

3.3 Degradation versus failure

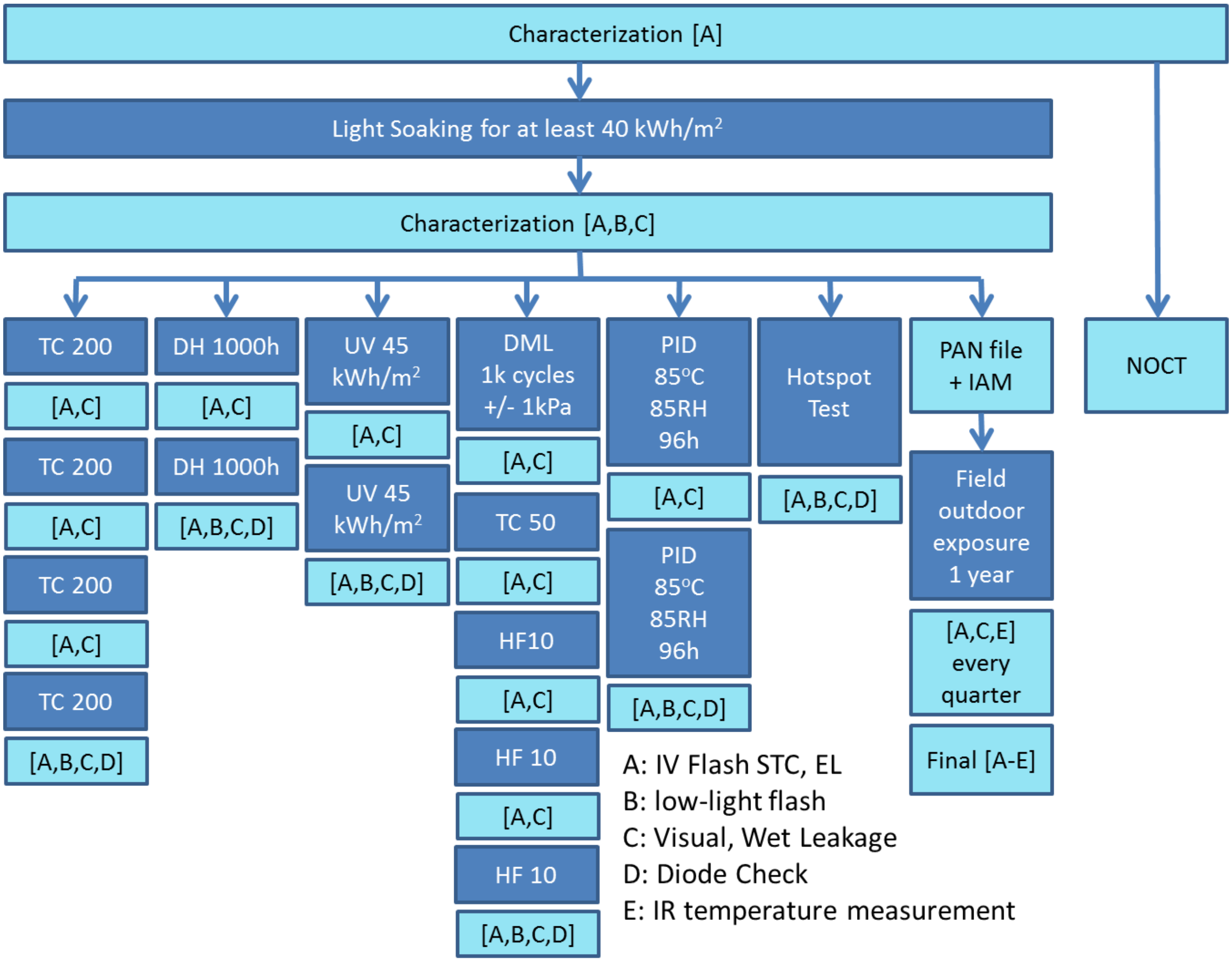
Module power degradation over time is built into project expectations and is warranted by the manufacturers. The current standard 25-year warranty is typically triggered if modules degrade more than 3% within the first year and at a linear rate down to 80% of their initial nameplate power in year 25. Small levels of power degradation in the field are difficult to accurately measure due to the uncertainty of measurement tools. PV module 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 PV MODULE PRODUCT QUALIFICATION PROGRAM

DNV GL[4] developed the Product Qualification Program (PQP) to support the downstream solar community in 2012. The objectives of the PQP are twofold. First, it provides PV equipment buyers and PV power plant investors with independent and consistent reliability and performance data to help implement an 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 scope is designed to align with downstream requirements. It appropriately evolves with time to take into account new insights in understanding degradation mechanisms, requests from DNV GL's downstream partners, and comments from the entire PV community, including manufacturers.

The PV Module PQP provides DNV GL's downstream partners with third-party performance data (PAN files, incidence angle modifier [IAM], nominal operating cell temperature [NOCT], and LID) as well as reliability data as outlined in Figure 4-1 below. Data in the PV Module Reliability Scorecard is extracted from this PQP. All modules are witnessed in production and tested in the same way and in the same environment to enable a levelled comparison. In the past 3½ years DNV GL has executed more than 75 PV Module PQPs with more than 40 module manufacturers. Nine of the top ten global module manufacturers and more than 70% of the latest Bloomberg New Energy Finance (BNEF) "Tier 1" manufacturers have taken part in the PQP.

[4] Formerly PV Evolution Labs a.k.a. PVEL.



Source: DNV GL Laboratory Services Group

Figure 4-1 DNV GL's PV Module Product Qualification Program

Abbreviations expanded, tests based on IEC and UL standards:

- TC: Thermal cycling
- DH: Damp heat
- UV: Ultraviolet light exposure
- DML: Dynamic mechanical load
- PID: Potential induced degradation

4.1 Module selection and sampling process

Independent PV module sampling is a critical step in testing and qualification. This step, and in particular the random sampling of the modules, builds confidence that the production process and Bill of Materials (BOM) are representative of actual commercial production. The BOM is controlled and verified during the sampling to allow DNV GL downstream partners to compare different BOMs. An Approved Product List for DNV GL downstream partners would typically include only BOM components qualified through the PQP. DNV GL often works with independent inspectors from SolarBuyer and Clean Energy Associates (CEA) for all modules tested in the PV Module Reliability Scorecard. This is a mandatory part of the PQP.

