MAKE DATA MATTER.

FIFTH EDITION

2019 PV MODULE RELIABILITY SCORECARD

In partnership with

DNV·GL

PV EVOLUTION LABS

Authors

Tara Doyle
Chief Commercial Officer
tara.doyle@pvel.com

Ryan Desharnais
Chief Technology Officer
ryan.desharnais@pvel.com

Tristan Erion-Lorico
Head of PV Module Business
tristan.erion-lorico@pvel.com

Contributors

Kenneth Sauer, Senior PV Engineer
Adam Gushansky, Project Manager
Emily te Amo, Sales Operations Analyst
Tori Clifford, Head of Marketing

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 nearly 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 300+ 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.

Contents

PART 1: INTRODUCTION

PART 2: PV MODULE RELIABILITY

PART 3: TEST RESULTS

PART 4: CASE STUDIES

PART 5: CONCLUSION

PART 1

INTRODUCTION

FOREWORD: A NOTE FROM OUR CEO

Since PV Evolution Labs (PVEL) was established in 2010, the global solar market completely transformed. Our industry broke record after record: total installed photovoltaic (PV) capacity expanded tenfold to over 400 GW. The world's largest solar power plants now exceed 1 GW in size. According to DNV GL's Energy Transition Outlook, total solar capacity is expected to reach 1 TW by 2023.

The global financial industry's acceptance of solar power as a safe, secure investment helped drive the last decade of growth. As we transition to subsidy-free markets, institutional financing remains critical. For solar power to contribute substantially to the global energy mix, prices must continue spiraling downward and confidence in reliable PV technology must increase.

PVEL itself has undergone almost a decade of rapid growth within the industry – by operating as PV Evolution Labs for four years, being acquired by DNV GL in 2014, and recently in January of this year, re-launching as an independent company. We continue to work closely with DNV GL and remain dedicated to helping PV equipment buyers better understand product reliability and performance.

Comprehensive, independent testing of solar PV equipment that builds confidence in cost-effective, high-performing PV equipment is more important now than ever. From its inception, PVEL has helped developers and the broader PV equipment buying community secure financing through innovative technical due diligence and bankability testing. This industry has a lot of data that supports a range of contradictory claims about equipment or systems, but PVEL is focused on the data that matters. We provide independent, comprehensive, relevant and transparent data that helps manufacturers validate claims, developers optimize financing and lenders minimize risks.

The 5th Edition of PVEL's PV Module Reliability Scorecard illustrates that thorough vetting of PV equipment remains crucial. Seemingly minute changes in product materials or construction cause unexpected reliability issues. New cell technologies bring new forms of degradation. Technical advancements may reduce the cost of solar power, but widespread deployment requires bankability. Performance gains are only financeable when they are quantifiable.

The latest PV Module Reliability Scorecard sheds light on product performance and reliability to support strategic PV module procurement around the world. We are pleased to introduce this year's report with our Scorecard partner, DNV GL.

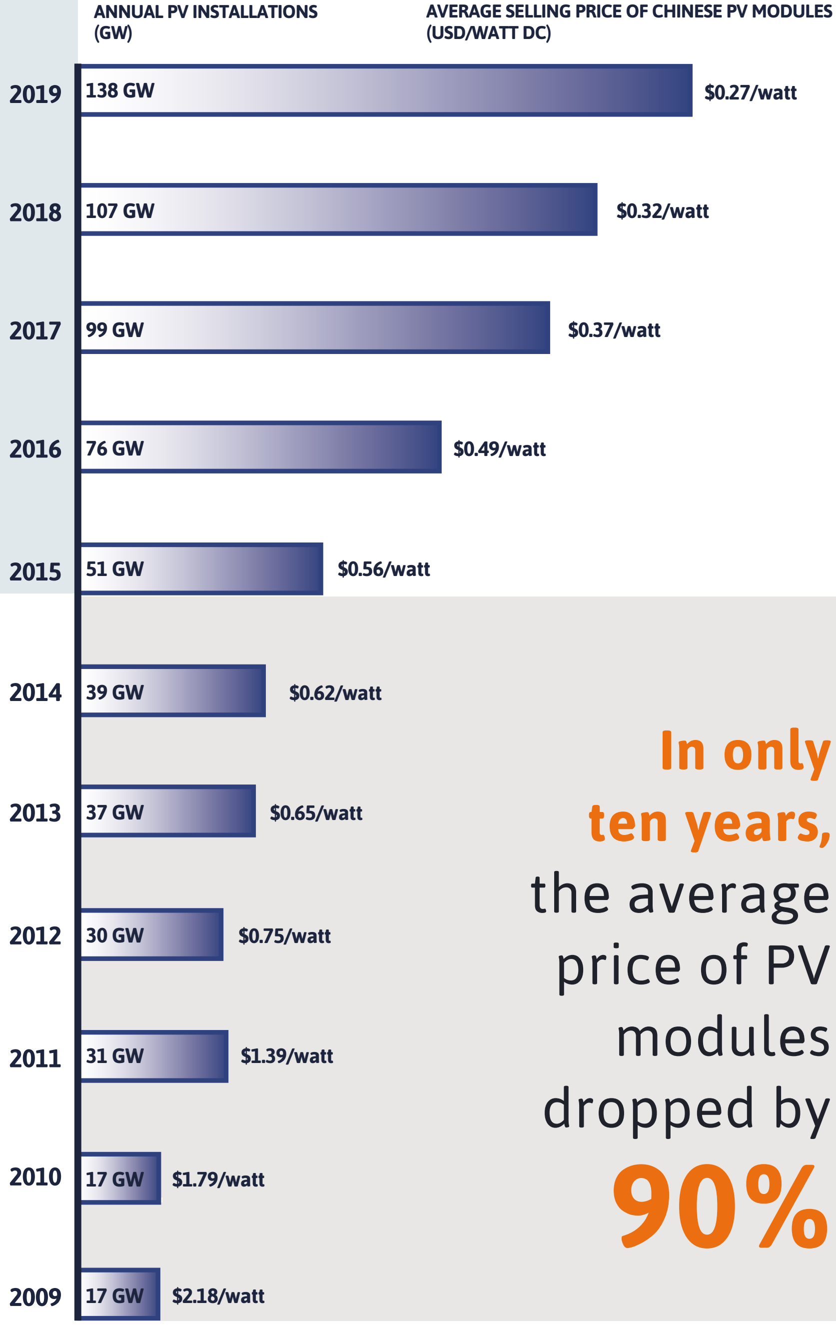
JENYA MEYDBRAY
CEO
PV Evolution Labs (PVEL)

“DNV GL is pleased to continue its support of the PV Module Reliability Scorecard. Over the past five years, the Scorecard has identified the data that solar investors and developers need the most for technical due diligence to inform their buying strategies. With the latest Scorecard, PVEL continues to provide the independent testing, data and reports that guide strategic procurement and minimize technology risk.

DITLEV ENGEL CEO, DNV GL - Energy

75%

of the world's installed solar PV capacity has operated for **less than five years**



In only ten years, the average price of PV modules dropped by

90%

Long-term field data that proves today's PV modules will perform reliably for decades does not exist.

