SIXTH EDITION

2020 PV Module Reliability Scorecard

In partnership with DNV·GL

PV EVOLUTION LABS

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About PV Evolution Labs

PV Evolution Labs (PVEL) is the leading reliability and performance testing lab for downstream solar project developers, financiers, and asset owners and operators around the world. With over ten years of experience and accumulated data, PVEL conducts testing that demonstrates solar technology bankability. Its trusted, independent reports replace assumptions about solar equipment performance with data-driven, quantifiable metrics that enable efficient solar project development and financing.

The PVEL network connects all major PV and storage manufacturers with 400+ global Downstream Partners representing 30+ gigawatts of annual buying power. PVEL's mission is to support the worldwide PV downstream buyer community by generating data that accelerates adoption of solar technology. Learn more online at pvel.com.

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Introduction

Foreword: A Note From Our CEO

This year's PV Module Reliability Scorecard is personal. When I established PV Evolution Labs (PVEL) ten years ago, I was preparing to become a father. I used to say that the systems installed back then would last until my unborn child graduated from university.

Unfortunately, not every system installed in 2010 was built to last. That very year, potential-induced degradation (PID) emerged as a failure mode that could reduce a power plant's energy yield by as much as 30%. This year, the median PID degradation from our PQP testing was the highest it has ever been in our lab's history. PID is a problem that many in our industry regarded as solved. Its resurgence is troubling, as are many of the other failures recorded in this report.

Over the past few years we've also observed tremendous innovation in PV technology. The list is impressive: bifacial, larger wafers, half-cut and shingled cells, novel cell-to-cell interconnect methods, PERC, HJT and a parade of other high-efficiency cell technologies. We've also tested thinner frames and glass, light-reflecting ribbon, novel encapsulants and backsheets, and many more. In this rush to innovate, some manufacturers have overlooked basic quality control.

Yet there is no question that advances in solar PV technology are critical. DNV GL, our Scorecard partner, notes in their Energy Transition Outlook that the planet is on track to warm by more than 2°C by 2050 – an outcome that will have devastating consequences around the world. Rapid expansion of renewable energy capacity is critical in the fight against climate change, and higher efficiency, lower cost PV cell and module technologies bring us closer to that goal.

Where does this leave the global solar industry? The pressure is on every player along the PV value chain to meet our energy transition needs while delivering profitable investment opportunities. At PVEL, we're creating data that matters for building the reliable, financeable solar power plants we need.

This sixth edition of PVEL's Scorecard highlights data from one of our most important test programs, the PV Module Product Qualification Program (PQP). It covers the exciting technologies we have tested, recognizes the excellence of top performing manufacturers and includes mission-critical risk mitigation strategies. These strategies are designed to help the global solar industry ensure quality and reliability as PV modules evolve and as the pressure to deploy exponentially more solar increases each passing year.

We hope that this year's Scorecard focuses the industry on deploying solar power systems that are built to last, for the sake of my ten-year-old son and for all of our children.

JENYA MEYDBRAY
CEO
PV Evolution Labs

A Decade of Testing at PVEL: Product Types Over Time

2010

The early days

- P-type mono and multi, thin film and CPV technologies
- All cells are 156mm with 3 busbars
- Monofacial only

2012

Limited cell innovation

- Half-cut cells introduced for early-adopter testing
- Incremental cell design improvements
- New backsheet and encapsulant materials

2014

Significant cell advances

- 8 different cell technologies tested, including n-type PERT, p-type PERC, heterojunction (HJT)
- 3 different cell sizes and 4 busbar combinations

2016

PERC begins to dominate

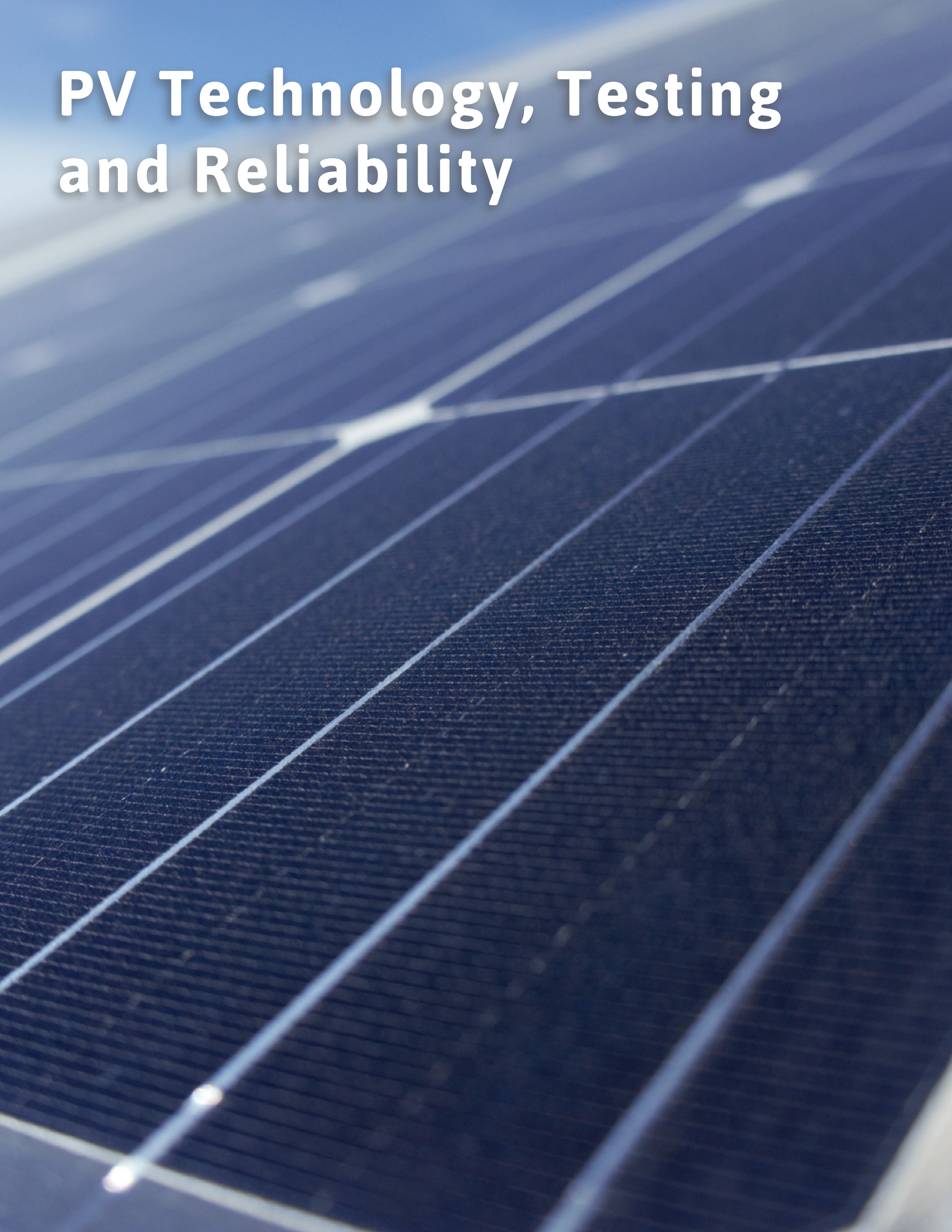
- Product mix tested is fairly consistent as manufacturers validate PERC cell technologies
- Larger cells are introduced (up to 161.7mm)

2018 to present

Major cell and module advancements

- 8 different cell sizes
  125mm, 156mm, 156.75mm, 157.25mm, 158.75mm, 161.7mm, 162mm, 166mm
- 8 different cell technologies
  p-type mono Al-BSF, p-type multi and mono PERC, n-type mono PERT, HJT n-type mono, p-type bifacial mono PERC, n-type bifacial mono PERT, CdTe
- Cells with 5 different counts of busbars
  3, 5, 6, 9, 12
- Monofacial and bifacial glass-glass modules
- Monofacial and bifacial glass-backsheet modules
- 4 different cell interconnection types
  Standard ribbons, ECA (shingled), interdigitated backcontact (IBC), metal wrap-through (MWT)

PV Technology, Testing and Reliability



Trends in PV Module Manufacturing

In only a few years, the PV module manufacturing landscape has changed dramatically. From the rapid ascendance of PERC cell technology to increased adoption of bifacial products, PV module buyers face an increasingly complex marketplace. The results in this year's Scorecard demonstrate that developers, investors and asset owners are directly affected when manufacturers adopt new processes or begin using new components. **PVEL has observed three important trends in PV module technology that are particularly important for downstream stakeholders to consider from a risk-mitigation perspective.**

1. Large-scale adoption of PERC cell architectures

Passivated emitted rear contact (PERC) cells have quickly replaced the once-predominant aluminum back surface field (Al-BSF) cells.

Risks

Some PERC cells are susceptible to light and elevated temperature induced degradation (LeTID), which can reduce energy yield by as much as 10% in the field. Susceptibility to boron-oxygen destabilization may also be a concern.

Rewards

PERC cells are higher efficiency and usually perform better in low-light and high-temperature conditions, and they can be produced at comparable costs to Al-BSF.

2. New cell designs: more busbars, round interconnect wires, larger wafers, half or third-cut cells

Manufacturers are now using cells with up to 4x more busbars than in 2012, new types of interconnect wires, various wafer sizes, as well as half-cut or smaller cells.

Risks

Some new cell designs are more susceptible to microcracks and may require difficult-to-implement process changes on manufacturing lines that lead to increased defect rates.

Rewards

New cell designs are driving higher efficiencies and nameplate power ratings in PV modules, and leading to decreased costs.

3. New module designs: thinner frames, glass-glass, bifacial, light-redirecting films (LRF)

PV module manufacturers are competing to introduce lighter weight modules, bifacial options, novel designs and physically larger modules.

Risks

Newer module form factors may be more susceptible to damage, and they may not be compatible with existing mounting systems. The industry lacks long-term field data for new components and designs.

Rewards

Lighter modules are easier to transport and install. New designs and materials can increase nameplate power ratings.

As manufacturers rush to bring new technologies to market, PVEL is observing a resurgence of known failure mechanisms, plus new degradation modes.

PV Module Failure Modes and Aging Mechanisms

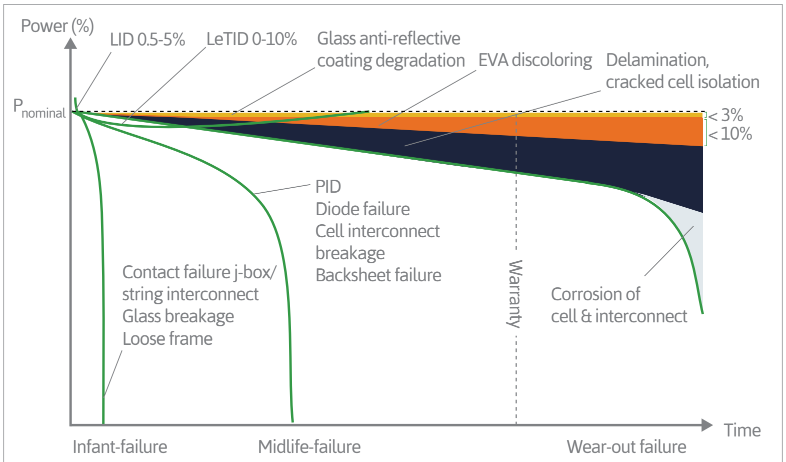
PV modules are vulnerable to a range of failure modes and aging mechanisms. For a PV module to perform reliably for the duration of its modeled lifetime, manufacturers must follow tightly-controlled processes and use quality components. **Premature failure is likely when quality assurance/quality control steps are overlooked or substandard materials are used.**

Lack of long-term field data

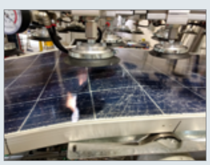
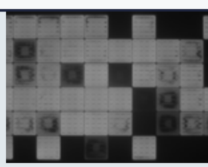
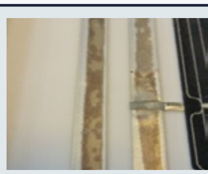
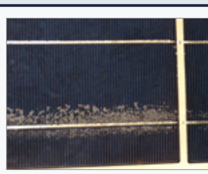
Projects built today utilize technologies and components that did not exist 25+ years ago.

Real-world data that proves the long-term reliability of many recent PV module designs does not exist today.

PV module defects are outlined in the chart to the right. PVEL has identified a selection of field-replicated defects following shipping or stress testing in the table below.



Source: IEA PVPS, 2014; LeTID and backsheet failure added by PVEL, 2019

Failure Mode	Test Sequence	Likely Cause	Project Impact
Glass breakage 	Dynamic mechanical loading (Pg. 20)	Poor frame or glass construction	Increased power loss; safety issues
Unsealing of junction box 	Damp heat (Pg. 18)	Poor component selection and/or improper potting technique	Safety issues
PID 	PID (Pg. 22)	Poor component selection, cell design and/or quality control	Increased power loss
Diode failure 	Thermal cycling (Pg. 16)	Poor diode selection and/or manufacturing quality control	Increased power loss; safety issues
Busbar corrosion 	Damp heat (Pg. 18) and humidity freeze (Pg. 20)	Poor lamination quality and/or component selection	Increased power loss
Delamination 	Damp heat (Pg. 18) and humidity freeze (Pg. 20)	Poor lamination quality and/or component selection	Increased power loss; safety issues

Limitations of Warranties and Certifications

Certifications and warranties are important prerequisites for global market acceptance and financing of solar PV technologies. However, certifications do not ensure the reliable long-term performance of modules in the field, and warranties do not provide full protection from financial losses when modules fail or degrade.