4.2 Light-induced degradation

Upon initial exposure to light, crystalline silicon modules typically 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 take this into account by factoring in a 3% power loss (typically) during the first year of the module warranty.

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

5 PV MODULE RELIABILITY SCORECARD RESULTS

5.1 Results summary

Similar to last year's report, most participating PV module manufacturers, models, and associated BOMs performed well this year, with relatively few incidents of outright failure. Participation in the DNV GL PQP suggests the importance that the participating manufacturers place on the reliability of their products. In other words, this is likely a self-selecting group. Because of this the median results presented here may be better than the median results of the broader industry taken as a whole. Results presented in the bar charts below show average values of multiple individual PV modules per BOM. Each bar represents a different BOM. The factory locations used and model names tested are listed in the tables below. Most PV modules are standard 60- or 72-cell mono- or multi-crystalline silicon modules. A different number of manufacturers participated in each test. Because the scope of every PQP is driven by re-test guidelines, not every BOM is submitted to every test leg.

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 green vertical line indicated on the results charts. The green vertical line is a visual guide chosen to represent an inflection point present in most of the datasets.

In this third installment of the PV Module Reliability Scorecard Report, the tables below the charts additionally indicate which manufacturers were also named in the 2014 and 2016 reports. This demonstrates both consistency and improvement of module quality over several very dynamic years.

Table 5-1 PV Module Reliability Scorecard test results summary

Reliability test	Duration reported	Top result	Bottom result	Median result
Thermal cycling	600 cycles	No measurable degradation	Complete failure	-1.9
Damp heat	2,000 hours	No measurable degradation	-5.5	-0.9
Humidity-freeze	30 cycles	-0.21	-7.6	-2.3
Dynamic mechanical load	1,000 cycles + TC50 + HF10	No measurable degradation	-11	-1.2
PID	96-100 hours	No measurable degradation	-92.2	-0.4

Source: DNV GL Laboratory Services Group

Table 5-2 Manufacturer factory locations (alphabetical order)

Manufacturer	Factory location
Astronergy	Haining, Zhejiang, China
BYD	Songjiang, Shanghai, China
Flextronics	Johor, Malaysia
GCL	Bac Glang Province, Vietnam
Hanwha Q CELLS	EumSeong-gun, Chungcheongbuk-do, Korea and Cyberjaya, Selangor, Malaysia
Hyundai	Eumseong Chungcheongbuk-do, Korea
Jinko Solar	Shangrao, Jiangxi, China
Kyocera	Tijuana, Mexico
LONGi	Quzhou, China
NSP	Hukou, Hsinchu, Taiwan
REC	Singapore
S-Energy	Daejon site, Korea
Seraphim	Changzhou, Linnan, China
Silfab	Ontario, Canada
Solaria	Fremont, CA USA
SolarWorld	Hillsboro, OR, USA
SunPower	Milpitas, CA USA
SunSpark	Riverside, CA, USA
Talesun	Changshu, Jiangsu Province, China and Pluakaeng, Rayong, Thailand
Trina Solar	Changzhou, China
Vikram	Kolkata, West Bengal, India
Yingli	Baoding, China and Hengshui, China

Source: DNV GL Laboratory Services Group

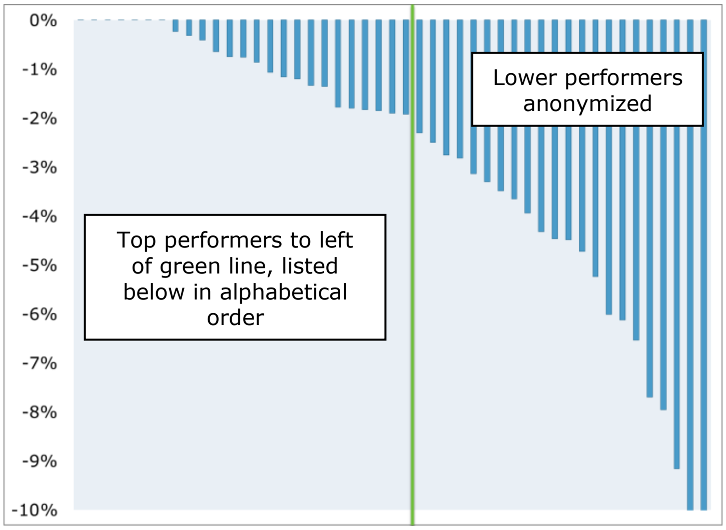
5.2 Thermal cycling

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 bus bar 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. DNV GL follows IEC 61215 current injection recommendations inside the chamber. This additional power injected into the modules causes localized heating if solder joints are degrading. IEC 61215 requires only 200 cycles which may be estimated to represent roughly 5 years of field exposure depending on the environment. The PV Module PQP extends the test to at least 600 cycles. It should be noted that the test procedure does not combine all conditions that modules may experience in very harsh environments. For instance, high-intensity and/or high-photon-energy light exposure is present in arid desert environments and may expose the modules to additional failure modes such as encapsulant browning. While the current PQP scope calls for TC800, the results at TC600 are presented in the PV Module Reliability Scorecard 2017.

5.2.1 Thermal cycling test results

Figure 5-1 shows the results of thermal cycling tests; 40 module models with 49 unique BOMs participated in the thermal cycling test with degradation rates varying from non-measurable to a complete failure.