Source: Exawatt

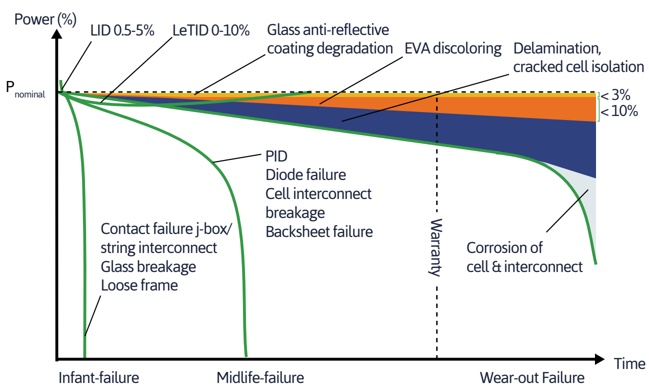
PART 2

PV MODULE RELIABILITY

RELIABILITY ISSUES IN THE FIELD

Module Failure Modes and Aging Mechanisms

PV modules are susceptible to a number of failure modes throughout their lifetime, from early failure issues such as glass breakage to longer term wear-out issues like cell corrosion. To this widely used graphic first published by IEA in 2014, PVEL added two additional failure mechanisms currently under industry-wide evaluation: Light and elevated Temperature Induced Degradation (LeTID) and backsheet failure.



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

Project Financial Impacts

Falling Power Purchase Agreement prices and profit margins make module performance and reliability more crucial to financial returns now than ever before. The National Renewable Energy Laboratory (NREL) has extensively studied the financial ramifications of PV sites experiencing higher than expected module degradation rates. In a recent study NREL determined that increasing the annual module degradation rate from 0.5% to 1.5% will cause the site's real Levelized Cost of Electricity (LCOE) to increase by 13.6%.[1] This could severely impact the project's economics, turning a profitable investment into a financial burden for the asset owner.

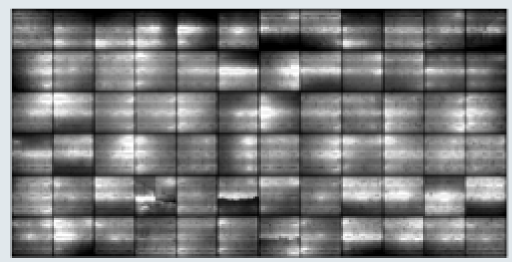
The impact of site underperformance on project financials is further demonstrated by a poll[2] conducted by PVEL where 70% of survey respondents replied that an **underperformance of 3-6% is enough to render their projects financially nonviable.**

Field Observations of Performance Loss

Having aerial infrared-scanned over 1,600 operating PV systems representing over 11 GW, Heliolytics has observed that **the average site shows 1.52% of lost DC energy generation.** Their analysis involves weighting each IR fault by its estimated impact to energy production, then summing them to determine DC loss per site. While it is clear in the graph to the right that half of the sites have less than 0.53% DC energy loss; the long tail ending with greater than 10% of sites suffering from DC energy losses of >10% is an alarming statistic.

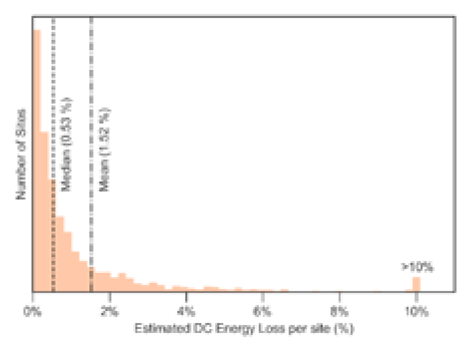
Underperformance Case Study

The following presents an example in which severe module underperformance turned a profitable project into one that is experiencing significant levels of lost energy generation, site investigation costs, plus labor and legal fees related to module warranty. Upon discovering that the site was not meeting expectations, the owner arranged for 23 modules to be sent for lab testing. **The lab measured module power decreases ranging from 8% to 36% after less than two years from site commissioning.** Through luminescence and thermal imaging, it was determined that the cell metallization paste suffered thermo-mechanical fatigue. This is shown in the numerous bright spots throughout the EL image.



EL image of a module taken from the underperforming site
Source: DuraMAT/NREL, 2019

Bright spots occur where high series resistance and interconnect failures prevent current from spreading across the cell leading to current concentrations along the cell bus bars. In addition to lost energy generation, this defect may lead to hot spots causing backsheet burns, glass cracking and potential safety issues at the site. A module defect such as this triggers uncertainty for long-term module reliability, and leads to difficulties in determining which modules are susceptible to high power loss in the future. **Properly sourcing modules through PVEL's recommended best practices would have prevented this costly issue for the site owner: thermal cycling testing via PVEL's Product Qualification Program (PQP) and serial defect testing would have undoubtedly caught this defect before the faulty modules were installed.**



Source: Heliolytics, 2019

[1]*NREL, 2019 – assumptions: 4.5% real discount rate. $10/kW-yr average O&M expense. $1.0/W(DC) capital cost.*
[2]*PVEL, Solar Asset Management North America, 2016*

PV MODULE TESTING

Certifications Only Address Product Safety

Most solar project developers and equipment buyers require two key certifications for solar PV modules – IEC 61215 and IEC 61730 or UL 1703. They demonstrate that PV modules are safe. **None of these test standards address long-term PV module reliability and performance in the field.**

- IEC 61730 and UL 1703 only certify that PV modules are not hazardous to operate.
- IEC 61215 only screens for defects that would appear in the first few years of operation.
- Manufacturers select the specific modules that are used in certification tests. It is possible to send "golden samples" that are constructed more carefully than commercially produced modules.
- Manufacturers can change some component combinations of their module BOM without re-certifying the module model.

Additionally, updating IEC and UL standards is a multi-year process that cannot keep pace with the rate of innovation in solar PV module technology. **Both standards fail to identify major field performance issues associated with technical advances,** such as Lig-ht and elevated Temperature Induced Degradation (LeTID) and Potential-induced Degradation (PID). An LeTID test will be included in the next version of the PVEL PQP, which will be released in summer 2019.

Testing for Reliability and Performance

While IEC and UL certifications are important indicators of module safety, long-term reliability and performance are also important to PV buyers. Since its founding in 2010, PVEL has consulted with developers and financial institutions to continually develop test programs that address specific issues observed in the field and with emerging and even proven technologies.

By extending IEC 61215 sequences and incorporating additional tests, PVEL's PQP approximates the impact that decades of exposure in the field has on PV modules.

Extended reliability testing at PVEL's Berkeley Lab

What are the limitations of PV module warranties?

Nameplate and Solvency

Some module power degradation is expected, so a degradation factor is usually built into solar assets' energy yield and financial models as well as manufacturers' warranty terms. Warranties typically guarantee approximately 97% of the nameplate rating during the first year followed by an annual 0.6 to 0.7% reduction in the subsequent 24 years. **However, warranties only protect buyers when manufacturers are solvent and responsive to claims.**

Imprecise Measurement

Measuring power degradation that could be a warranty claim is extremely difficult – if not impossible – in the field. Measurement tools and sensors simply lack sufficient precision. A 3% allowance for uncertainty is usually applied for warranty enforcement, which effectively reduces guaranteed power output by 3%. Most successful warranty claims are therefore limited to excessive underperformance or total failure.

Coverage Limitations

Even when claims are accepted, most warranties only cover the cost of replacement modules, not costs associated with labor or lost energy production. Advances in the manufacturing process can also jeopardize future module replacement. For example, the product roadmaps of many major manufacturers today call for increasing wafer size and thus module size. This will result in modules that are not compatible with the modules they sell today. **Asset owners may be unable to replace defective modules in operating systems, which makes procuring reliable PV modules even more important.**

Certifications and warranties cannot fully protect PV module buyers from field failures and subsequent financial consequences.