Challenges of warranties

1. **Solvency and responsiveness**
   Warranties do not protect buyers when manufacturers become insolvent or are unresponsive to claims.

2. **Imprecise measurement**
   Measuring power degradation in the field with precision is extremely difficult, so most successful warranty claims are for excessive underperformance or total failure. Warranties typically include a 3% buffer for measurement uncertainty. This 3% reduction in energy yield on top of expected annual degradation can equate to millions of dollars in lost revenue.

3. **Coverage limitations**
   Even when claims are accepted, warranties usually cover the cost of replacement modules only – not costs associated with labor or lost energy production. Due to manufacturing advances, suitable replacement modules may not even be available for older systems, and warranties do not cover the costs of system upgrades to become compatible with current module replacements.

Shortcomings of certifications

Scope limitations

IEC/UL 61730 certifications are focused on safety and non-hazardous operation. IEC 61215 only screens for defects that appear in the first few years of operation.

Golden samples

Manufacturers can submit carefully constructed samples for certification instead of testing their commercially available products, and they can often change component combinations in their module BOM without recertifying.

Slow advancement

Updating certification standards is a multi-year process that cannot keep pace with new failure modes that emerge with technology changes. Specifically, standards have been slow to address PID and LeTID.

Reliability Failures in the Field

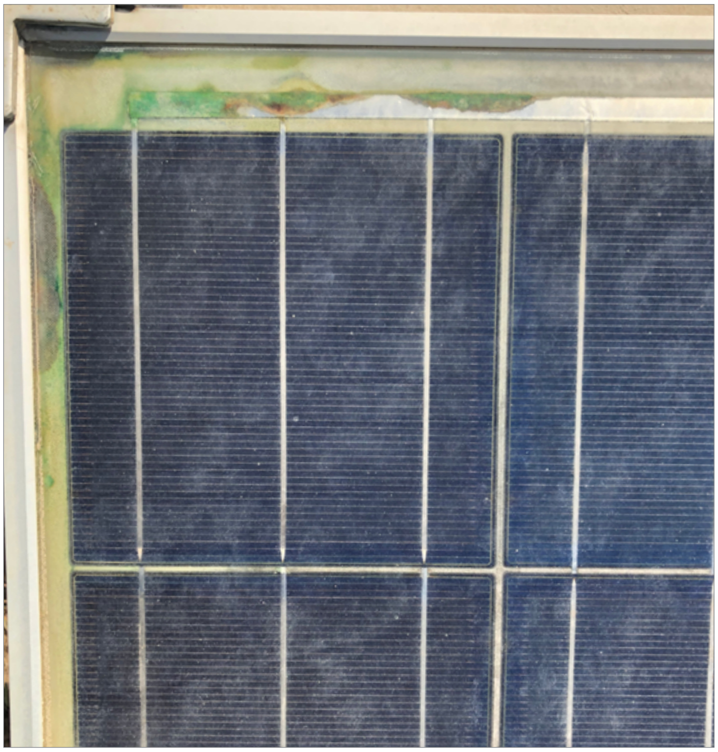
PV module failure and warranty case study

A large-scale commercial and industrial project developer deployed modules made by a Tier 1 manufacturer across multiple sites in the United States. Poor module construction led to moisture ingress that ultimately resulted in delamination, corrosion, high current leakage (a safety concern), ground faults and finally, total system failure.

Following an extended dispute with the manufacturer, the asset owner is now replacing about 100 MW of product at a cost of tens of millions of dollars.

- The warranty only covered the product itself - not replacement costs, system upgrades or lost revenue as the assets sat untouched.
- A power mismatch in the replacement modules required re-configuration of some systems.

Careful review of PVEL reports for this module would have revealed faulty construction. The product passed the damp heat testing required by IEC 61215 certification, **but showed signs of delamination and corrosion after PVEL's more rigorous damp heat test.**

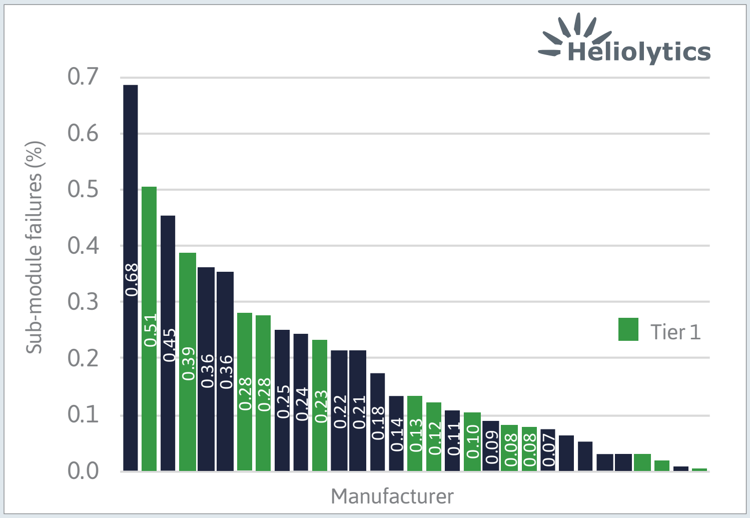


Damaged PV module from the field with evidence of busbar corrosion and delamination.

Poor module construction translated directly to lost revenue for the asset owner. Certification testing and warranties did not provide full protection from losses.

Field reliability per manufacturer

Heliolytics has aerial-infrared scanned 3,500+ operating PV systems globally, representing over 37 GW. Aerial infrared scans identify defects in PV modules that cannot be seen by visual inspection. **Analysis of this data reveals that global top tier status lists do not always correlate with PV module reliability.**



The bar graph shows the percentage of modules with sub-module faults from different manufacturers, ranging from 0.68% down to almost 0.00%.

The chart to the left shows sub-module failures per module manufacturer. These are failures with at least one third of the module in short circuit, leading to at least a 33% drop in module power. They are a good indicator of major reliability issues caused by poor soldering, diode failures, backsheet and/or cell reliability issues. The data set covers manufacturers that supplied five or more sites scanned by Heliolytics.

Four of the top 10 manufacturers exhibiting faults in Heliolytics' site surveys appear on the BloombergNEF Tier 1 list*, which indicates that consulting the industry's top tier lists is not sufficient due diligence for PV module procurement.

**PVEL partners with BloombergNEF to indicate Tier 1 manufacturers that are active participants in PVEL's PQP.*

Test Results

Methodology: PVEL's Product Qualification Program

Scorecard rankings are based on results from PVEL's PQP for PV modules. PVEL established the rigorous, comprehensive program in 2012 with two goals:

1. To provide solar project developers, investors and asset owners with independent, consistent reliability and performance data for effective supplier management.
2. To independently recognize manufacturers who outpace their competitors in product quality and durability.

The PQP is now a required step in procurement risk mitigation for developers around the world. PQP reports are complimentary for downstream companies.

Industry perspective

"Deploying PV modules with even one flawed component or manufacturing defect can dramatically affect both capex and system-level energy yield.

That's why using PVEL's PQP reports to specify PV module bills of materials is part of our standard procurement risk mitigation process."

KEVIN SHEEHAN
Sr. Director of Supply Chain, Americas
BayWa r.e.

Core principles of PVEL's PQP

The PQP is unique in the marketplace as a consistent, methodical sequence of tests that are specifically designed to support downstream solar equipment buyers, investors and asset owners. It enables objective supplier evaluations and rigorous due diligence.

The program is guided by these four principles:

- **Empirical data**
  The PQP replaces performance assumptions with empirical metrics for revenue and energy yield model optimization.
- **No hand-picked samples**
  All bills of materials (BOMs) of products submitted to PQP testing are witnessed in production and factory sealed by PVEL's auditors.
- **Updated regularly**
  The PQP is updated annually to provide buyers with consistently relevant data as new technologies and manufacturing techniques are introduced.
- **Standardized processes**
  All BOMs are tested in the same way with consistently calibrated equipment and in consistent environments.

Factory witness process: BOM-level testing

To verify the BOM of a PV module, PVEL's auditors follow an 8-step factory witness process:

1. Conduct a high-level process audit of the factory.
2. Photograph BOM components as materials are removed from their original packaging.
3. Observe and record over 100 technical details about the BOM.
4. Strictly track each BOM component through every step of production.
5. Collect backsheet, encapsulant and connector samples for testing and/or inventory at PVEL.
6. Document recipes used for soldering and laminating.
7. Sign each module and seal the pallets with tamperproof tape.
8. Ship pallets directly to PVEL for PQP testing.

PV module buyers can ensure they receive the exact BOM combination that performed well in PQP testing by using exhibits to specify approved BOMs in their supply agreements. Free of charge, PVEL provides buyers with detailed BOM listings for inclusion in supply agreements.

PVEL's 2019 Product Qualification Program

PVEL's PQP is updated annually in response to feedback from the market, including downstream buyers, asset owners, financiers, independent engineers (IEs), manufacturers and independent research institutions. **In August 2019, PVEL released the most significant update in the history of its PQP. Changes to the program include new tests for backsheet durability, LeTID and mechanical stress.**

Because PVEL's new tests were introduced mid-way through 2019, the Top Performers for all of the new tests are not ranked in this Scorecard. Results for the backsheet durability sequence and LeTID susceptibility test are discussed as case studies in this report. A white paper on the mechanical stress sequence results will be released later this year.

However, reports for the PV modules that have undergone these new tests are available to PVEL's Downstream Partners.

Factory Witness

Intake Characterizations

Light Soaking for Light-Induced Degradation

Post-Light Soaking Characterizations

Thermal Cycling	Damp Heat	Backsheet Durability Sequence	Mechanical Stress Sequence	Potential-Induced Degradation	LeTID Sensitivity	PAN File & IAM Profile	Field Exposure
TC 200	DH 1000	DH 1000	Static Mechanical Load	85°C, 85%RH MSV (+ and/or –) 96 hrs	LeTID 162 hrs (75°C, Isc-Imp)	PAN File	Field Exposure 6 Months
Characterization	Characterization	Characterization	Characterization	Characterization	Characterization	IAM Profile	Characterization
TC 200	DH 1000	UV 65 kWh/m²	Dynamic Mechanical Load	85°C, 85%RH MSV (+ and/or –) 96 hrs	LeTID 162 hrs (75°C, Isc-Imp)		Field Exposure 6 Months
Characterization	Characterization	Characterization	Characterization	Characterization	Characterization		Characterization
TC 200	Stabilization 85°C, Isc, 48 hrs	TC 50 + HF 10	TC 50		LeTID 162 hrs (75°C, Isc-Imp)		
Characterization	Characterization	Characterization	Characterization		Characterization		
		UV 65 kWh/m²	HF 10				
		Characterization	Characterization				
		TC 50 + HF 10					
		Characterization					
		UV 65 kWh/m²					
		Characterization					
		TC 50 + HF 10					
		UV 6.5 kWh/m²					
		Characterization					

For bifacial modules, PVEL also conducts rear side characterizations and field exposure over two albedos.

Results Overview

The following pages summarize the results from PVEL's PQP testing and list Top Performers for 2020.

Reading the results

The Top Performers in each category are listed in alphabetical order on the subsequent pages. An example of high levels of degradation including EL images and electrical parameters for each category is also provided. The electrical parameters in the graphs are defined as follows: maximum power (PMP), voltage at maximum power (VMP), open circuit voltage (VOC), short circuit current (ISC) and current at maximum power (IMP).

Results presented in the bar charts show average power degradation for the different test samples and BOMs which together represent a single module model. The bar charts also compare the 2020 Scorecard results to PVEL's historical dataset.

Not all products or model types are represented in every test as some results may not have been available at the time of publication. Manufacturers with top performing results can also decline to be listed at their discretion. Although PVEL tests and reports at the BOM level, Top Performers are identified at the model-level only in the Scorecard.

Scorecard eligibility

Scorecard eligibility requirements are as follows:

- Completion of a factory witness within 18 months of 2020.
- Submission to all test sequences in the PQP*.
- Submission of at least two factory-witnessed PV module samples per test sequence.
- Top Performers have less than 2% degradation following each reliability test sequence.
- Top Performers for PAN performance are in the top quartile of energy yield in PVsyst simulations.

The following PV technologies of note were eligible for inclusion in the 2020 Scorecard:

- 78% of eligible BOMs use PERC cells.
- 77% of eligible BOMs use half-cut cells.
- 26% of eligible BOMs are bifacial.
- 13% of eligible BOMs are glass-glass.

Industry perspective

"Since 2015, we have used our PQP test results to build worldwide recognition of LONGi's high-performing, reliable and innovative products.

The PQP is now an important step in our go-to market process for new products and new BOM combinations."

DR. HONGBIN FANG
Director of Product and Technology
LONGi

Submitting samples to all reliability test sequences is required for manufacturers to earn Top Performer designations in the Scorecard, but characterizations for PAN files and IAM profiles are optional.