2017 top performers Name in alphabetical order	Model name	Top performer in 2016 report	Top performer in 2014 report
Astronergy	CHSM6612M/HV-xxx		yes
Astronergy	CHSM6612P/HV-xxx		yes
BYD	BYD P6C-36		
Jinko Solar	JKMxxxP/PP		yes
Kyocera	KUxxx-6XPA	yes	yes
LONGi	LR6-72-xxxM		
LONGi	LR6-72PE-xxxM		
NSP	D6MxxxB4A		
NSP	D6MxxxB3A		
SolarWorld	SW xxx Mono Black		
SolarWorld	SW xxx Mono		
SunPower	SPR-P17-xxx-COM		
Talesun	TP672M-xxx		
Talesun	TP660P-xxx		
Trina Solar	DD14A(II)	yes	yes
Trina Solar	TSM-xxxPD05.18	yes	yes
Trina Solar	TSM-xxxPD14.18	yes	yes

Source: DNV GL Laboratory Services Group

Figure 5-1 Difference in P_{max} [%] observed after thermal cycling (TC600)

5.3 Dynamic mechanical load

The dynamic mechanical load (DML) test determines a PV 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.

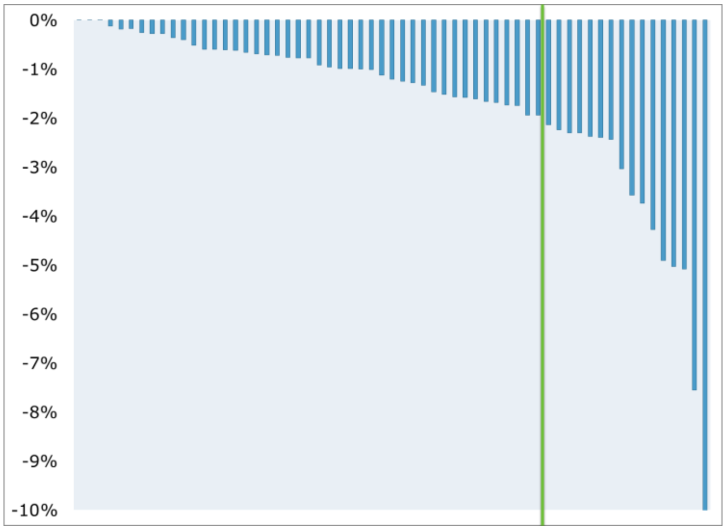
Various aspects of the processing steps such as cell soldering and cell etching, as well as the selection of glass, EVA encapsulant, and backsheet material impact a module's sensitivity to physical damage from mechanical loads. It should also be noted that in real-life conditions, large pressure loads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

The PV Module PQP utilizes a test sequence of mechanical stress to cause cell cracks (1,000 cycles at ±1,000 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 caused, for instance, 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

Figure 5-2 shows the results of the DML tests; 49 module models with 61 unique BOMs participated in the DML test with degradation rates varying from non-measurable degradation to -11%.



2017 top performers: Name in alphabetical order	Model name	Top performer in 2016 report	Top performer in 2014 report
Astronergy	CHSM6612M/HV-xxx		yes
Astronergy	CHSM6612P/HV-xxx		yes
BYD	BYD P6C-36		
GCL	GCL P6/72315		
Hanwha Q CELLS*	Q.PLUS BFR G4.1	yes	
Jinko Solar	JKMxxxP/PP		
Kyocera	KUxxx-6XPA	yes	yes
LONGi	LR6-72-xxxM		
LONGi	LR6-72PE-xxxM		
NSP	D6MxxxB3A		
NSP	D6MxxxB4A		
REC	RECxxxTP BLK		
S-Energy	SNxxxP-15		
Seraphim	SRP-xxx-6PA		
Seraphim	SRP-xxx-6PB		
SolarWorld	SW xxx Mono Black		
SolarWorld	SW xxx Mono		
SunPower	SPR-P17-xxx-COM		
SunSpark	SMX-xxxP		
Talesun	TP672M-xxx		
Talesun	TP660P-xxx		
Solaria	PowerXT-xxxU		
Trina Solar	DD14A(II)	yes	
Trina Solar	TSM-xxxPD14.18	yes	
Trina Solar	TSM-xxxPD05.18	yes	
Vikram	VSP.72.aaa.03		
Vikram	VSP.60.aaa.03		
Yingli	YLxxxD-36b	yes	yes

Source: DNV GL Laboratory Services Group
*Past performance references either "Q CELLS" or "Hanwha SolarOne" which have since merged.

Figure 5-2 Difference in P_{max} [%] observed after Mechanical Load test sequence (DML + TC50 + HF10)

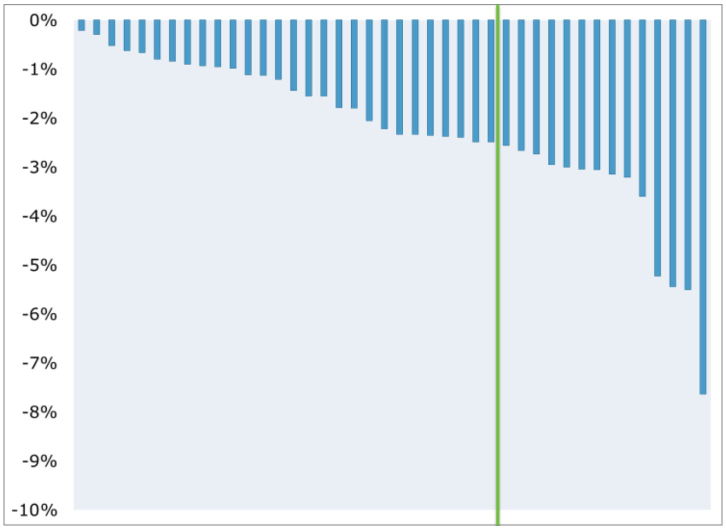
5.4 Humidity-freeze

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 failures. 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 30 minutes (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 PQP extends the test to 30 cycles.

5.4.1 Humidity-freeze test results

Figure 5-3 shows the results of the humidity freeze tests; 33 module models with 45 unique BOMs participated in the humidity-freeze test, with degradation rates varying from -0.2% to -7.6%.