PART 3

TEST RESULTS

PV MODULE PQP METHODOLOGY

PVEL launched the PV Module Product Qualification Program (PQP) in 2012 with two goals:

1. To provide PV equipment buyers and power plant investors with independent, consistent reliability and performance data that supports effective supplier management.
2. To independently recognize manufacturers who outpace their competitors in product quality and durability.

Today the PVEL PQP is a common requirement for PV modules installed in systems around the world.

PQP Test Development

Throughout the year and on a global scale, PVEL investigates field failures and monitors developments in the PV standards community. We work with research institutes, conduct experiments, and receive feedback from the upstream module manufacturers and downstream module purchasers (i.e. EPCs, developers, investors and insurance companies).

These inputs guide annual updates to the PQP and ensure that PVEL's reports deliver the data that equipment buyers need.

The Key Principles of the PVEL PQP

Empirical data
The PQP replaces performance assumptions with empirical metrics that help PVEL's Downstream Partners optimize revenue and energy yield models. Each PVEL PQP provides nine detailed test reports that PVEL's partners freely access to support their purchasing decisions.

No hand-picked samples
All Bills of Materials (BOMs) of products submitted to PQP testing are witnessed in production - from opening of raw materials packages through every step of the production process - to wrapping the completed pallet in tamper-proof tape.

Standardized processes
All BOMs are tested in the same way, using consistently calibrated equipment and in consistent laboratory environments. This enables a leveled comparison across all manufacturers.

Updated regularly
The rapid pace of technology development requires a test program that stays current in order to properly assess and qualify new products. PVEL updates the PQP annually to provide buyers with consistently relevant data to evaluate PV products.

What is a factory witness?

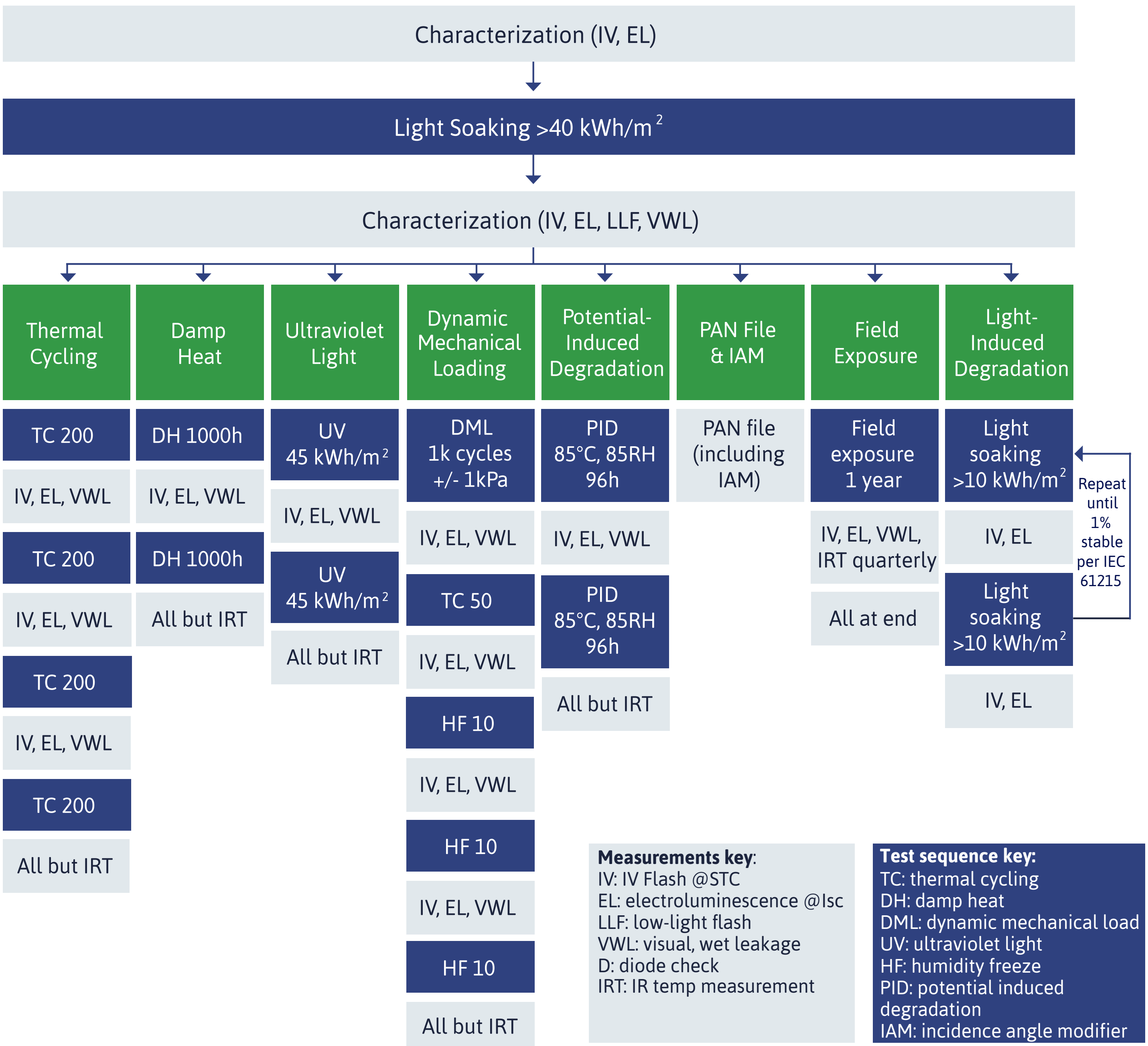
Years of PQP test results demonstrate that the module's Bill of Materials (BOM) is one of the key quality drivers. To verify the specific BOM combination used in module production, PVEL's auditors follow a 5-step factory witness process:

1. Photograph BOM components as materials are removed from their original packaging
2. Observe and record over 100 technical details about the BOM
3. Strictly track each BOM component through every step of production and packaging
4. Document recipes used for soldering and laminating
5. Conduct a high-level process audit of the factory

Using exhibits to specify BOMs in their contracts helps PV module buyers ensure that they receive products with the exact components that achieved satisfactory PQP test results. **PVEL provides Downstream Partners with detailed BOM listings in exhibits for inclusion in module supply agreements.**

> “As an early champion of rigorous technical due diligence, we know first-hand that mitigating risk through strategic procurement is a much sounder strategy than relying on warranties alone. PVEL’s Product Qualification Program is designed to help developers invest confidently in new technologies that promise greater returns, particularly when long-term field performance data is unavailable.”
>
> **ABHIJEET SATHE** Chief Operating Officer, SB Energy, a division of Softbank

2018 PVEL PRODUCT QUALIFICATION PROGRAM



RESULTS OVERVIEW

Methodology

The PQP results presented in the 2019 Scorecard were factory witnessed within 18 months of 2019. Results presented in the bar charts on the subsequent pages show average values for the different test samples and BOMs which together represent a single module model. Each test sequence had a varying number of manufacturers and model types participating.

The Top Performers in each test category are listed in alphabetical order. Top Performers are model types that degraded less than 2% for the entirety of the test sequence.