Thermal Cycling: Overview and Results

Background

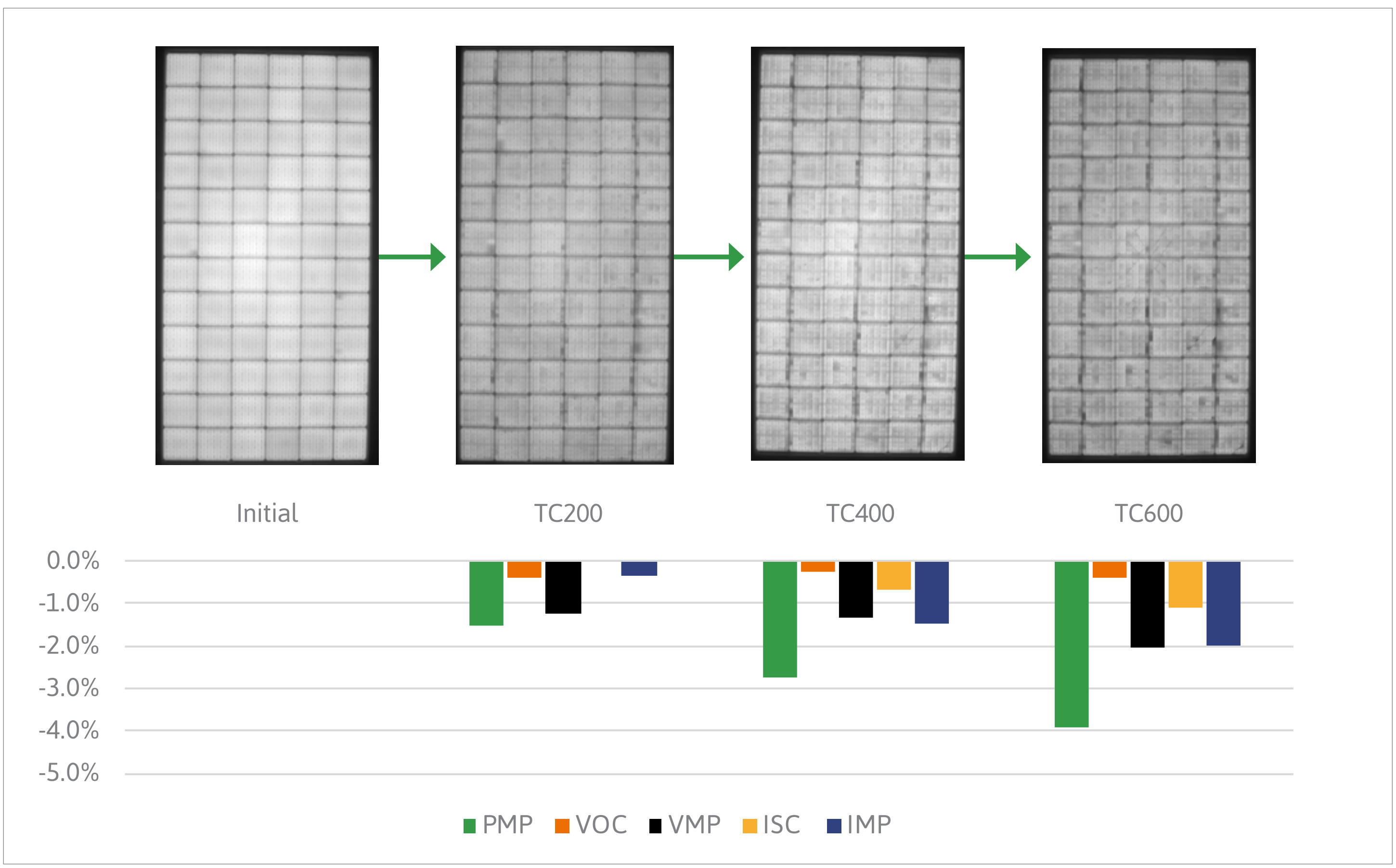
As ambient temperatures change, the components in fielded PV modules expand and contract depending on the level of heat or cold. The components have different thermal expansion coefficients, so they can expand and contract at different rates in the same environmental conditions. This results in a thermomechanical effect called interfacial stress that stresses the bonds between each layer of the PV module. An example of such stress is solder bond fatigue, which increases series resistance, thus increasing the voltage drop in the module as current passes through a higher resistance internal circuit and diminishing performance when the sun is at its brightest.

Why the test matters

Over the expected 25+ year lifetime of a solar power plant, the material components of PV modules will expand and contract thousands of times, even in moderate climates. This effect occurs throughout the day with dynamic irradiance events and with module temperatures operating well above ambient. It can be extreme in deserts and other arid environments. The thermal cycling test sequence reveals whether the temperature cycling is likely to cause undue interfacial stress that damages the modules and decreases system performance.

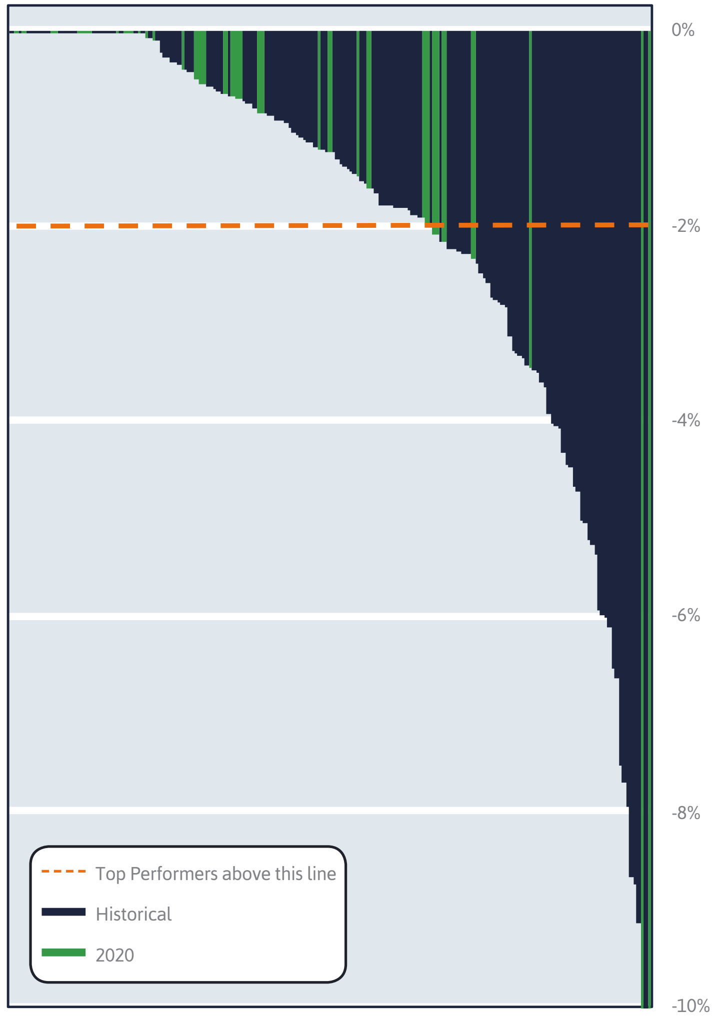
Thermal cycling procedure

For this test, modules are subjected to extreme temperature swings. They are put in an environmental chamber where the temperature is chilled to -40°C, dwelled, then heated to 85°C, and dwelled again. While the temperature is increased, the modules are also subjected to maximum power current. For the PVEL PQP the cycling is repeated 200 times over three periods to a total of 600 cycles, equating to about 84 days in the climate chamber. This procedure is much more rigorous than IEC 61215 testing, which requires only 200 cycles in total.



2020 TC TOP PERFORMERS	
Manufacturer	**Module Model**
Adani/Mundra	ASP-7-AAA / ASP-6-AAA
Astronergy	CHSM72P-HC-xxx / CHSM60P-HC-xxx; CHSM72M-HC-xxx / CHSM60M-HC-xxx; CHSM72M (DG)-B-xxx / CHSM60M (DG)-B-xxx
Canadian Solar	CS1H-MS
First Solar	FS-6xxxA
GCL	GCL-M3/72H / GCL-M3/60H; GCL-M6/72H / GCL-M6/60H; GCL-M3/72GDF; GCL-M6/72GDF; GCL-M3/72DH / GCL-M6/72DH
Hanwha Q CELLS	Q.PEAK DUO G5; Q.PEAK DUO L-G5.2; Q.PEAK DUO G6; Q.PEAK DUO G7
Heliene	72M-xxx / 60MBLK HOME PV
HT-SAAE	HT72-156M (V) / HT60-156M (V); HT72-156M (PDV)-BF / HT60-156M (PDV)-BF
Jinko	JKMxxxM-72HL-V / JKMxxxM-60HL-V
LONGi	LR4-72HPH-xxxM / LR4-60HPB-xxxM; LR6-72HPH-xxxM / LR6-60HPB-xxxM; LR6-72PH-xxxM / LR6-60PB-xxxM; LR4-72HIH-xxxM / LR4-60HIB-xxxM; LR4-72HIBD-xxxM / LR4-60HIBD-xxxM
Panasonic	VBHNxxxSA17
REC Group	RECxxxTP2M
Silfab	SLGxxxM / SLAxxxM
Sunergy California	CSUNxxx-72MH5 / CSUNxxx-60MH5
Suntech	STPxxxS-24/Vfh / STPxxxS-20/Wfh
Trina Solar	TSM-xxxPE14H / TSM-xxxPE05H
ZNShine	ZXP6-72-xxx/P / ZXP6-60-xxx/P

Power Degradation from TC Test Sequence for Each Module Model



Results in Context: Key Takeaways

A variety of module technologies exhibited strong TC results this year, including many full-cell and half-cut module types, as well as thin film, shingled cells, multi-bus bar and heterojunction modules. For further analysis of past TC performance, see page 33.

Median power degradation for all 2020 Scorecard eligible module types was 0.67%. However, some modules did not perform to this level, including the example shown here where poor cell metallization and imperfect soldering of the cell interconnection ribbons led to a 4% power degradation. Other TC failures include two module types that experienced diode failure leading to catastrophic power loss and one module type that suffered a wet leakage failure due to a breakdown in the module's electrical insulation. While TC performance has improved overall, PVEL observed major failures in some BOMs.

Bifacial considerations

Both glass-glass and glass-backsheet bifacial modules achieved Top Performer status. Thus far in PVEL's TC testing, the amounts of front-side and rear-side power degradation are aligned.

Damp Heat: Overview and Results

Background

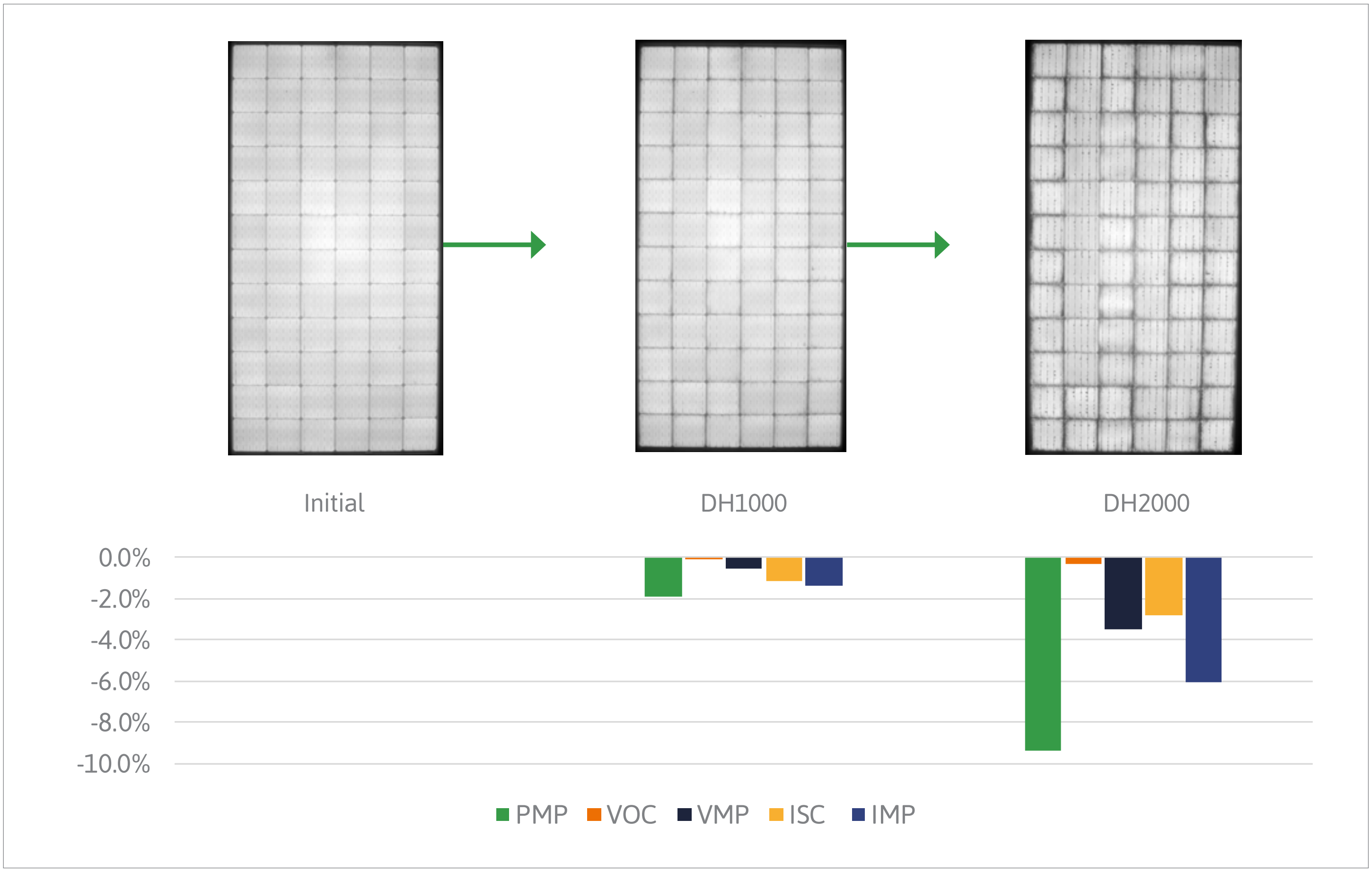
While high temperatures and humidity are common in many tropical and subtropical regions, PV modules in moderate climates also experience periods of high temperature and humidity. When these conditions occur, premature module failures and degradation may take place when inferior quality components or substandard lamination procedures are used. To assess module durability and reliability, the damp heat test replicates degradation and failure mechanisms that can occur in the field.