2017 top performers Name in alphabetical order	Model name	Top performer in 2016 report	Top performer in 2014 report
BYD	BYD P6C-36		
Hanwha Q CELLS*	Q.PRO BFR-G4	yes	
Jinko Solar	JKMxxxP/PP	yes	yes
Kyocera	KUxxx-6XPA	yes	yes
LONGi	LR6-72-xxxM		
LONGi	LR6-72PE-xxxM		
NSP	D6MxxxB4A		
REC	RECxxxTP BLK		
SolarWorld	SW xxx Mono Black		
SolarWorld	SW xxx Mono		
SunPower	SPR-P17-xxx-COM		
Talesun	TP672M-xxx		
Talesun	TP660P-xxx		
Trina Solar	DD14A(II)		yes
Trina Solar	TSM-xxxPD14.18		yes
Trina Solar	TSM-xxxPD05.18		yes
Vikram	VSP.72.aaa.03		
Vikram	VSP.60.aaa.03		

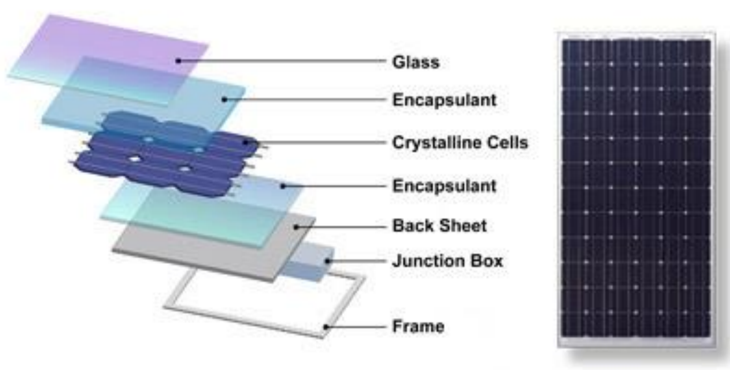
Source: DNV GL Laboratory Services Group
*Past performance references either "Q CELLS" or "Hanwha SolarOne" which have since merged.

Figure 5-3 Difference in P_{max} [%] observed after Humidity Freeze (HF30)

5.5 Damp heat

High ambient temperature and humidity such as those in some parts of Southern U.S. (e.g., Florida) and in parts of Europe 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.

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. Today, the PV Module PQP extends the test procedure to 2,000 hours. Figure 5-4 shows the various layers in a typical crystalline-Si PV module. All of these layers need to stay adhered for decades in the field.

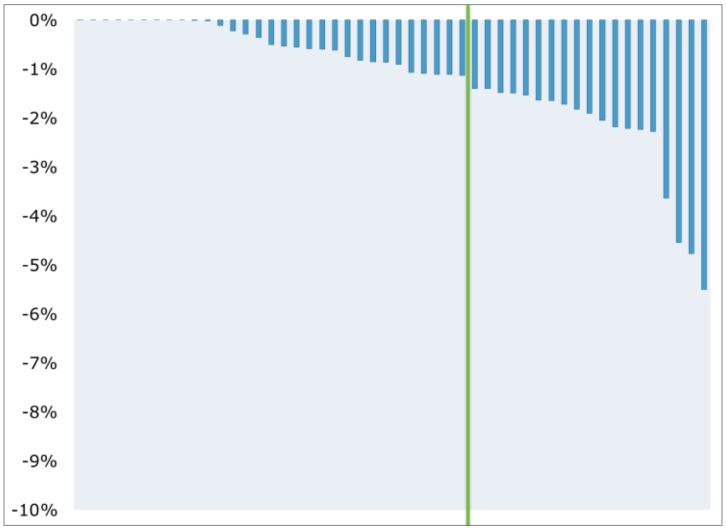


Source: Dow Corning: http://www.dowcorning.com/content/solar/solarworld/solar101.aspx

Figure 5-4 Layers of a PV module

5.5.1 Damp heat test results

Figure 5-5 shows the results of the damp heat tests; 42 module models with 50 unique BOMs participated in the damp heat test, with degradation rates varying from non-measurable degradation to -5.5%.



2017 top performers: Name in alphabetical order	Model name	Top performer in 2016 report	Top performer in 2014 report
BYD	BYD P6C-36		
Hanwha Q CELLS	Q.PRO L-G2		
Hanwha Q CELLS	Q.PRO BFR-G4		
Hyundai	HiS-SxxxRG		
Jinko Solar	JKMxxxP/PP	yes	yes
Kyocera	KUxxx-6XPA	yes	yes
LONGi	LR6-72-xxxM		
LONGi	LR6-72PE-xxxM		
NSP	D6MxxxB3A		
NSP	D6MxxxB4A		
REC	RECxxxTP BLK	yes	
Silfab	SLG320M		
SolarWorld	SW xxx Mono Black		
SolarWorld	SW xxx Mono		
SunPower	SPR-P17-xxx-COM		
SunSpark	SMX-xxxP		
Talesun	TP660P-xxx		
Talesun	TP672M-xxx		
Trina Solar	DD14A(II)	yes	yes
Trina Solar	TSM-xxxPD05.18	yes	yes
Trina Solar	TSM-xxxPD14.18	yes	yes
Vikram	VSP.60.aaa.03		
Yingli	YLxxxD-36b		

Source: DNV GL Laboratory Services Group

Figure 5-5 Difference in P_{max} [%] observed after Damp Heat (DH2000)

5.6 PID test

During operation, because the modules are connected in series and because the frames are all connected, the inner circuitry of the modules experiences a static voltage bias relative to the module frame. Several system design decisions impact the voltage between inner circuitry and frame such as system grounding configuration (negative vs. bi-polar vs. floating) and string maximum voltage (600 vs. 1 kV vs. 1.5 kV). The static 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.