Reading the Results

Each test sequence is detailed over two pages and includes:

1. An overview of the stress testing and real-world context of the specific failure mechanism
2. An example of high levels of degradation, including electroluminescence (EL) images and electrical parameters
3. The 2019 results graphically presented showing the average power loss percentage by model type
4. An alphabetical list of Top Performers
5. A results summary for that specific test

PVEL cautions that not all products/model types are represented in every test. For example, some model types are not subjected to all tests, or some results may not have been available at the time of publication. Buyers should contact PVEL to obtain the full reports that comprise these results. The full reports contain BOM-level results whereas the results herein are reported at the model level.

Results Summary

New for this Scorecard edition is the inclusion of PVEL's historical data from nearly ten years of testing. The bar charts that follow indicate how the 2019 Scorecard results compare to PVEL's historical dataset.

The presented data indicates a general trend of improved performance in thermal cycling and potential-induced degradation; however, a wider range of performance can be observed for damp heat and the dynamic mechanical load sequence.

PQP participants tend to place a higher value on the quality of their products than non-participants. As such, the median results may be better than those of the broader industry, especially for modules one might source on the open market. See Procurement Best Practices on page 30 for PVEL's module purchasing recommendations.

> "Earning PVEL's Top Performer designation helped us grow U.S. market share at a pivotal moment in Jinko Solar's international expansion. Since then, we have leveraged PVEL's Product Qualification Program to prove the reliability and performance of our most advanced products to prospective buyers in markets around the world.
>
> **DANIEL CHANG** Technical Director - North America, Jinko Solar

THERMAL CYCLING: OVERVIEW AND RESULTS

Background

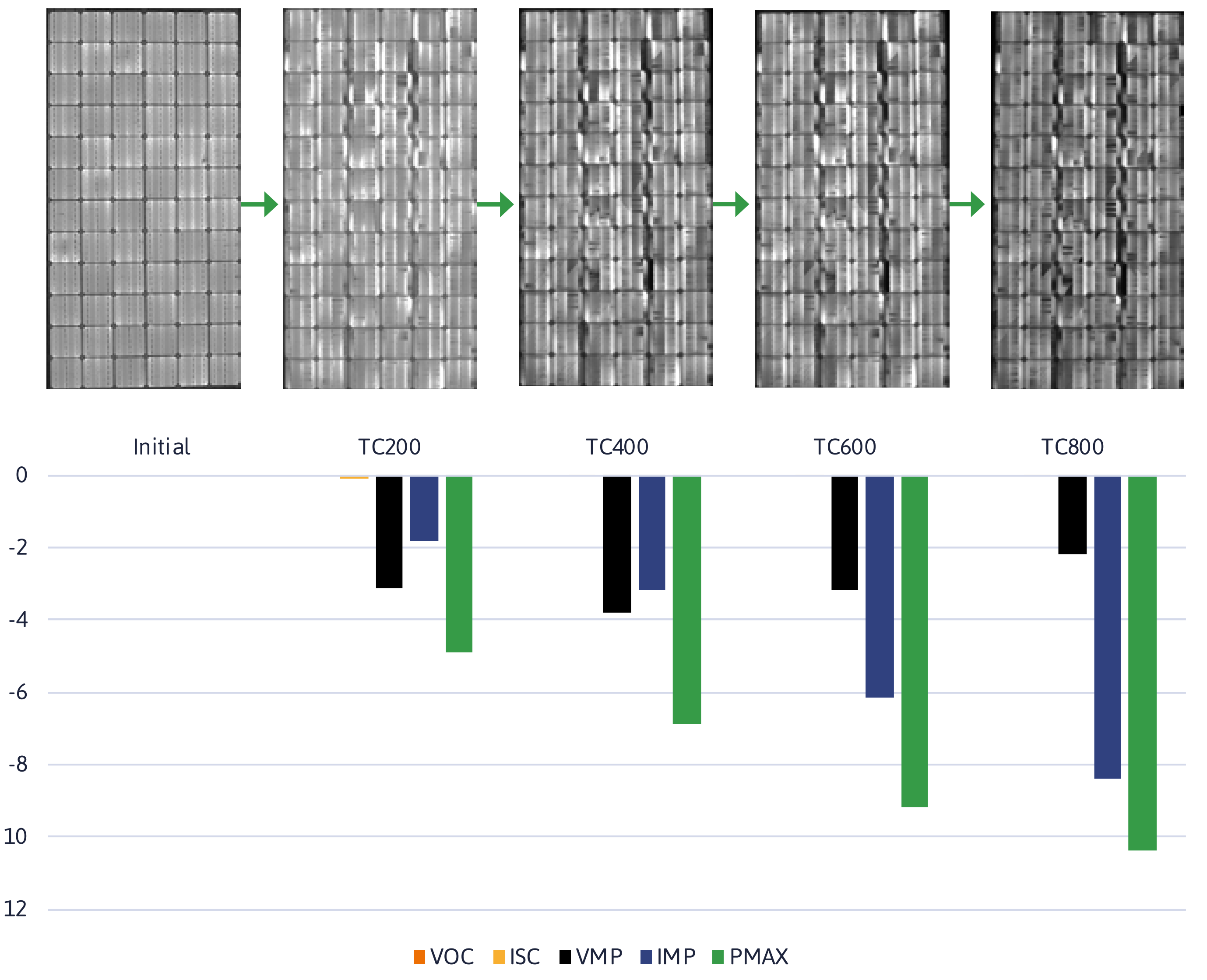
PV module components expand and contract in response to changes in temperature. Because these components have different thermal expansion coefficients, they change size at different rates in the same environmental conditions. This creates interfacial stress, a thermodynamic effect that reduces the strength of the bonds between each layer of the PV module. One example is solder bond fatigue, which increases series resistance and decreases module performance at high irradiance.

Why the Test Matters

The material components of PV modules will expand and contract many times over 25+ years in the field, even in temperate climates. With module operating temperatures well above ambient, this effect occurs daily and can be extreme in deserts and other arid environments. This test demonstrates if the temperature cycles are likely to cause undue interfacial stress that decreases performance.

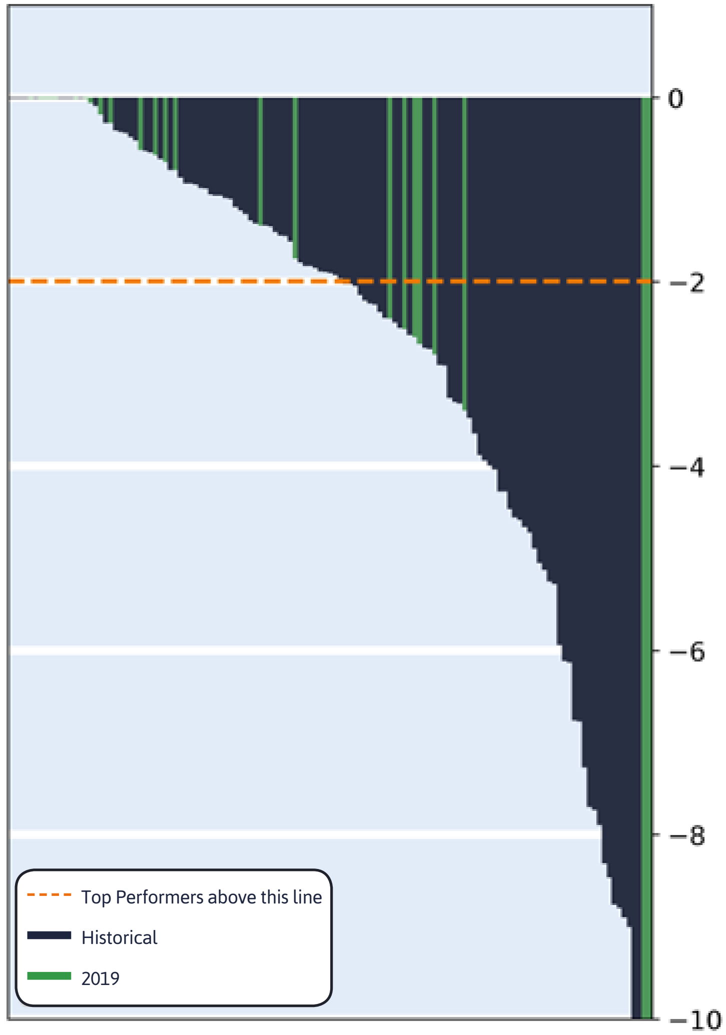
Thermal Cycling Procedure

Modules are placed in an environmental chamber where the temperature is lowered to -40°C, dwelled, then increased to 85°C and dwelled again. Maximum power current is applied to the modules while the temperature is increased and decreased. This is repeated 800 times for PVEL's PQP. One cycle takes about three hours to complete. IEC 61215 testing requires only 200 cycles.