Why the test matters

Many different components are laminated together in PV modules. To meet performance expectations over the life of the PV asset, these layers must remain firmly adhered. If moisture and high temperature weaken the adhesives that bond these layers together, water, dirt, soil and other foreign materials can enter the module and degrade its internal components, thus reducing energy yield and impacting overall system performance. Delamination is also a safety issue because it may decrease the insulation resistance of a PV module, increasing the likelihood of an electrical shock.

Damp heat procedure

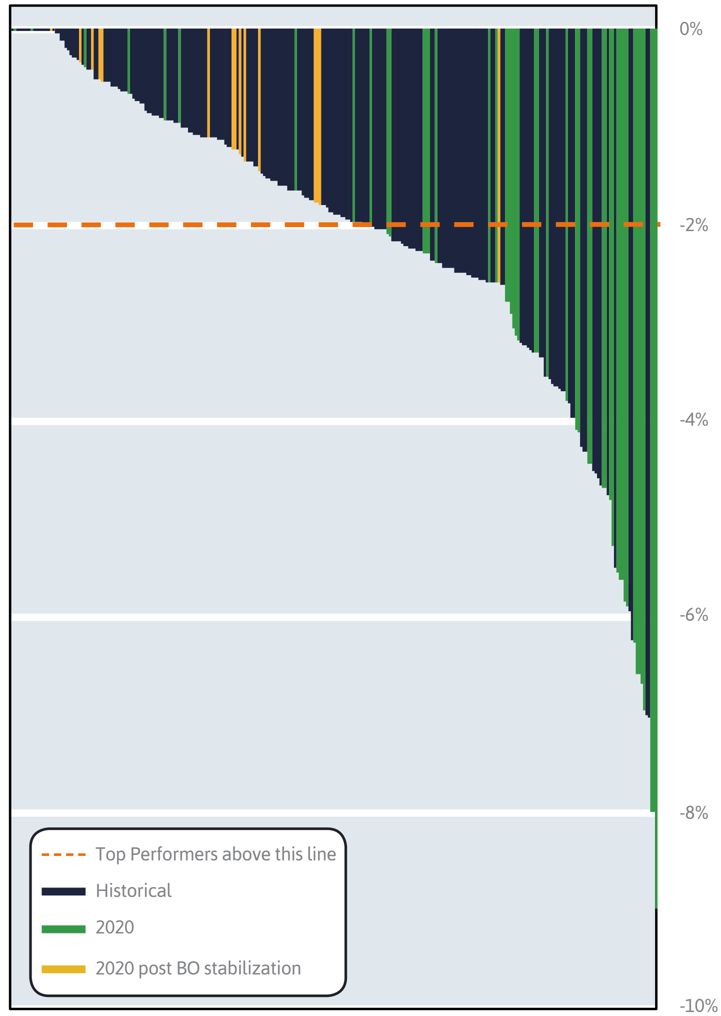
After being placed in an environmental chamber, modules are subjected to a constant temperature of 85°C and 85% relative humidity for two periods of 1000 hours (about 84 days in total), double the duration needed to meet IEC certification requirements. The combination of high heat and intense moisture stresses the layers of the PV module and provides insights into their likely behavior and performance in the field. However, the test's high temperature and no current environment can also lead to destabilization of the passivated boron-oxygen (BO) complexes within some PERC cells. To further explore this phenomenon, PVEL added to our latest PQP a post-DH2000 boron-oxygen stabilization process for all modules. This stabilization process was offered to previous PQP participants when modules exhibited the common signs of BO destabilization following DH.



2020 DH TOP PERFORMERS	
Manufacturer	**Module Model**
Astronergy	CHSM72P-HC-xxx / CHSM60P-HC-xxx; CHSM72M-HC-xxx / CHSM60M-HC-xxx; CHSM72M (DG)-B-xxx / CHSM60M (DG)-B-xxx
Canadian Solar	CS1H-MS*
First Solar	FS-6xxxA
GCL	GCL-M6/72H / GCL-M6/60H
Hanwha Q CELLS	Q.PLUS DUO L-G5.2*; Q.PEAK DUO G6*; Q.PEAK DUO G7*
Heliene	72M-xxx* / 60MBLK HOME PV*
HT-SAAE	HT72-156M (V)* / HT60-156M (V)*; HT72-156M (PDV)-BF* / HT60-156M (PDV)-BF*
Jinko	JKMxxxM-72HL-V* / JKMxxxM-60HL-V*
LONGi	LR6-60HPB-xxxM; LR6-72PH-xxxM
REC Group	RECxxxTP2M*
Silfab	SLGxxxM* / SLAxxxM*
Sunergy California	CSUNxxx-72MH5* / CSUNxxx-60MH5*
Vikram	Eldora VSP.72.AAA.05 / VSP.60.AAA.05; Somera VSM.72.AAA.05 / VSM.60.AAA.05

**Top performing result achieved following BO stabilization.*

Power Degradation from DH Test Sequence for Each Module Model



Results in Context: Key Takeaways

Damp heat is a critical test to identify underperforming modules susceptible to moisture ingress and corrosion. This can be seen in the example EL images, where the module performed well to the 1000-hour IEC 61215 duration. The performance difference after 2000 hours is stark: corrosion is seen along the bus bars and edges of the cells, and power degradation surpasses 9%.

The graph above shows power degradation results for both pre- and post- BO stabilization. In the most extreme example, PVEL measured 8.4% degradation in a post-DH2000 module that recovered to 1.3% degradation following BO stabilization. While some industry research has shown that BO destabilization is a test artifact that occurs during periods of high heat and no current (conditions which do not occur in the field[1]), more research is required to determine if destabilization will occur in the 25+ year lifetime of a module. It is worth noting this phenomenon only affects some PERC modules.

Bifacial considerations

It is well-documented that glass-glass modules have performed poorly in damp heat testing in the past. However, newer bifacial glass-glass and glass-backsheet combinations have shown similar performance in PVEL's PQP testing thus far. This is likely due to the move from EVA to POE in glass-glass modules.

[1] *F. Kersten et al., "Stability investigations of Cz-PERC modules during damp heat testing and transport: the impact of the boron-oxygen defect", AIP Conference Proceedings 2147, 090001 (2019); https://doi.org/10.1063/1.5123869*

Dynamic Mechanical Load Sequence: Overview and Results

Background

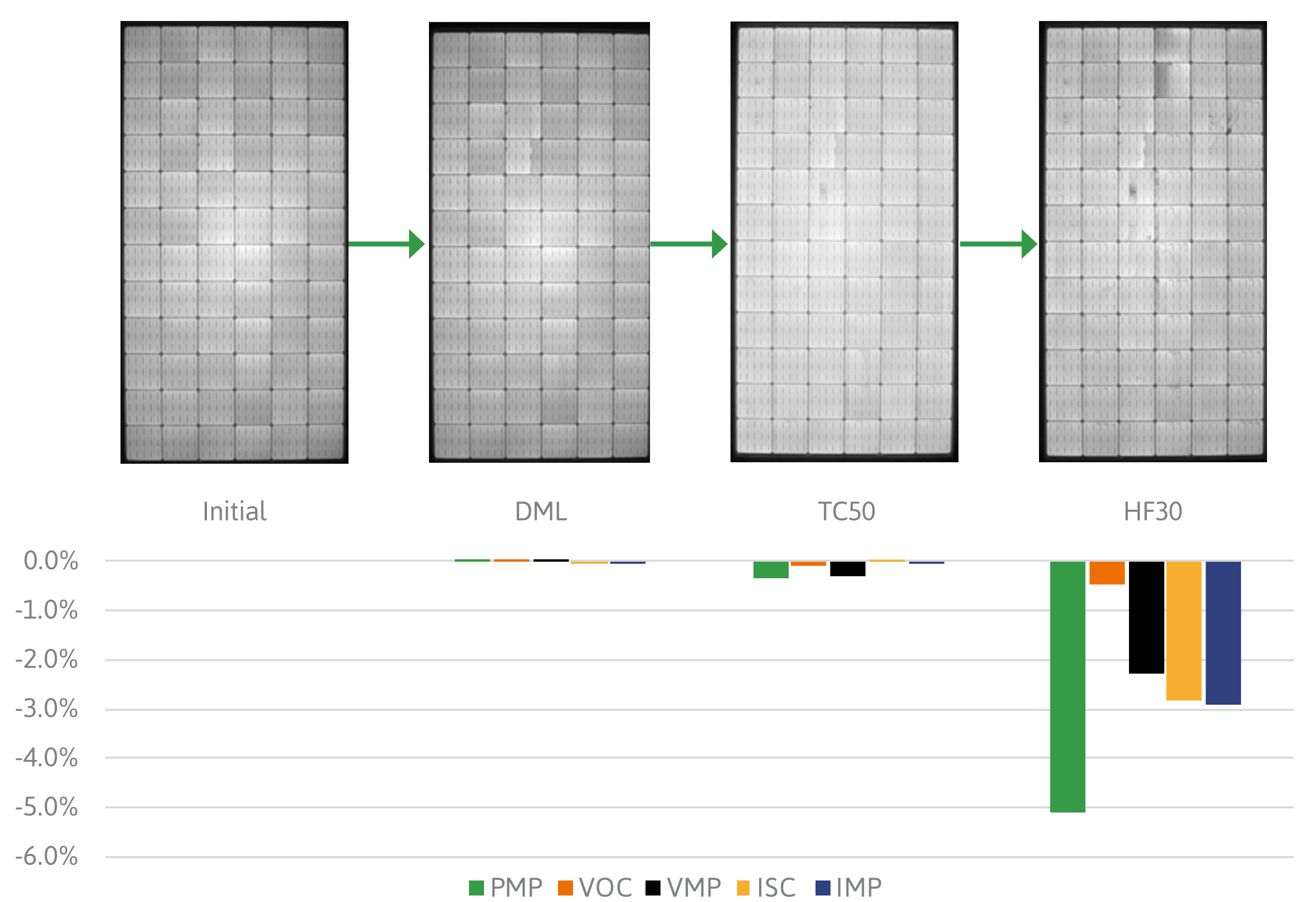
One of the most rigorous PQP test sequences, the dynamic mechanical load (DML) sequence, combines DML, thermal cycling and humidity freeze tests. When PV modules are subjected to mechanical loads like heavy snow or forces like high winds or hail, components become stressed and can break. When this happens, a range of performance degradation-inducing issues can result, such as moisture ingress, cell crack development and propagation, solder joint fatigue and cell corrosion. These issues often lead to reduced energy yield and even module and system field failures.

Why the test matters

Wind and snow subject modules to stress from dynamic loads, which are forces applied in different directions and speeds. Dynamic loading can also take place before the system is built. Improper packaging or handling can result in damage during the transportation, delivery and installation of modules. The DML test helps predict if PV modules can withstand these common loading conditions.