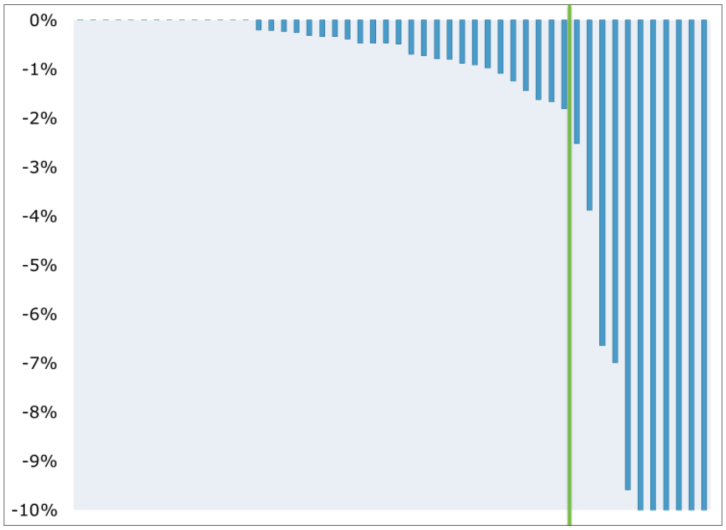
It should be noted that there are reversible and non-reversible PID mechanisms. Electrochemical corrosion and some sodium ion damage to the PN junction are widely considered irreversible, while PID due to the accumulation of static charge on the surface of cells, also known as polarization, can be countered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

5.6.1 PID test procedure

During the test, a voltage bias equal to the system voltage rating of the module (either -1 kV or -1.5 kV) is applied in damp heat testing conditions (T= 85°C, RH= 85%) for a duration between 96 and 100 hours. This provides the temperature and moisture conditions necessary to stimulate increased leakage currents.

5.6.2 PID test results

Figure 5-6 shows the results of the PID tests; 47 module models with 50 unique BOMs participated in the PID test, with degradation rates varying from non-measurable degradation to -92.2%. It is important to note that not all modules claim to be stable under PID stress.



2017 top performers: Name in alphabetical order	Model name	Top Performer in 2016 report	Top Performer in 2014 report
Astronergy	CHSM6612M/HV-xxx		yes
Astronergy	CHSM6612P/HV-xxx		yes
BYD	BYD P6C-36		
Flextronics	FXS-XXXBC-SAD1W		
GCL	GCL P6/72315		
Hanwha Q CELLS*	Q.PLUS L-G4.2	yes	
Hanwha Q CELLS*	Q.PLUS BFR G4.1	yes	
Hyundai	HiS-SxxxRG		
Hyundai	HiS-MxxxTI		
Jinko Solar	JKMxxxP/PP	yes	
Kyocera	KUxxx-6XPA	yes	yes
LONGi	LR6-72-xxxM		
LONGi	LR6-72PE-xxxM		
NSP	D6MxxxB4A		
REC	RECxxxTP BLK	yes	
S-Energy	SNxxxP-15		
Silfab	SLG320M		
SolarWorld	SW xxx Mono Black		
SolarWorld	SW xxx Mono		
SunPower	SPR-P17-xxx-COM		
SunSpark	SMX-xxxP		
Talesun	TP672M-xxx		
Talesun	TP660P-xxx		
Solaria	PowerXT-xxxU		
Trina Solar	DD14A(II)		yes
Trina Solar	TSM-xxxPD05.18		yes
Trina Solar	TSM-xxxPD14.18		yes
Yingli	YLxxxD-36b		
Yingli	YL310P-35b		yes

Source: DNV GL Laboratory Services Group

*Past performance references either "Q CELLS" or "Hanwha SolarOne" which have since merged.

Figure 5-6 Difference in P_{max} [%] observed after PID test (96-100h)

6 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 myriad 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 Approved Vendor/Product List's by setting degradation thresholds (e.g., 5%, or top 40% of the PQP participants).

Additionally, accelerated testing should be used to screen for PV module defects in large procurements. The schematics below show a recommended flow of how laboratory test data are used to minimize some of the technology risks in a PV plant. The qualification part (the PQP scope) should occur when a product is initially being evaluated for the module buyer's Approved Vendor List. The statistical batch testing part, or serial defect screening (typically IEC scope), should occur on the actual modules produced and shipped to the project's site. The red flags indicate moments in the process where the module buyer can check the quality of the modules purchased, provided the right language is included in the procurement agreements.

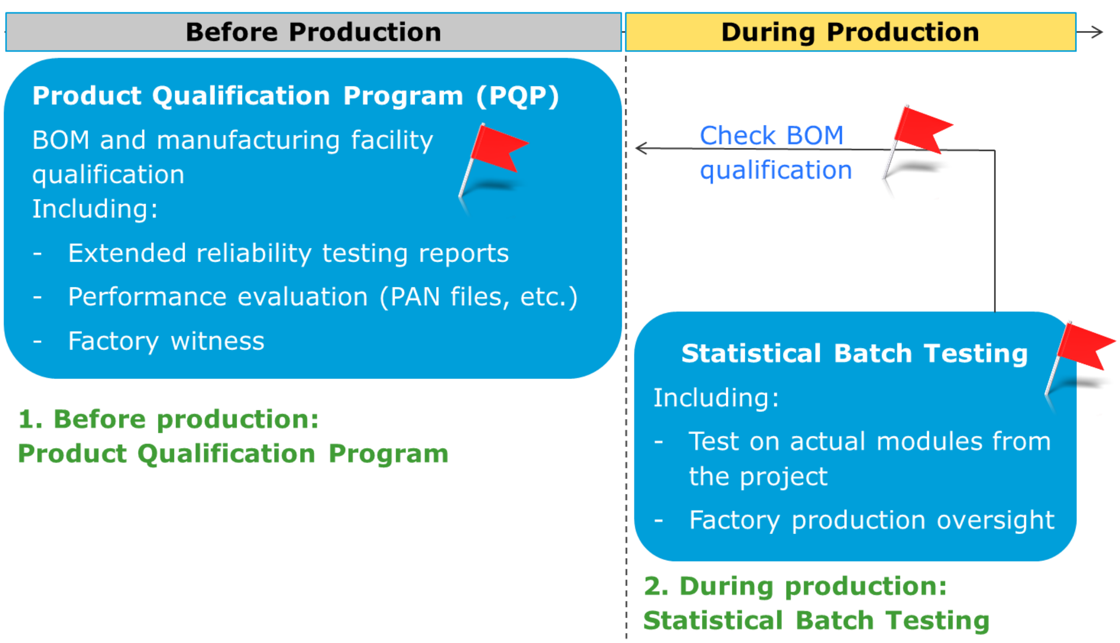


Figure 6-1 Recommended procurement quality plan

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

These tests provide information on how vendors, modules, BOMs, and factories compare with one another in a given set of controlled environmental conditions, simulating a given set of failure mechanisms encountered in the field.