2019 TC TOP PERFORMERS	
Manufacturer	**Module Model**
Boviet	BVM6612M-xxx-H / BVM6610M-xxx-H
GCL	GCL-M6/72Hxxx / GCL-M6/60Hxxx GCL-P6/72Hxxx / GCL-P6/60Hxxx
Hanwha Q CELLS	Q.PEAK DUO L-G5.2 xxx Q.PEAK DUO-G5 xxx
JA Solar	JAM60S02-xxx/PR JAP72S01-xxx/SC / JAP60S01-xxx/SC
Jinko	JKMxxxM-60B JKMxxxM-72 / JKMxxxM-72-V / JKMxxxM-60 / JKMxxxM-60-V
LONGi	LR6-72PH-xxxM / LR6-60PB-xxxM
REC Solar	RECxxxTP2M RECxxxTP2
Silfab	SLGxxxM / SLAxxxM
Trina Solar	TSM-xxxPE14H / TSM-xxxPE05H TSM-xxxDE14H(II) / TSM-xxxDE05H(II)

Power Degradation from TC Test Sequence for Each Module Model



Results in Context: Key Takeaways

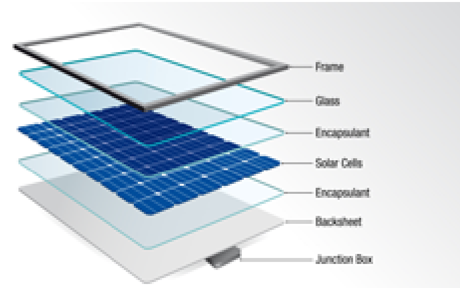
The 2017 and 2018 Scorecards presented thermal cycling data from past PQPs where the sequence duration was 600 cycles. Therefore a third of the historical data (in blue) terminates at 600 cycles. The 2019 data (in green) represents 800 cycles. Despite this 25% increase in test duration, performance clearly improved. Two notable exceptions include high degradation data points, which are discussed in relation to diode failures on page 26.

The EL images show a module that barely passed the IEC 61215 TC threshold with less than 5% degradation after TC200. Additional thermal cycling revealed increased failures in solder bonds between cells and interconnecting ribbons. This demonstrates the absolute importance of proper materials selection, process quality control, and extended stress testing.

DAMP HEAT: OVERVIEW AND RESULTS

Background

PV modules are constructed of different components that are laminated together. These layers must remain firmly adhered for the PV module to meet performance expectations. Moisture and high temperature can degrade the adhesives that bond these layers together, allowing water, dirt, soil and other materials to enter the module and degrade its internal components, thus reducing energy yield. Delamination may also decrease the insulation resistance of a PV module, which makes electrical shock more likely.

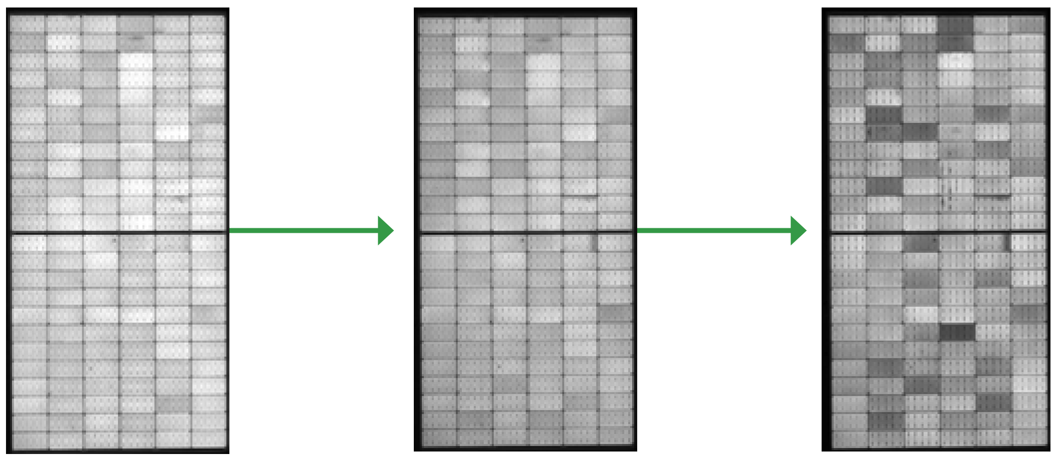


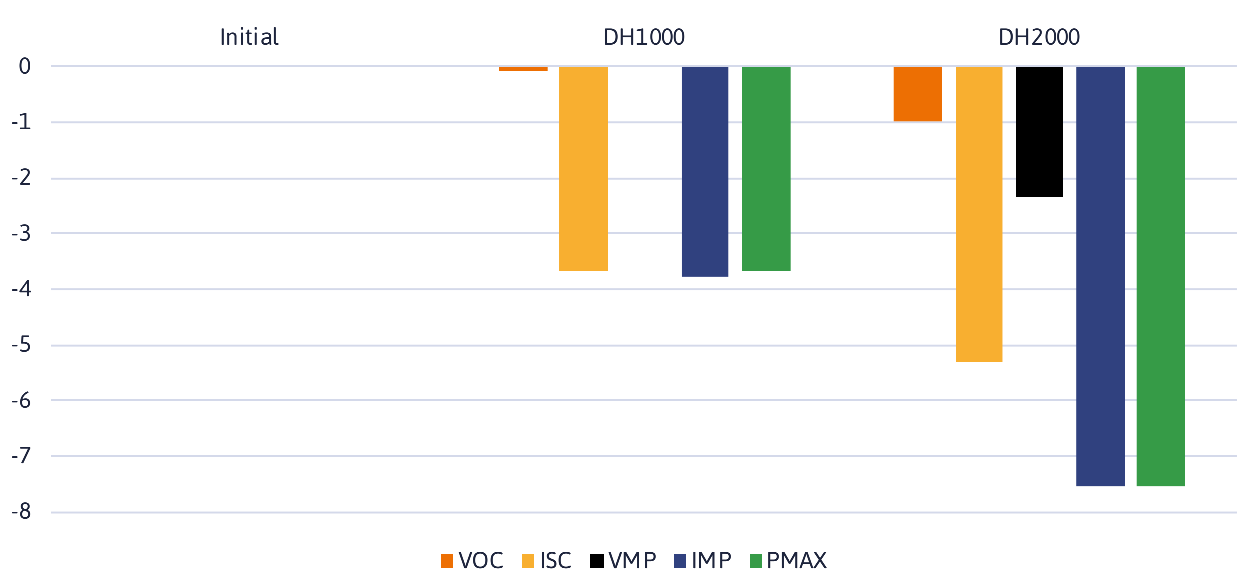
Why the Test Matters

High temperature and high humidity are common in many tropical and subtropical parts of the world. PV modules in moderate climates also experience periods of high temperature and humidity. These exposures can cause premature failures and degradation when poor quality components or improper lamination procedures are used. PVEL's damp heat test reproduces degradation and failure modes that occur in the field.