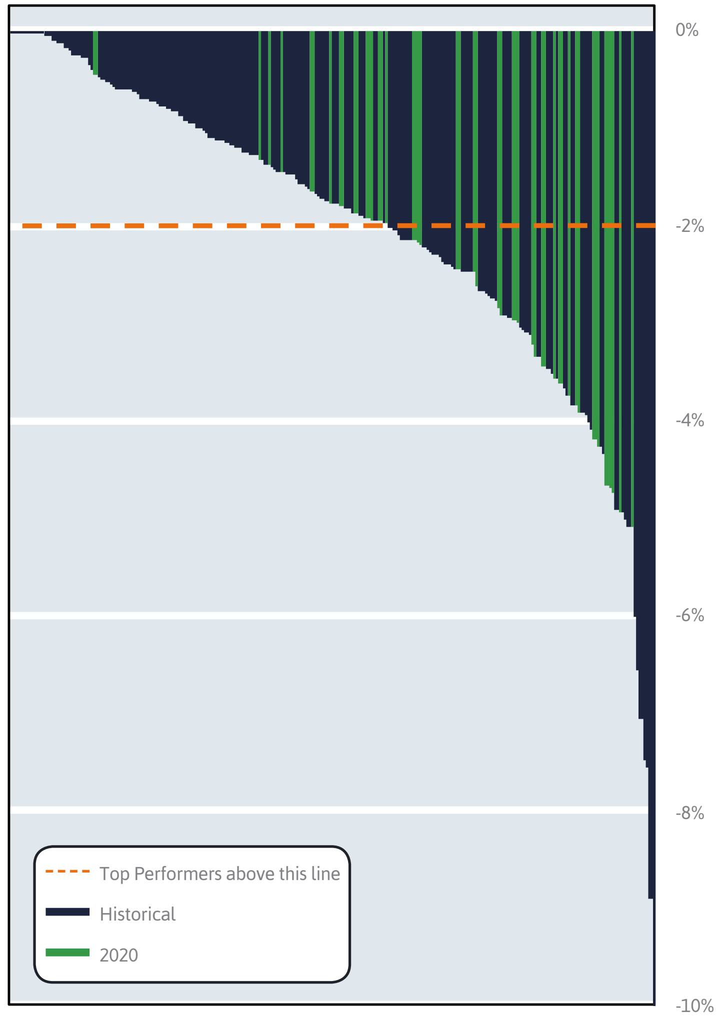
Dynamic mechanical load sequence procedure

First the module is installed according to the manufacturers' recommended mounting configuration. It is then subjected to 1000 cycles of alternating loading at 1000 Pa. Next, the module is placed in an environmental chamber and undergoes 50 thermal cycles (-40°C to 85°C) that can lead to cell crack propagation, followed by three sets of 10 humidity freeze cycles (85°C and 85% relative humidity for 20 hours followed by a rapid decrease to -40°C) to stimulate potential corrosion and further cell cracks. After each step in the sequence the module is characterized and visually inspected for any signs of component failure.



2020 DML TOP PERFORMERS	
Manufacturer	**Module Model**
Adani/Mundra	ASP-7-AAA / ASP-6-AAA
Astronergy	CHSM72P-HC-xxx / CHSM60P-HC-xxx; CHSM72M (DG)-B-xxx / CHSM60M (DG)-B-xxx
Canadian Solar	CS1H-MS
LONGi	LR6-72HPH-xxxM / LR6-60HPH-xxxM; LR4-60HPB-xxxM; LR6-60HPB-xxxM; LR6-72PH-xxxM
REC Group	RECxxxTP2M
Silfab	SLGxxxM / SLAxxxM
Vikram	Eldora VSP.72.AAA.05 / VSP.60.AAA.05
ZNShine	ZXP6-72-xxx/P / ZXP6-60-xxx/P

Power Degradation from DML Test Sequence for Each Module Model



Note: approximately 80% of the historical data includes only 10 humidity freeze cycles, which reflects past PQP test durations.

Results in Context: Key Takeaways

The DML sequence produced a wide range of degradation results, continuing last year's trend. A potential cause for these results is that BO destabilization may occur as a result of the damp heat conditions during humidity freeze testing. However, there are some module types that experienced BO destabilization following DH2000 but are DML Top Performers.

Another reason for the range of DML performance is susceptibility to power loss caused by cell cracking and rapid temperature changes. This can be seen in the provided example where the module suffered over 5% power loss after HF30 due to increased series resistance from metallization defects, cell cracks and loss of active area.

As seen in the updated PQP chart (see Pg. 14), the DML+TC50+HF30 test has been replaced by the new mechanical stress sequence ("MSS"). Early results indicate that the range of performance will continue with MSS testing. PVEL plans to release a separate publication featuring MSS results in the coming months.

Bifacial considerations

To date, glass-glass and glass-backsheet bifacial modules show similar performance results following the DML sequence, with fairly aligned front-side and rear-side degradation. Over 20 bifacial BOMs are queued for the new MSS test and PVEL is eager to share those results with the industry when available.

Potential-induced Degradation: Overview and Results

Background

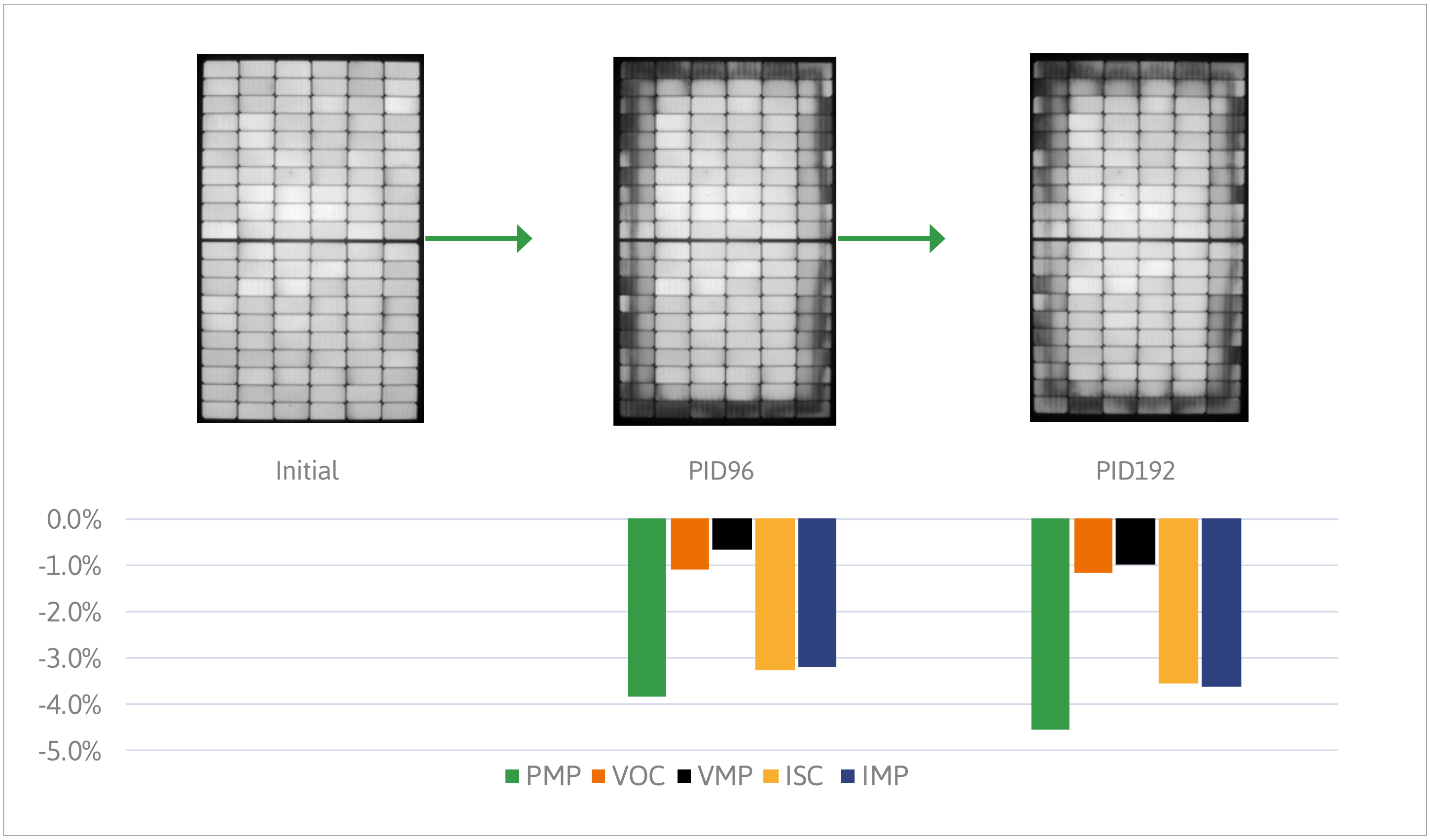
The phenomenon of potential-induced degradation (PID) has emerged over the past 10 years with the development of higher system voltages and ungrounded systems. PID can occur within weeks or even days of commissioning. It generally occurs when the internal PV electrical circuit is biased negatively in relation to ground. The voltage between the frame and the cells can cause sodium ions from the glass to drift toward the cell surface which typically has a silicon nitride (SiN) antireflective coating. If pinholes in this coating are large enough to allow sodium ions to enter the cell, then performance can be irreparably damaged. Additionally, this voltage can cause a buildup of static charge which can also reduce performance, although this effect is typically reversible.

Why the test matters

While not a concern for utility-scale sites employing central inverters equipped with negative system grounding, PID can significantly diminish module performance at sites with transformerless inverters, which are electrically ungrounded. While certain PID mechanisms are reversible in the early stages of degradation, some are irreversible and can lead to chronic underperformance. One solution to PID is through system design, including the use of specific grounding configurations or distributed electronics. PVEL recommends that developers and EPCs evaluate these alternative solutions if PID-resistant modules are not being procured for a project.

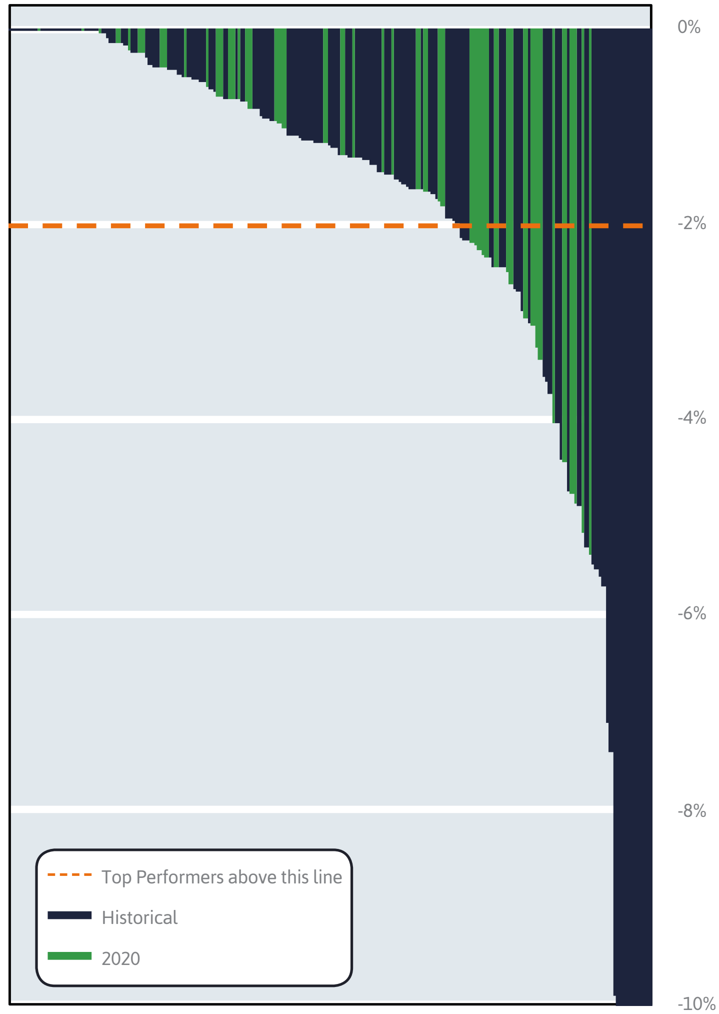
PID procedure

Once the module is placed in an environmental chamber, the voltage bias equal to the maximum system voltage (MSV) rating of the module (-1000V or -1500V) is applied with 85°C and 85% relative humidity for two cycles of 96 hours. These temperature, moisture, and voltage bias conditions help PVEL evaluate possible degradation and failure mechanisms related to increased leakage currents.



2020 PID TOP PERFORMERS	
Manufacturer	**Module Model**
Adani/Mundra	ASP-7-AAA / ASP-6-AAA
Astronergy	CHSM72P-HC-xxx / CHSM60P-HC-xxx; CHSM72M-HC-xxx / CHSM60M-HC-xxx; CHSM72M (DG)-B-xxx / CHSM60M (DG)-B-xxx
Boviet	BVM6612M-xxx-H / BVM6610M-xxx-H
Canadian Solar	CS1H-MS
First Solar	FS-6xxxA
GCL	GCL-M6/72H / GCL-M6/60H
Hanwha Q CELLS	Q.PLUS DUO L-G5.2; Q.PEAK DUO G6; Q.PEAK DUO G7
HT-SAAE	HT72-156M (V) / HT60-156M (V)
JA Solar	JAM72S09-xxx/PR / JAM60S09-xxx/PR
Jinko	JKMxxxM-72HL-V / JKMxxxM-60HL-V; JKMxxxM-72H-TV / JKMxxxM-72HL-TV
LONGi	LR6-72PH-xxxM; LR4-72HIBD-xxxM / LR4-60HIBD-xxxM
Panasonic	VBHNxxxSA17
REC Group	RECxxxTP2M
Seraphim	SRP-xxx-6MA-HV / SRP-xxx-6MB-HV
Silfab	SIL-xxxBL; SLGxxxM / SLAxxxM
SunPower	SPR-Axxx-G-AC
Suntech	STPxxxS-24/Vfh / STPxxxS-20/Wfh
Trina Solar	TSM-xxxPE14H / TSM-xxxPE05H; TSM-xxxPE14A / TSM-xxxPE05A; TSM-xxxDE14A(II) / TSM-xxxDE05A(II)
Vikram	Somera VSM.72.AAA.05 / VSM.60.AAA.05
ZNShine	ZXP6-72-xxx/P / ZXP6-60-xxx/P

Power Degradation from PID Test Sequence for Each Module Model



Results in Context: Key Takeaways

There are many Top Performers listed here for their excellent PID results, yet susceptibility to this degradation mode remains a concern. PVEL's median PID degradation result was higher for testing conducted for the 2020 Scorecard than at any time in PVEL's history. When PVEL's testing uncovered PID issues the module manufacturers typically responded with surprise, having thought their modules to be PID-resistant.