Choosing vendors with lower degradation levels increases the likelihood of technical and financial success of the project.

6.2 Take-aways

DNV GL has identified a few key takeaways from the results presented in the 2017 Scorecard.

6.2.1 The Bill of Material matters

Most module types in the market today utilize several (or many) different BOMs. The same label may be printed on the back of a module with different materials and cells made even in different countries. The same module type can be represented in the market with different interconnection schemes (e.g., regular busbars versus multi-busbars) and different cell types (e.g., aluminum-BSF versus PERC). As an illustrative example, Figure 6-2 below represents two modules with the same nameplate label and very different BOMs, performing very differently when undergoing accelerated testing.

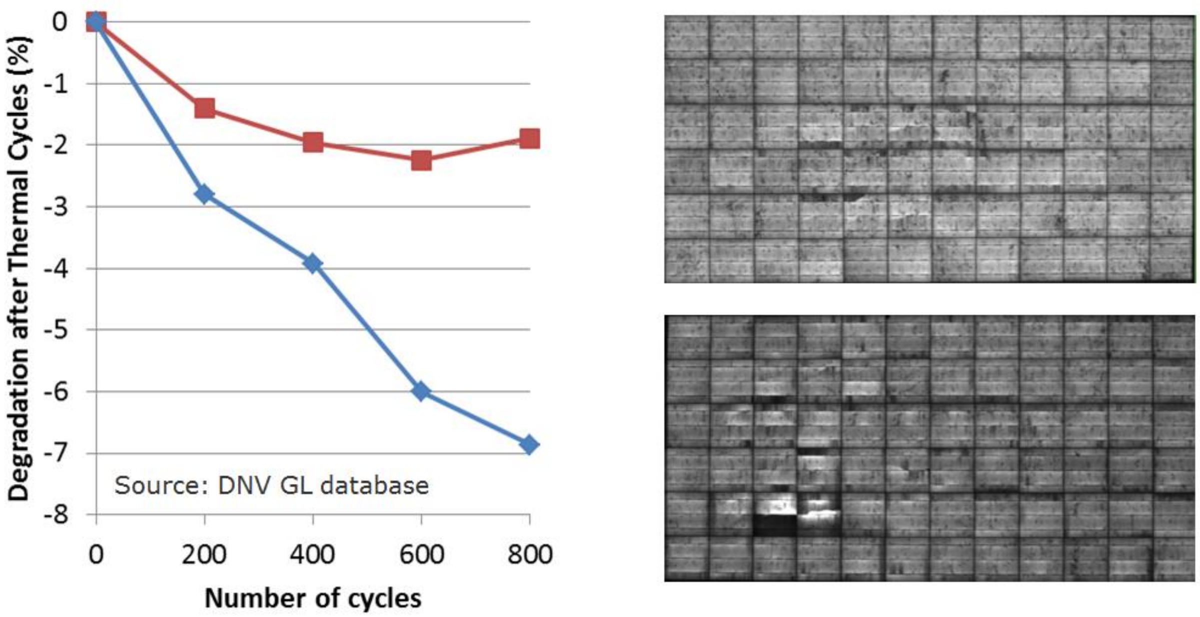


Figure 6-2 Two modules with the same label and a different BOM may perform differently in accelerated tests

DNV GL recommends acquiring knowledge of the BOM and of accelerated test results for the specific BOM shipped to the project. The modules tested should be randomly selected, their BOM recorded, and their provenance controlled up to the test lab facility. Upon request, DNV GL can match a given BOM with the list of PQP test reports relevant to the specific BOM.

6.2.2 The production factory matters

Similar to the observations concerning the BOM, DNV GL's dataset suggests that the same module type with the same BOM manufactured in a different factory may perform differently through the different PQP test legs.

The distribution of manufacturing locations amongst the test results is shown in Table 6-1 below. No single region of production dominates the "top performers." However, China is systematically over-represented in the 2017 Scorecard top performer's group compared to the rest of the world.

Table 6-1 Distribution of manufacturing location among test results

	Thermal cycling		Damp heat		Humidity-freeze		Dynamic mechanical load		PID	
	Top Group	All	Top Group	All	Top Group	All	Top Group	All	Top Group	All
China	54%	37%	38%	43%	45%	36%	51%	44%	34%	32%
Other Asia	27%	41%	38%	41%	32%	43%	33%	37%	39%	45%
North America	19%	22%	25%	16%	23%	20%	16%	19%	26%	23%

To further illustrate the regional distribution of the test results, the results of the thermal cycling testing presented in Figure 5-1 have been color-coded to highlight the location of the production of each module tested and are shown in Figure 6-3 below. Although some modules coming from other regions perform very well, China, in red, is over-represented in the better part of the chart.