Damp Heat Procedure

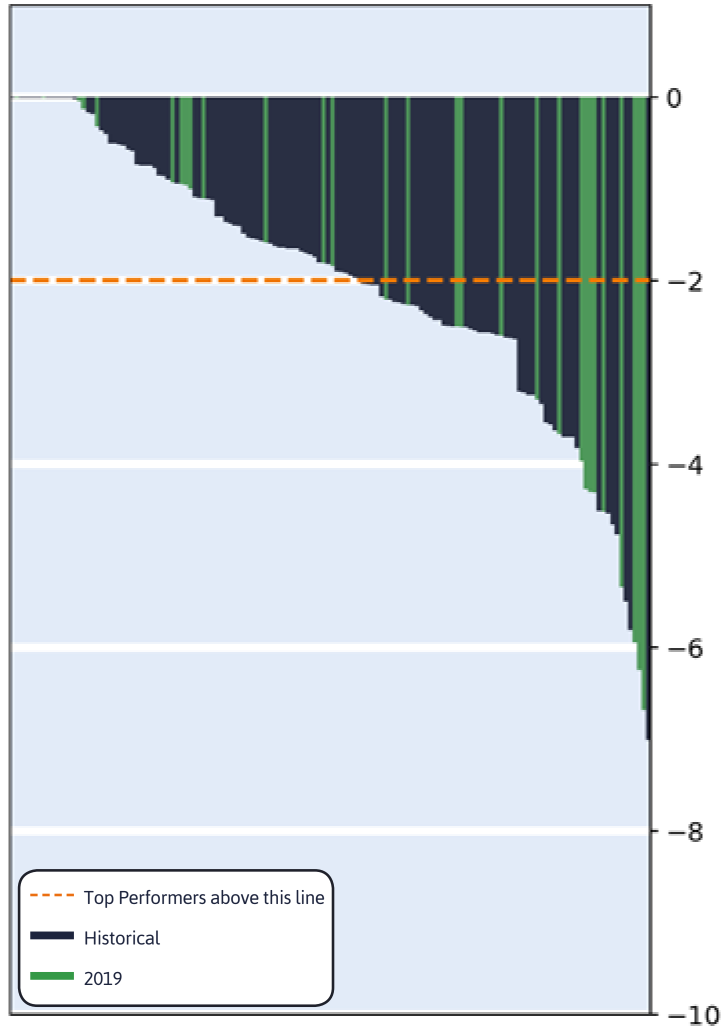
Modules are placed in an environmental chamber and held at a constant temperature of 85°C and 85% relative humidity for 2,000 hours (about 84 days). The heat and moisture ingress stress the layers of the PV module. IEC testing has a duration of only 1,000 hours.





2019 DH TOP PERFORMERS	
Manufacturer	**Module Model**
Adani/Mundra	ASM-7-PERC-AAA / ASM-6-PERC-AAA ASP-7-AAA / ASP-6-AAA
GCL	GCL-P6/72Hxxx / GCL-P6/60Hxxx
JA Solar	JAM60S02-xxx/PR
LONGi	LR6-60PB-xxxM LR6-60HPB-xxxM LR6-72PH-xxxM
Phono Solar	PSxxxP-24/T / PSxxxP-20/U
Vikram Solar	Somera VSM.72.AAA.05 / VSM.60.AAA.05 Eldora VSP.72.AAA.05 / VSP.60.AAA.05

Power Degradation from DH Test Sequence for Each Module Model



Results in Context: Key Takeaways

Damp heat results from the 2018 Scorecard showed increased degradation compared to previous Scorecards. This trend has continued in 2019 with a significant number of tested modules exhibiting greater than 4% degradation. Most of the module types demonstrating anomalous degradation were made with PERC cells (both full-size and half-cut). As shown in the example, they exhibit a checkerboard pattern of cell brightness levels in post-DH2000 EL images. However, this is not the case for all PERC modules as some Top Performers use that cell technology.

PVEL continues to work with module manufacturers, research institutes, and Downstream Partners to understand the cause of this new degradation mode and its potential impact on field performance.

DYNAMIC MECHANICAL LOAD SEQUENCE: OVERVIEW AND RESULTS

Background

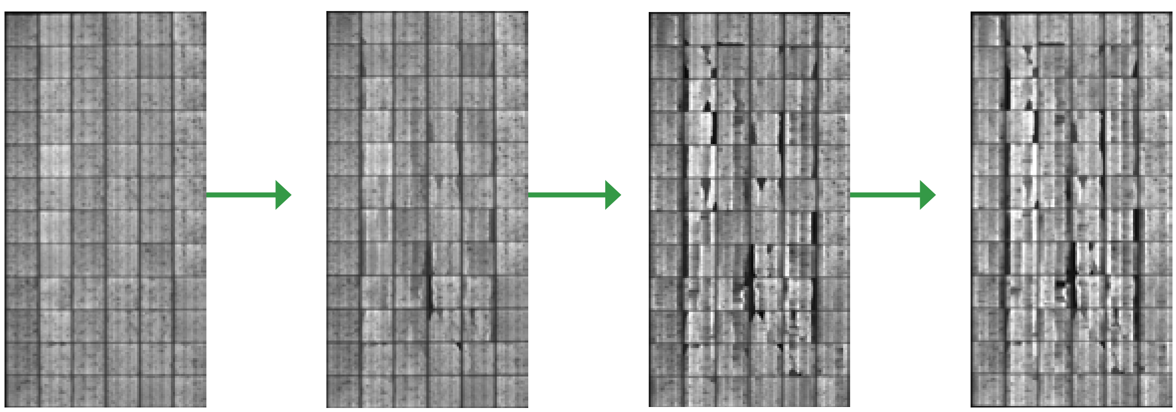
The dynamic mechanical load (DML) sequence involves a combination of DML, thermal cycling, and humidity freeze tests. Applying mechanical loads, or forces, to PV modules can stress and break components. Stress and breakage can cause a range of issues, including moisture ingress, microcrack development and propagation, solder joint fatigue and cell corrosion. Such issues often result in reduced energy yield and field failures.