Clearly more work needs to be done to ensure all modules are PID-resistant, and the PQP remains a key tool to uncover defects such as PID that can lead to significant financial losses in the field.

Bifacial considerations

PID testing of bifacial modules produced a wide range of front-side degradation and an even wider range of rear-side degradation, with a rear-side power loss of over 30% in one case. It is possible that some rear side degradation is due to a reversible polarization effect that can occur in bifacial modules during PID testing, but not all p-type bifacial modules are susceptible to this phenomenon.

PAN Performance: Overview and Results

Background

PVsyst is the industry's standard modeling software used to predict the performance of PV sites. A PAN file is used by PVsyst to model the irradiance- and temperature-dependent behavior of a PV module. PVsyst default PAN files are typically created from the specifications listed on a module's datasheet, which may not define all module performance parameters sufficiently. While the resulting PAN file is functional, it usually does not model the behavior of a PV module accurately for the entire range of potential irradiance and temperature conditions.

Why the test matters

Energy yield predictions factor heavily in procurement decisions, cost of capital calculations and risk assessments. A custom PAN file provided by PVEL that is based on laboratory-measured irradiance- and temperature-dependent behavior of the PV module will result in more accurate energy models. To better illustrate performance from optimized PAN files, each PAN report includes two site simulation results: a 1 MW site in a temperate climate at a 0° tilt (in Boston, USA), and a 1 MW site in a desert climate at 20° tilt (in Las Vegas, USA).

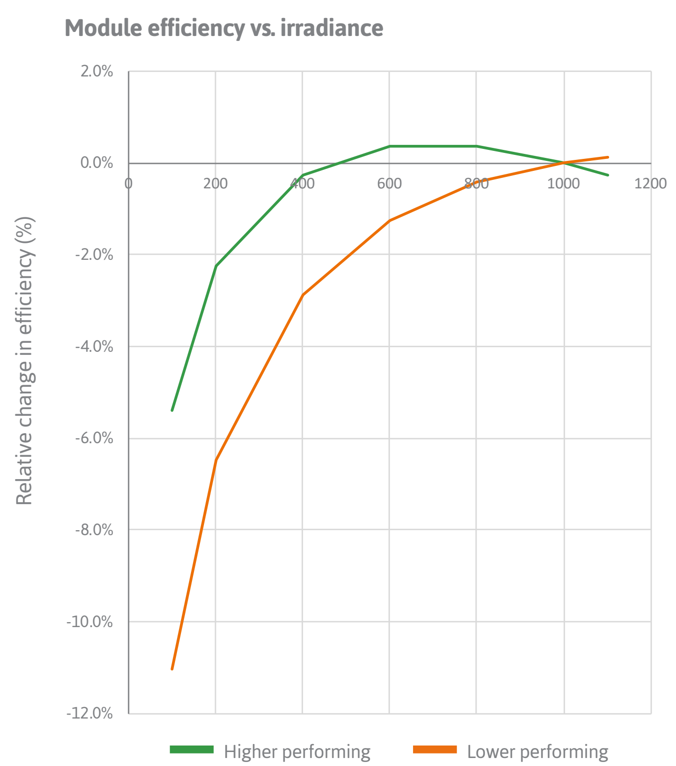
PAN test procedure

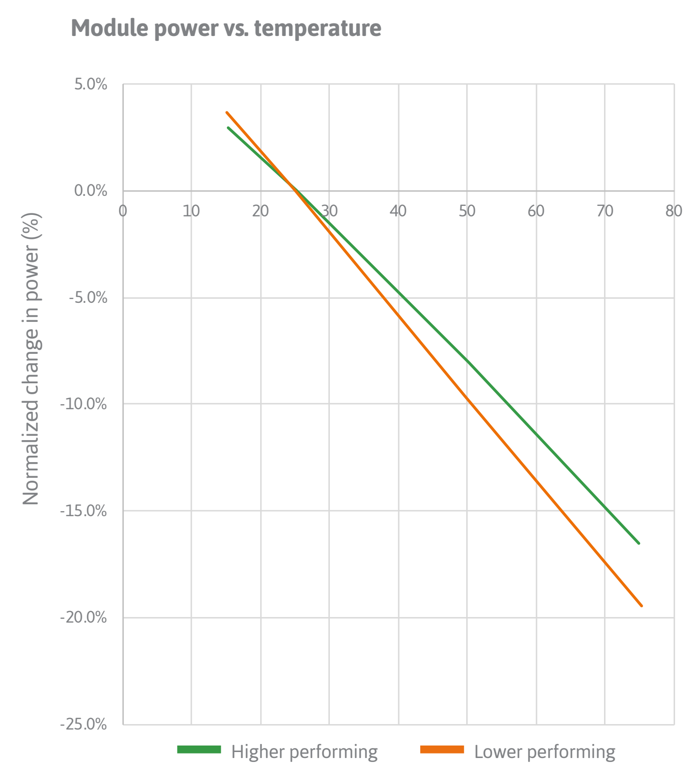
Three identical PV modules are tested across a matrix of operating conditions per IEC 61853-1, ranging in irradiance from 100 W/m² to 1100 W/m² and ranging in temperature from 15°C to 75°C. A custom PAN file is then created with PVsyst's model parameters optimized for close agreement between PVsyst's modeled results and PVEL's measurements across all conditions.

PAN performance differences

The graph on the left shows relative change in module efficiency versus irradiance. The lower performing module shows greater efficiency losses at lower irradiance. Although this difference affects performance at low insolation locations, such as the simulated Boston site, it is also impactful for high insolation locations due to the low irradiance experienced at different times of the day and year.

The graph on the right shows relative change in module efficiency versus temperature. Here, the lower performing module exhibits greater efficiency losses at high temperatures. This difference would be most significant in high temperature environments.





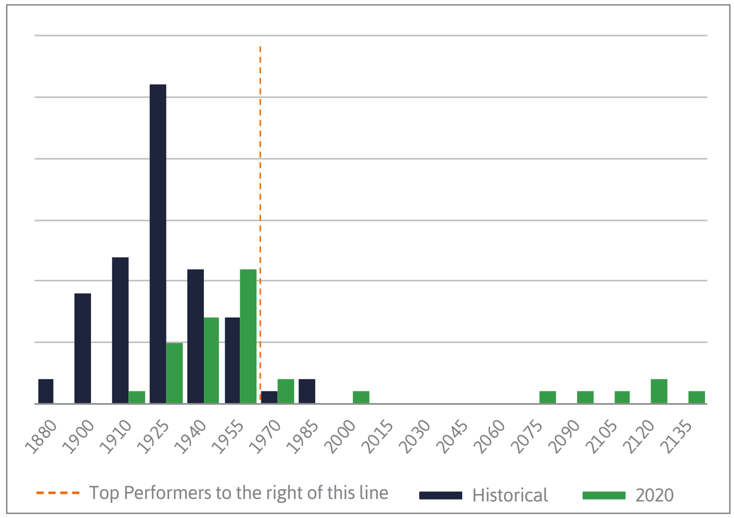
All modules shown here are p-type monofacial crystalline from the 2020 Scorecard dataset.

2020 PAN TOP PERFORMERS	
Manufacturer	**Module Model**
Astronergy	CHSM72M (DG)-B-xxx; CHSM60M (DG)-B-xxx
GCL	GCL-M3/72GDF; GCL-M6/72GDF
HT-SAAE	HT72-156M (PDV)-BF
JA Solar	JAM72S09-xxx/PR
Jinko	JKMxxxM-72H-TV / JKMxxxM-72HL-TV
Panasonic	VBHNxxxSA17
Trina Solar	TSM-xxxDE14A(II)

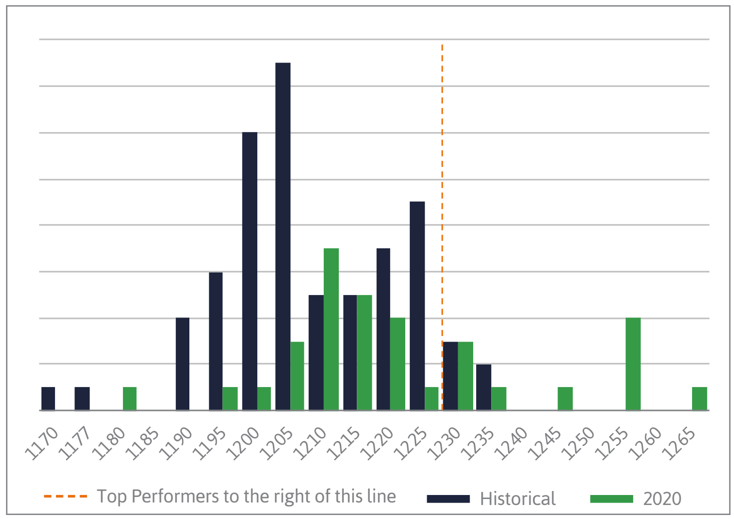
Top Performer Criteria

The Top Performers listed are module types whose PVsyst simulations for the Las Vegas or Boston site resulted in a kWh/kWp energy yield within the top quartile of all eligible results. The data presented here is only from PVEL's PAN testing as part of a PQP where the samples are factory witnessed.

kWh/kWp for 1 MW project in Las Vegas, USA



kWh/kWp for 1 MW project in Boston, USA



Results in Context: Key Takeaways

The presented historical data provides context for the performance improvements seen in the 2020 Scorecard PAN dataset. Module energy yield is clearly increasing with improved module designs. Of PVEL's historical data from all PQPs since 2016, only 4% of modules tested would receive a 2020 Scorecard Top Performer designation.

Bifacial modules are strongly represented in the Top Performers in this category. There is also a heterojunction module, which offers inherent high temperature performance gains. Two full-cell monofacial p-type PERC modules are also represented. A full-cell module's low light performance will be higher at the same nameplate rating than that of an identical half-cut module, which can result in higher annual energy yield. In one case, a full-cell BOM had a modeled energy generation for the Boston site that was 1.5% higher than an identical half-cut BOM. However, half-cut modules offer the benefit of higher power classes for the same cell efficiency. Module performance involves more than the datasheet values alone; PVEL's custom PAN files allow project stakeholders to model energy yield performance and determine which module choice is best for their site.

Bifacial considerations

The results show that bifacial modules represent a step-function performance improvement as two thirds of the Top Performers are bifacial modules. With no inverter clipping, the median energy yield of all the Las Vegas sites with bifacial modules was 7.7% higher than that of monofacial sites. At the horizontal tilt site in Boston the median bifacial energy yield was 3.3% higher than the monofacial median.

Historical Scorecard

The Historical Scorecard below shows the 2020 Top Performers and their history of top performance in past Scorecards. Manufacturers are listed by the number of years they have been designated a Top Performer, in alphabetical order.

A select group of manufacturers have earned Top Performer designations in PVEL's PV Module Reliability Scorecard multiple times through the years. PVEL commends these manufacturers for their commitment to product quality and reliability.

2020 TOP PERFORMER
PVEL | DNV·GL
PV MODULE RELIABILITY SCORECARD

	2020	2019	2018	2017	2016	2014
Jinko	●	●	●	●	●	●
Trina Solar	●	●	●	●	●	●
Hanwha Q CELLS	●	●	●	●	●	
JA Solar	●	●	●		●	●
REC Group	●	●	●	●	●	
GCL	●	●	●	●		
LONGi	●	●	●	●		
Suntech	●	●	●			●
Adani/Mundra	●	●	●			
Astronergy	●		●	●		●
Seraphim	●	●		●		
Silfab	●	●		●		
SunPower	●		●	●		
Vikram	●	●		●		
ZNShine	●	●			●	
Boviet	●	●				
First Solar	●		●			
HT-SAAE	●		●			
Panasonic	●		●			
Canadian Solar	●					
Heliene	●					
Sunergy California	●					

The Impact of Factory Location

Evidence of the impact of factory location on product quality was recently observed by PVEL when two very similar BOMs were produced at different locations. One was produced at a manufacturer's own factory and the other was produced at their contract manufacturer's factory. The DH2000 power degradation from the manufacturer's own factory was 1.0%. The same test performed on the modules produced at their contract manufacturer's factory yielded results of 3.9% degradation.

Two factories produced near-identical BOMs. One BOM was a Top Performer while the other degraded nearly 2x the Top Performer threshold.