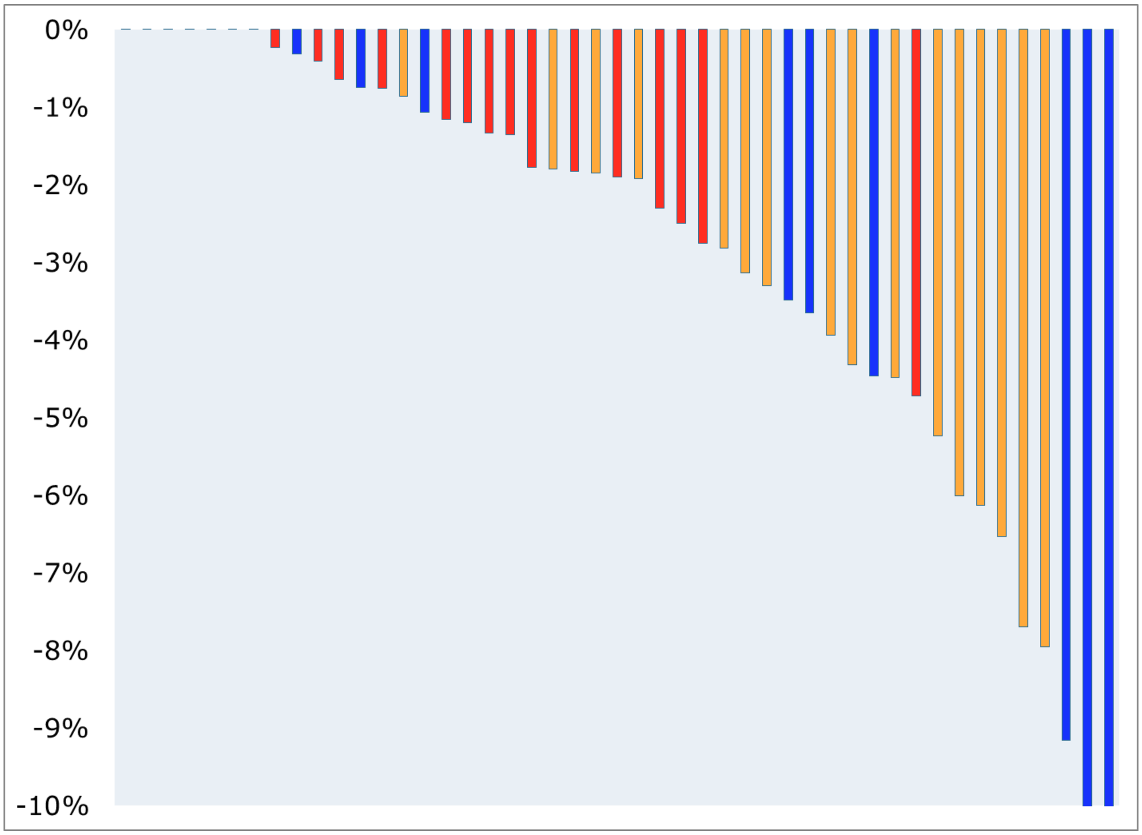


Figure 6-3 Difference in P_{max} (in %) observed after TC600 - color-coded with location of the factory (red = China; yellow = rest of Asia; blue = rest of the World)

As mentioned above, import tariffs and minimum price policies in the U.S. and Europe have driven many manufacturers to outsource manufacturing or build new factories in tariff-free countries such as Malaysia, Vietnam, Thailand, India, etc.

DNV GL recommends acquiring knowledge of the factory details (location, workshop, etc.) and carrying out factory oversight during the production of the module batches during project construction. During this oversight, samples may be randomly selected and tested for serial defect screening as described in Section 6.1.

The DNV GL PQP includes a factory witness report with useful information on the production factory. In addition to other reports (reliability and performance test data), DNV GL downstream partners may request this witness report to obtain visibility in the BOM and factory.

6.2.3 The attention manufacturers pay to quality matters

DNV GL's experience shows that the attention to quality that a manufacturer invests in its products is not homogeneous among manufacturers, and does matter. The more a manufacturer invests in improving and demonstrating the quality of the products, the better the results in accelerated testing.

As an illustration of this, Figure 6-4 below reproduces the thermal cycling test results from Figure 5-1 with a color-code representing the relative engagement of the manufacturer in the DNV GL PQP. The manufacturers most engaged in producing and demonstrating high-quality products end up producing modules with better results in reliability testing.

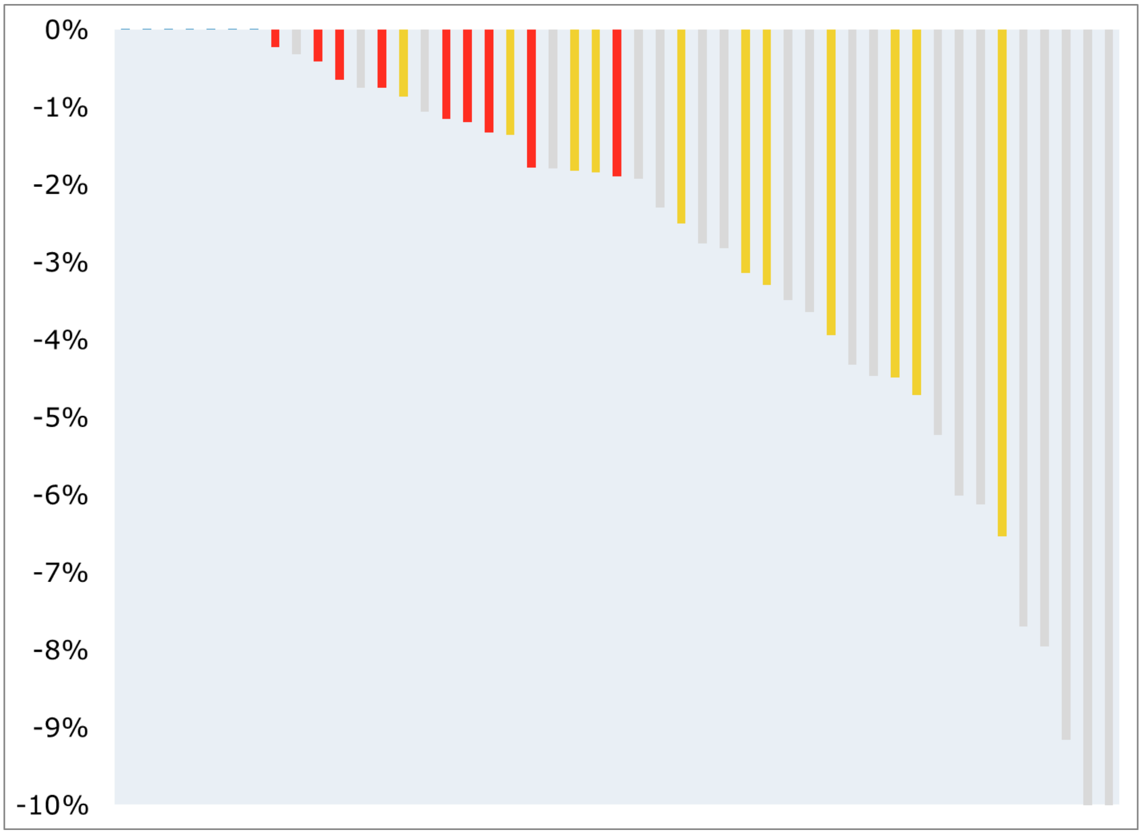


Figure 6-4 Difference in P_{max} (in %) observed after TC600 – color-coded with the relative engagement in the DNV GL PQP program (red = very engaged PQP participant [several PQPs per year and claiming all U.S. BOMs systematically tested]; yellow = engaged PQP participant [several PQPs per year and most of the U.S. BOMs tested])