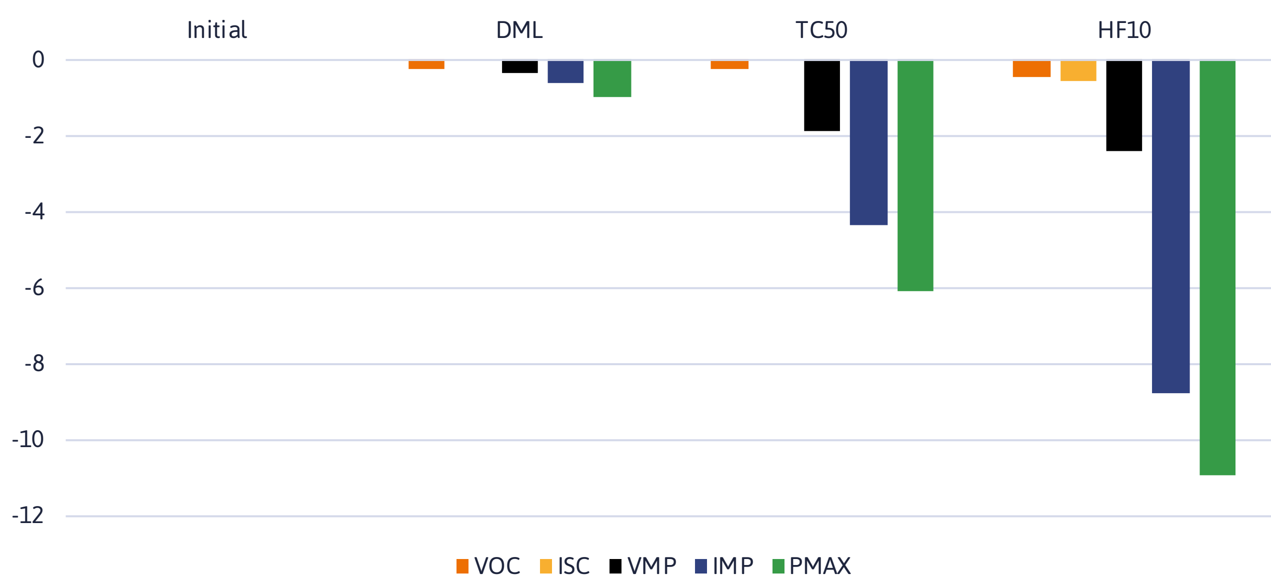
Why the Test Matters

Wind and snow subject modules in the field to dynamic mechanical loads, or forces applied in different directions and speeds. Dynamic loading can also occur during transportation, delivery, and installation of modules, especially if they are packaged or handled improperly. This test demonstrates if module components and material combinations are likely to break down in these conditions.

DML Sequence Procedure

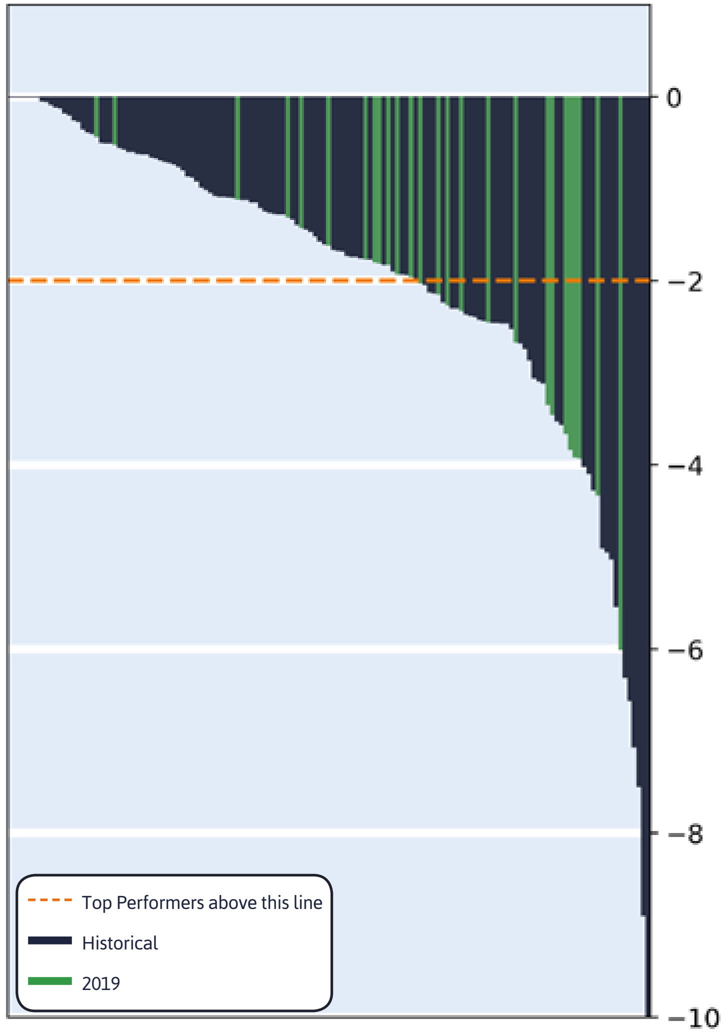
The module is installed according to the manufacturers' recommended mounting configuration, then subjected to 1,000 cycles of alternating loading at 1,000 Pa. Next the module is placed in an environmental chamber and subjected to 50 thermal cycles (-40°C to 85°C) to cause microcrack propagation, then three sets of 10 humidity freeze cycles (85°C temperature and 85% relative humidity for 20 hours followed by a rapid decrease to -40°C) to stimulate potential corrosion. The module is characterized and inspected visually to evaluate the status of the module's frame, edge seal and cell interconnections.





2019 DML TOP PERFORMERS	
Manufacturer	**Module Model**
Adani/Mundra	ASP-7-AAA / ASP-6-AAA
Boviet	BVM6612M-xxx-H / BVM6610M-xxx-H
GCL	GCL-P6/72Hxxx / GCL-P6/60Hxxx
Hanwha Q CELLS	Q.PEAK DUO L-G5.2 xxx
JA Solar	JAM60S02-xxx/PR
LONGi	LR6-72PH-xxxM LR6-60PB-xxxM
REC Solar	RECxxxTP2M
Silfab	SLGxxxM / SLAxxxM
Vikram Solar	Eldora VSP.72.AAA.05 / VSP.60.AAA.05

Power Degradation from DML Test Sequence for Each Module Model



Results in Context: Key Takeaways

The 2019 Scorecard is the first edition where the data presented for the DML sequence extends to 30 humidity freeze cycles. About 80% of the historical test data includes only 10 humidity freeze cycles, which reflects past PQP test durations. Extending the humidity freeze cycles to 30 resulted in a wider range of degradation values across the 2019 sample set compared to the 2018 Scorecard.

The EL image example demonstrates how dynamic mechanical loading can induce microcracks that do not necessarily result in significant power loss. It is only after thermal cycling and humidity freeze testing that metal conductors affected by cell cracks break, which leads to black inactive areas and increased power degradation.

To better gauge microcrack susceptibility, the next iteration of PVEL's PQP will include static mechanical load testing at the start of this sequence.

POTENTIAL-INDUCED DEGRADATION: OVERVIEW AND RESULTS

Background

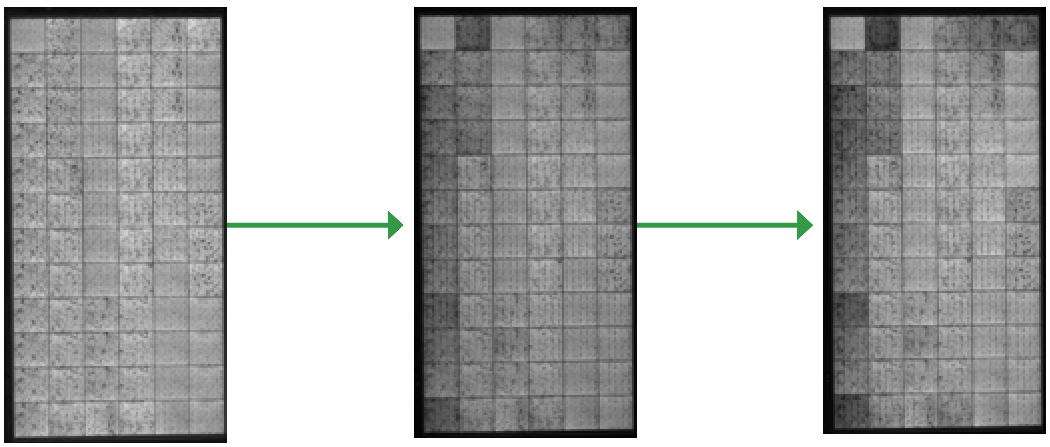
Potential-induced Degradation (PID) can occur within weeks or even days of commissioning. PID emerged in the last ten years with the development of higher system voltages and ungrounded systems. It generally occurs when the internal PV electrical circuit is biased negatively in relation to ground. The combination of voltage and humidity can cause sodium ions from the glass or cell surface to create current paths from the internal PV electrical circuit to the frame and mounting system. This reduces module performance as some of the module's generated electrons are lost to these newly formed current paths.