Top Performer Factory Locations	
Adani (Mundra Solar PV Ltd.)	Gujarat, India
Astronergy (Chint Solar [Zhejiang]) Co., Ltd.	Haining, China; Yixing, China
Boviet Solar Technology Co., Ltd.	Song Khe-Noi Hoang Industrial Zone, Vietnam
Canadian Solar Inc.	Sriracha, Thailand
First Solar Inc.	Perrysburg, U.S.A.
GCL System Integration Technology Co., Ltd.	Van Trung Industrial Park, Vietnam
Hanwha Q CELLS Co., Ltd.	Jincheon-gun, South Korea; Cyberjaya, Malaysia; Dalton, U.S.A.
Heliene Inc.	Mountain Iron, U.S.A.
JA Solar Technology Co.	Hefei, China; Fengxian, China
Jinko Solar Co., Ltd.	Shangrao, China; Van Trung Industrial Park, Vietnam
LONGi Solar Technology Co., Ltd.	Kuching, Malaysia; Taizhou, China
Panasonic Corporation	Buffalo, U.S.A.
REC Group	Tuas, Singapore
Seraphim Solar System Co., Ltd.	Changzhou, China
Silfab Solar Inc.	Mississauga, Canada; Bellingham, U.S.A.
Shanghai Aerospace Automobile Electromechanical Co. ("HT-SAAE")	Istanbul, Turkey
Sunergy California, LLC	Dinh Tram Industrial Zone, Vietnam
SunPower Corporation	Ensenada, Mexico
Trina Solar Co., Ltd.	Changzhou, China; Van Trung Industrial Park, Vietnam; Sriracha, Thailand
Vikram Solar Ltd.	Kolkata, India
Wuxi Suntech Power Co., Ltd.	Wuxi, China
ZNShine PV-Tech Co., Ltd.	Changzhou, China

Industry perspective

"After more than 300 audits on over 95 GW of manufacturing capacity, we frequently see inconsistent product quality coming from different factories under one manufacturer. Even among tier one suppliers, factories and individual workshops within a factory may differ in production quality."

IAN GREGORY
Managing Director
PI Berlin North America

Case Studies

PQP Failures

20% of BOMs eligible for inclusion in this year's Scorecard had at least one failure. Without BO stabilization after damp heat testing, the 2020 failure rate is consistent with the overall failure rate observed in 2019.

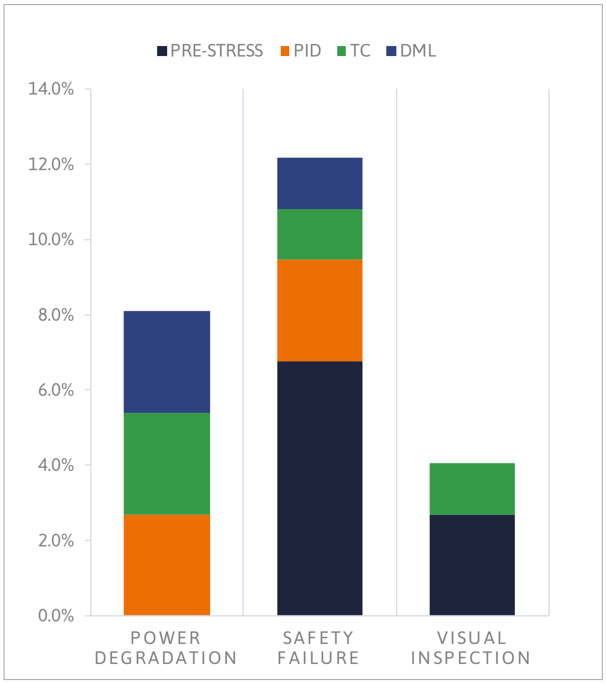
What is a failure?

There are three types of failures in the PQP:

1. **Safety**
   Safe operation is determined via wet leakage testing using the IEC 61215 standard, which evaluates the electrical insulation of the PV module under wet operating conditions (i.e. rain, fog, dew, humidity, snow melt). **Failure means that module operation may be hazardous in the field.**
2. **Visual inspection**
   Modules are examined for delamination, corrosion, broken or cracked surfaces and other changes to the module using the IEC 61215 criteria. **Failure indicates that major manufacturing defects are present, leading to premature failure in the field.**
3. **Power degradation**
   Although the PQP does not assign specific pass/fail thresholds for degradation, module manufacturers are able to remove their products from testing if rates fall below expectations. In these cases, manufacturers usually change their BOM or production process, then submit new samples for retesting. PVEL notes all retests in PQP reports for full transparency with downstream buyers. **Failure means the modules may underperform in the field and ultimately result in financial losses for the asset owner.**

20% of BOMs had at least one failure

The chart below describes failures per test per BOM that occurred in PQP testing for the 2020 Scorecard. Pre-stress failures are those that were detected upon initial inspection prior to testing.



PQP Failures Continued

Junction box defects in the field

The image above shows a PV module at the project site with a junction box that melted due to electrical arcing.

A 50 MW PV plant in Africa built in 2013 began to exhibit serious failures from poor soldering and failed diodes after just five years of operation.

Over 3,000 modules were affected by poor soldering in the junction box, which led to catastrophic junction box failures due to electrical arcing.

In one case, the molten plastic from the melted junction box started a brush fire in the dried grasses below the modules.

The asset owner's warranty claim is being resolved at the manufacturer's discretion, so field repairs of the affected modules have been prioritized over full replacement.

As the volume of module failures grows over time, the site owner is increasingly concerned with the plant's long-term viability and profitability.

Junction box defects in the lab

PVEL observed an increase in junction box related failures in PQP testing for the 2020 Scorecard as compared to the 2019 and 2018 Scorecards. These include bypass diode failures following thermal cycling, and wet leakage failures originating at the junction box before testing, and after thermal cycling, PID and the DML sequence.

Short-circuited bypass diodes are categorized as power degradation failures because they cause power drops of at least 33%. However, diode failures are also a safety concern: an open-circuited bypass diode cannot prevent hot spots when the module is partially shaded.

In extreme cases, hot spots can crack the module glass and/or burn through the backsheet. Improper component selection or poor electrostatic discharge controls on the junction box or module production line can cause failed diodes in the field.

Many of the recorded wet leakage failures were traced to poor sealing around the junction box via the junction box lid, adhesive or pottant. Correct placement of the lid and application of sealants are critical manufacturing processes, but they can be overlooked in the pursuit of production targets.

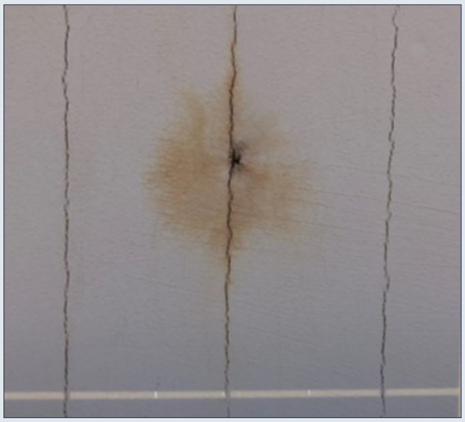
The junction box above became unsealed after damp heat testing.

One in five manufacturers tested for the 2020 Scorecard period experienced at least one junction box failure.

Backsheet Durability Sequence

Backsheet failures have serious safety and performance consequences that can ultimately result in financial losses for asset owners and investors. While specific degradation modes depend on environmental conditions and backsheet materials, failure often begins with yellowing and/or chalking (powder accumulation on the backsheet) and can progress to cracking.

Field failure: a seven-year-old project



The pictures above are from a 17 MW project in the Southwest U.S. One hundred percent of the backsheets in this project are cracked. The severe scorching in the backsheet above was caused by electrical arcing at the backsheet cracks that intercept the frame. The thermal event shattered the front-side glass.

Backsheet failures

When moisture enters PV modules via backsheet cracks, it can result in:

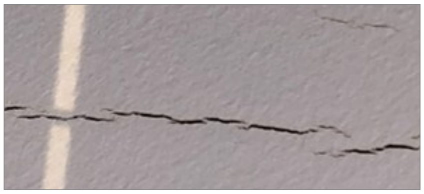
- **Ground faults**: Water creates a path to ground, and these high leakage currents can cause inverters to shut down. Inverters may also experience delayed startup in sites with morning dew.
- **Delamination**: As moisture accumulates in a PV module, the layers of the module can separate and the electrical components can corrode.
- **Safety concerns**: When moisture enters delaminated, degraded PV modules, thermal events such as arc faults are more likely to occur.

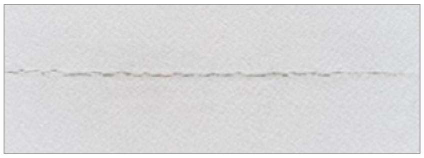
Replicating field failures in the lab

In just six months, PVEL's backsheet durability sequence replicates backsheet degradation modes that begin occurring after five to seven years in the field. The goal of the test is to recreate failure modes observed in the field inside of a controlled laboratory environment using the following parameters:

- The test is conducted on full PV modules with witnessed* BOMs – not on backsheet coupons – to capture mechanical stresses.
- The test includes rear-side UV and other stresses to mimic field conditions.

Lab test results (see images on right) show a range of issues affecting backsheet durability and reliability. A clear conclusion is that backsheet material selection can impact the performance of a PV module, and that there is a broad range of backsheet quality in the modules available on the market today.





The images above show backsheet failure in the field (top) and the lab (bottom).

To prevent backsheet failures in the field, always specify BOMs with PVEL-tested, high-performing backsheets in PV module supply agreements.

* *Learn about PVEL's factory witness requirements on page 13.*

Light and Elevated Temperature Induced Degradation

With reported degradation rates as high as 10% in the field, light and elevated temperature-induced degradation (LeTID) has become an industry-wide concern for PERC/PERT modules. PVEL has added an LeTID sensitivity test to our PQP to help buyers mitigate ensuing risk.

LeTID in the field

A forthcoming NREL paper[1] details a 12 MW utility scale solar site in the Mid-Atlantic U.S. with LeTID. The site consists of six 2 MW arrays, five of which degraded quickly. **Based on the corrected in-field IV curves, module power degradation reached up to 7.5% of nameplate, with an average power degradation of 5% in less than three years.**

The unaffected array showed an average power degradation of 0%. In-lab flash testing and analysis of year-on-year degradation rates also show higher degradation in the five affected arrays.

All modules were provided by the same manufacturer and have the same model number. They were visually indistinguishable. Destructive analysis by NREL revealed that at least two different cell types were used, suggesting that one cell type was more susceptible to LeTID.

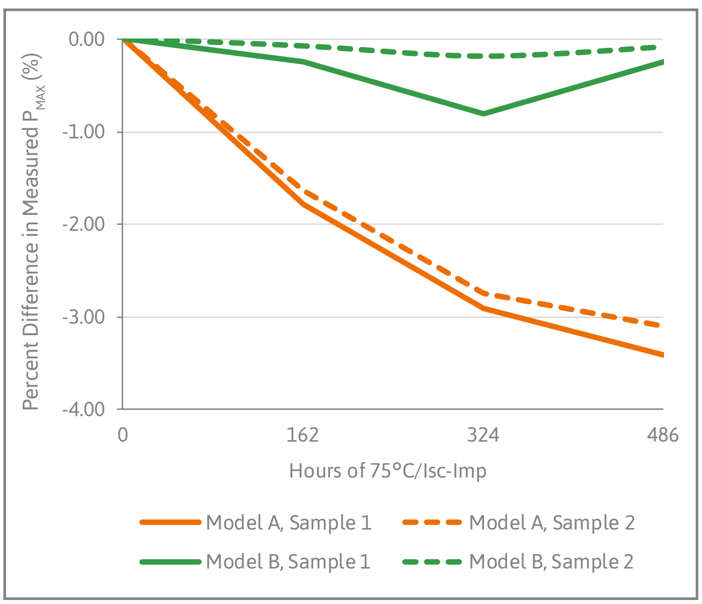
Industry research

"This underscores the importance of a robust quality program on the part of manufacturers and the importance of re-qualification of modules when changes are made to the cells, materials, or manufacturing processes associated with a module model."[1]

[1]Michael G. Deceglie, Timothy J Silverman, Steve W. Johnston, James A. Rand, Mason J. Reed, Robert Flottemesch, and Ingrid L. Repins, "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System", IEEE Journal of Photovoltaics, 2020, DOI: 10.1109/JPHOTOV.2020.2989168

LeTID in the lab

PVEL's LeTID sensitivity test follows the same sequence that was previously proposed for IEC 61215*. The test conditions are designed to slowly approach the maximum degradation point, so as not to trigger additional degradation mechanisms. At the time of publication, PVEL had tested over 50 modules for LeTID susceptibility through a combination of PQP and project-level batch testing projects (see Pg. 36), and more than 25 additional BOMs are queued for testing.



Results to date

The majority of results thus far show that manufacturers have implemented strong LeTID controls in cell production lines, with a median degradation of 0.96% and a mean of 1.17% after 486 hours of testing.

Yet there are cases of different degradation rates in multiple module types from the same manufacturer as shown in the example on the left. This manufacturer markets themselves as having "LeTID-free" PERC modules, which is clearly the case for Model B. However, that is not the case with the 3% degradation measured for Model A.

Given the rapid increase in the module types available on the market, it is crucial that buyers require PQP testing to ensure they receive truly "LeTID-free" BOMs.

**Note: LeTID testing was ultimately not included in the current update of the IEC 61215 standard.*

IE Perspective: Key Findings from DNV GL

DNV GL and PVEL collaborate to support downstream project developers and asset owners. In the following two pages, DNV GL explains how PVEL's independent data informs their assessments of PV module technology and project lifetimes.