DNV GL believes that the manufacturers participating in the DNV GL PQP and featured in this report are, within the industry, amongst the manufacturers paying a high level of attention to quality and may therefore already stand out compared to the rest of the industry.

DNV GL recommends selecting modules with a rigorous testing history.

6.2.4 The size of the company is not a good proxy for quality

More than 40 manufacturers, large and small, have been submitting modules to the DNV GL PQP over the years. Looking back into the DNV GL database, we do not see a direct correlation between the size of the manufacturers and the performance in accelerated testing. To illustrate further this claim, the thermal cycling test data from Figure 5-1 has been color-coded as a function of the volume of shipment of the manufacturer in 2016 (see Figure 6-3 below), the red bars corresponding to top-10 global manufacturers by volume. Some small manufacturers have obtained very good results, while some large manufacturers have produced modules falling in the second half of the result pool.

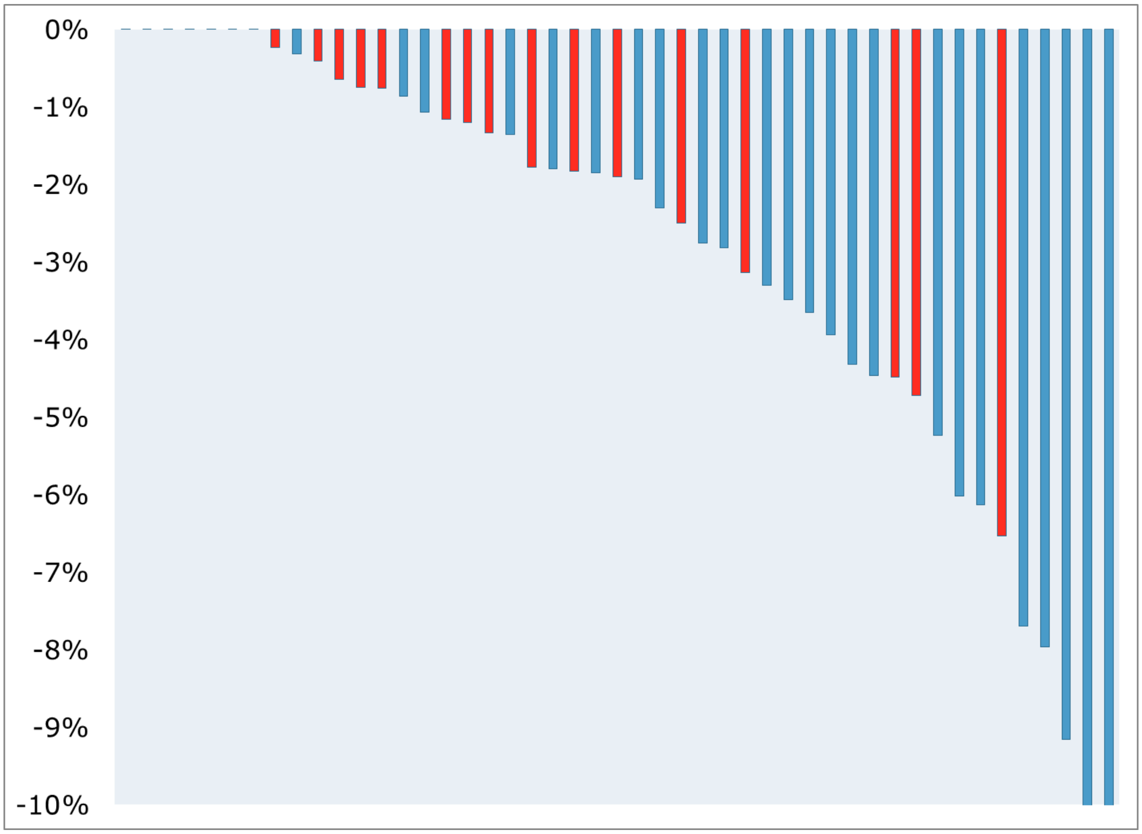


Figure 6-5 Difference in P_{max} (in %) observed after TC600 – color-coded with the shipment volume in 2016 (red = top 10 largest manufacturers)

DNV GL recommends obtaining accelerated test results on the specific BOM, instead of solely relying on the volume shipment or reputation of the supplier to evaluate PV products.

7 CONCLUSIONS

This “PV Module Reliability Scorecard Report 2017” document is the third edition of the DNV GL PV Module Reliability Scorecard. All the results presented in this document have been generated by DNV GL on modules participating in the DNV GL Product Qualification Program, selected and tested in the same manner. Manufacturers’ participation in the DNV GL PQP suggests the importance that they place on the reliability of their products. The group of modules represented here is therefore likely a self-selecting group, adding further to the merit of the top performers within this group.

As a general comment, we find that most modules submitted to the DNV GL PQP perform well in the different test legs of the PQP, with the exception of a few notable degradation levels which may put the financial success of solar projects using these modules at risk. We see several factors having a strong impact on reliability test results, including bill of materials, factory, and the importance that the manufacturer places on quality and reliability. We do not recommend relying solely on the volume shipment or reputation of the manufacturer for procurement decisions.

DNV GL downstream partners enjoy access to additional details and content at no cost. Contact DNV GL if you wish to become a downstream partner.

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