Analysis of PVEL PQP test results

Result trends

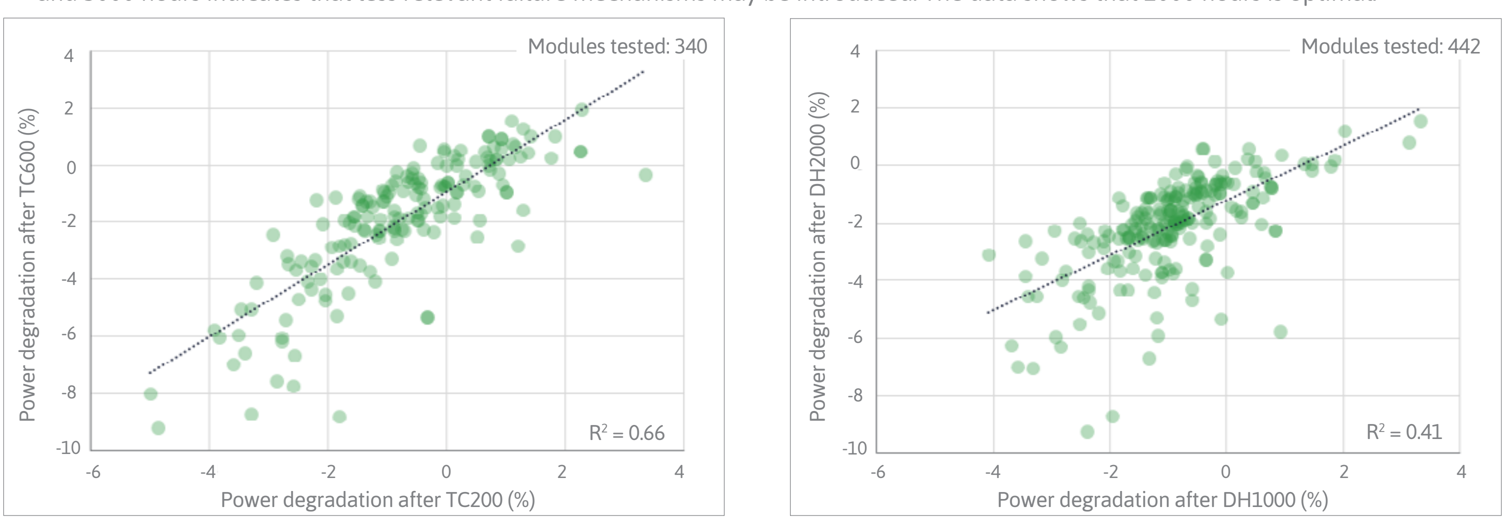
DNV GL analyzed PVEL PQP test results from 2014 to present. While the PQP has evolved over time, TC600 and DH2000 have remained common tests with statistically significant trends. TC600 results improved from 2014 to 2017 followed by a plateau with little degradation (see figure below left). This improvement may be explained by the transition to monocrystalline cells, more busbars, and thicker encapsulants. However, damp heat results indicate a deteriorating trend since 2015 (see figure below right). This may be due to the adoption of PERC cells which may require the additional boron-oxygen LID stabilization step following DH2000. Alternatively, it may reflect utilization of non-fluoropolymer backsheets or thinner screen-printed fingers, which may be more sensitive to corrosion via moisture ingress.

Results of the thermal cycle and damp heat tests since 2014

Appropriate test durations

Ideal test durations are often debated. The tests are meant to simulate stresses and degradation mechanisms that occur in the field. If the test duration is too short, degradation may not be detected. If the duration is too long, then new, non-representative failure mechanisms could be introduced.

For the thermal cycling test, the correlation between 200 cycles and 600 cycles indicates no new mechanisms are being introduced by the 600 cycle test, yet stopping at 200 cycles might be premature (see figure below left). Reviewing the historical 600 cycle and 800 cycle correlation indicates that TC600 is a sufficient test duration. The damp heat correlation between 1000 hours and 2000 hours suggests 1000 hours is not an adequate substitute for 2000 hours (see figure below right), while the historical correlation between 2000 and 3000 hours indicates that less relevant failure mechanisms may be introduced. The data shows that 2000 hours is optimal.



Scatterplots showing correlations between various stages of the TC and DH tests

Using PVEL's data in DNV GL's useful life assessments

There has been a significant push to extend the useful life of PV systems beyond the conventional 25 years. Extending the useful life to 30-40 years results in lower levelized cost of electricity (LCOE) by 16-20% and higher asset value. To achieve extended useful life, many system components require improvement and/or replacement over time.

DNV GL determines the module useful life by considering the failure rate of the module where failure is defined as a significant drop in module power in a short period of time, which may be caused by PID, corrosion, failed backsheets, etc.

Module classification

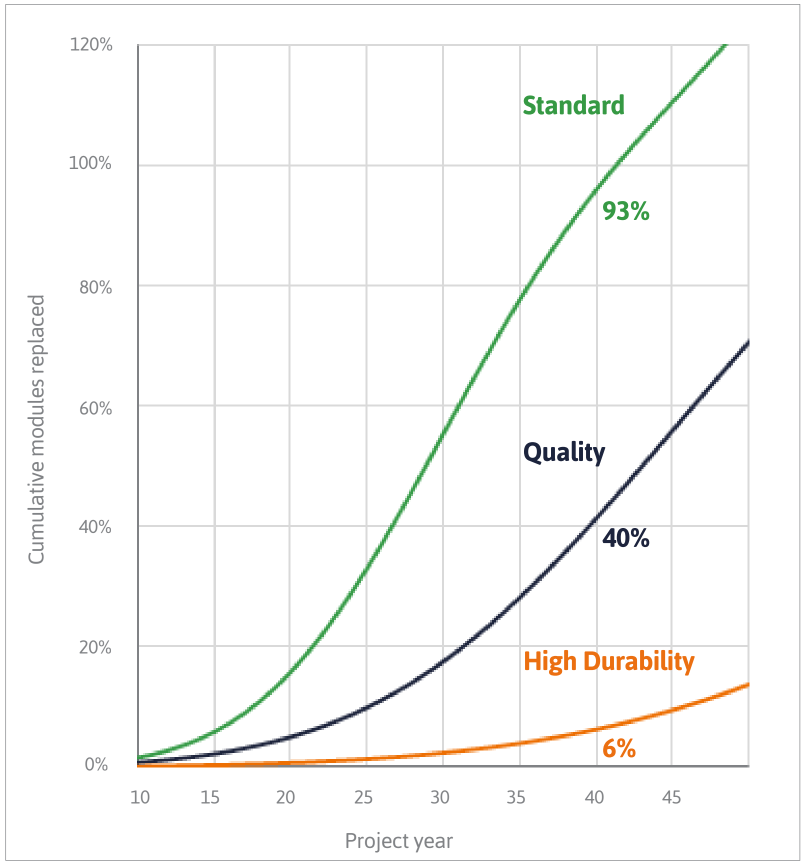
DNV GL has developed a three-tier module classification: Standard, Quality and High Durability, with associated failure rates and replacement schedules for each classification.

Module classifications primarily depend on results from a suite of accelerated stress tests such as PVEL's PQP. Additional considerations include factory audit reports, detailed BOM review and historical field data. A Quality or High Durability classification would necessitate low degradation following extended-duration testing.

With these classifications, downstream buyers and financiers can compare the economics of different module choices.

Targeting a system life of 40 years would entail almost all of the Standard modules to be replaced while only 40% and 6% of the Quality and High Durability modules would be replaced respectively (see figure on right).

Analysis by Henry Hieslmair, Ph.D.
Principal Engineer, Solar Technology
DNV GL



Cumulative modules replaced for the three module classifications: Standard, Quality and High Durability.

Industry perspective

"PVEL's carefully designed PQP tests provide the data the industry needs to extend the useful lifetime of PV systems and thereby reduce LCOE."

ANAT RAZON
Head of Section, Solar Due Diligence & Technology
DNV GL

Conclusion

Five Steps to Mitigate Revenue Risk

By following the five key steps outlined below, downstream solar energy companies can significantly reduce their exposure to technology risk while also maximizing long-term financial returns by building reliable, high-performing projects.

1. Conduct factory audits

A factory audit is an independent inspection of a manufacturer's production lines. Conducting third-party factory audits helps downstream buyers select producers that follow rigorous quality assurance and quality control processes.

2. Review PVEL PQP reports

PVEL's PQP reports provide empirical data for models that improve forecast accuracy and ultimately guide the selection of BOMs that meet unique project requirements. By requiring suppliers to participate in the PQP, buyers can ensure that data is available for benchmarking.

3. Specify PV module bills of materials

After selecting the PV modules, buyers should work with PVEL to specify approved BOM(s) and factory location(s) in their supply agreements. PVEL provides these complimentary BOM exhibits for contracts.

4. Confirm product quality during production

Once specific project production begins at the factory, buyers should conduct additional third-party oversight. Independent auditors will confirm that the specified BOM is used for the order and that appropriate quality control processes are followed.

To ensure that the PV modules produced will meet performance and reliability expectations, send a statistical sample of the modules to PVEL for batch testing, which will help validate performance and quickly identify serial defects. PVEL works with downstream customers to create a mitigation plan should modules fail to perform as expected.

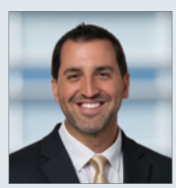
5. Verify performance after installation

PVEL conducts field EL and project acceptance capacity testing to ensure expected operation. This testing also detects cell cracks that may have occurred during transportation and installation. Field EL additionally provides baseline data for future insurance claims and can be used to diagnose system underperformance.

Industry perspective

"Arevon, North America's leading renewable energy company with over 3,500 MWdc of operating PV solar, is relying on data from PVEL's Product Qualification Program (PQP) and statistical batch testing to inform PV module procurement and technical due diligence for several GWs of projects in our pipeline.

From utility solar power plants to distributed generation, PVEL's program enables objective assessments of potential suppliers and new technologies that can be leveraged as a powerful tool to optimize project finance assumptions."



JARED PORPIGLIA
Director of Procurement
Arevon

Beyond large-scale procurement

Following every step of PVEL's recommended best practices is not always possible for all PV module buyers. PQP reports are available to all downstream companies that sign up to partner with PVEL, regardless of size. At minimum, PVEL recommends using PQP reports to provide valuable data for performance and reliability assessments.

Conclusion

Ten years ago, a utility scale project was a 1MW fixed tilt groundmount array built with standard-issue 3-busbar, 72-cell multicrystalline modules. Today's utility-scale power plants contain hundreds and even thousands of MWs. Buyers can choose product features as though they're ordering at a restaurant or coffee shop: "I'd like 166mm half-cut bifacial cells and transparent backsheets, please."

Today's technologies are advancing at a breathtaking pace, far faster than we have ever seen before. To keep up with global supply demand and falling PPA rates, manufacturers are under pressure to produce modules faster and cheaper. But not always better. In the rush to achieve economies of scale, basic quality controls can be overlooked.

The International Energy Agency predicts that in just four years, renewable energy will contribute to 30% of the world's total generating capacity. While this growth is impressive, it is not enough in the fight against climate change.

To improve on this prediction for the sake of our planet and future generations, we all need to work smarter, we need to work cheaper, we need to work faster. But we also need to work with quality at every stage of the solar deployment process: from materials and production to construction, operation and decommissioning.

The pursuit of quality defines our work at PVEL and we take it seriously. We work together with manufacturers to encourage the production of lasting products. We diligence project-level construction and deployments. We support tens of gigawatts of development and asset ownership worldwide. We are honored to partner with some of the brightest minds and most creative thinkers around the globe. We make data that matters.

Data for the future

"I am proud to see the impact that PERC cells introduced by my team at UNSW in the mid-1980s is having upon the industry and the wave of new module designs that PERC has stimulated.

This is placing even more emphasis on PVEL's work in developing confidence in module field performance, ensuring that we are building and installing PV modules that are truly built to last."

DR. MARTIN A. GREEN
Australian Centre for Advanced Photovoltaics
University of New South Wales

PVEL

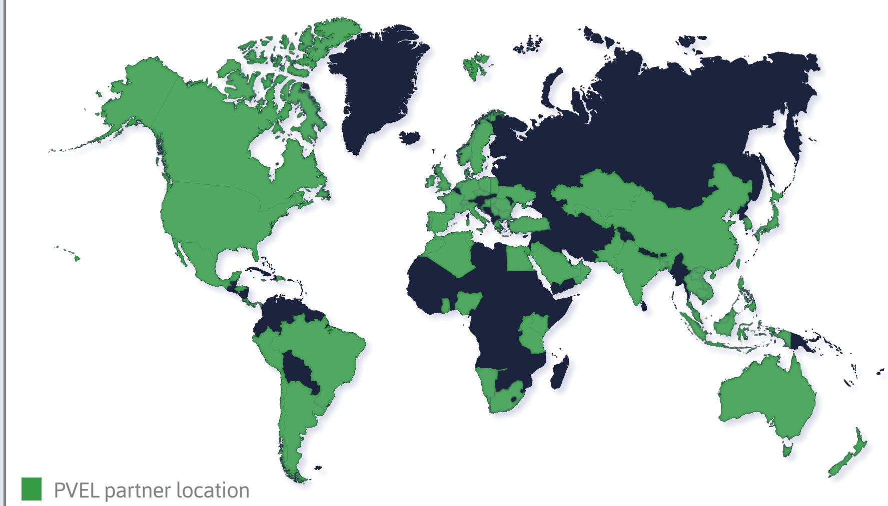
PV EVOLUTION LABS

Interested in becoming a PVEL Downstream Partner?

Join our global network for complimentary access to our PQP reports for PV modules, inverters and energy storage systems.

Learn more about our PQPs and sign up online at pvel.com/pqps

The PVEL Network



PVEL's downstream partners operate in solar markets around the world.