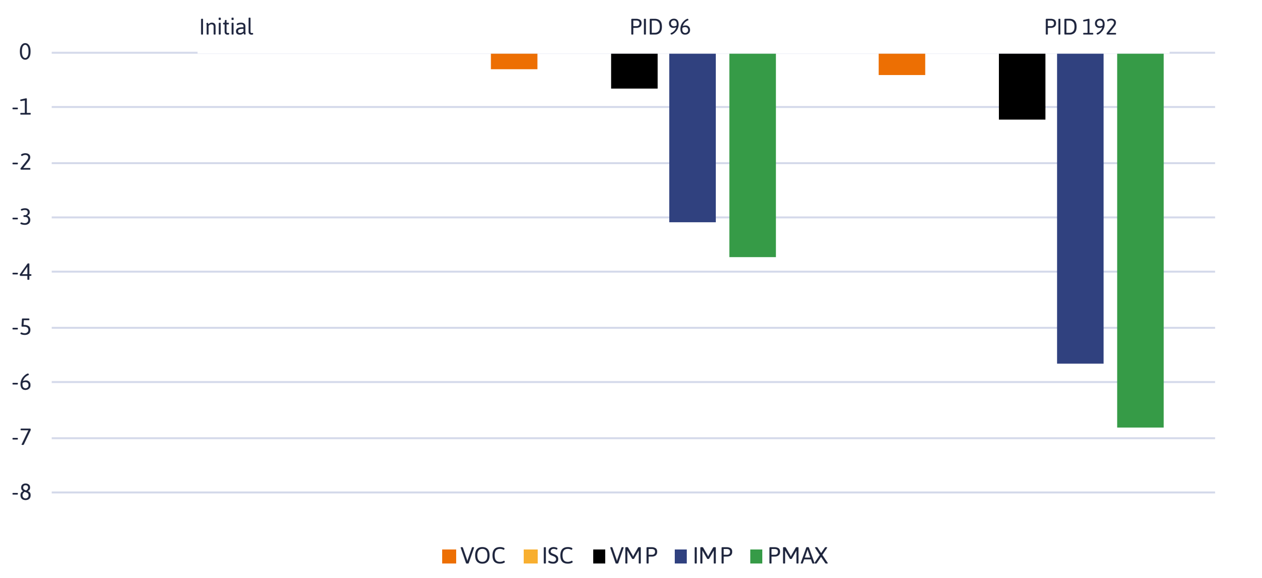
Why the Test Matters

PID can reduce performance by more than 30%. While some PID mechanisms are reversible in the early stages of degradation, some are not. PID can also be managed through system design, including use of specific grounding configurations and distributed electronics. PVEL recommends evaluating these alternative solutions if not procuring PID-resistant modules.

PID Procedure

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

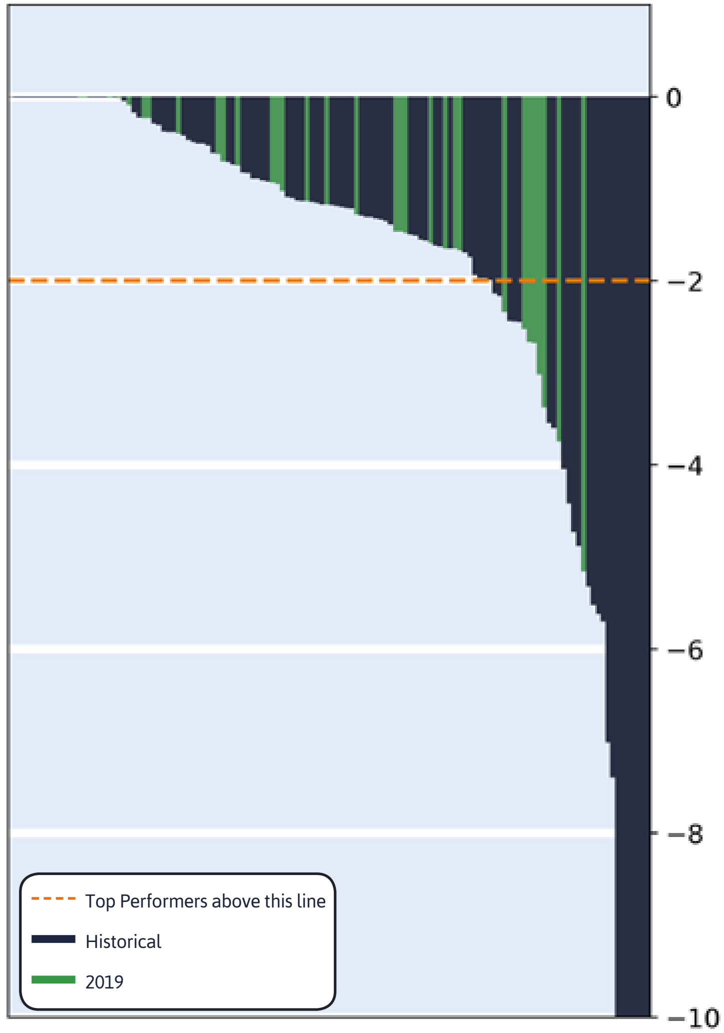




2019 PID TOP PERFORMERS

Manufacturer	Module Model
Adani/Mundra	ASP-7-AAA / ASP-6-AAA ASM-7-PERC-AAA / ASM-6-PERC-AAA
Boviet	BVM6612M-xxx-H / BVM6610M-xxx-H
GCL	GCL-M6/72Hxxx / GCL-M6/60Hxxx GCL-P6/72Hxxx / GCL-P6/60Hxxx
Hanwha Q CELLS	Q.PEAK DUO-G5 xxx Q.PEAK DUO-G6 xxx
JA Solar	JAM60S02-xxx/PR JAP72S01-xxx/SC / JAP60S01-xxx/SC
Jinko	JKMxxxM-60B
LONGi	LR6-60PB-xxxM LR6-72PH-xxxM
Phono Solar	PSxxxP-24/T / PSxxxP-20/U
REC Solar	RECxxxTP2 RECxxxTP2M
Seraphim	SRP-xxx-6MA-HV / SRP-xxx-6MB-HV
Silfab	SLGxxxM / SLAxxxM
Suntech	STPxxxS-24/Vfh / STPxxxS-20/Wfh
Trina Solar	TSM-xxxPE14H / TSM-xxxPE05H
Vikram Solar	Somera VSM.72.AAA.05 / VSM.60.AAA.05
ZNShine	ZXP6-72-xxx/P / ZXP6-60-xxx/P

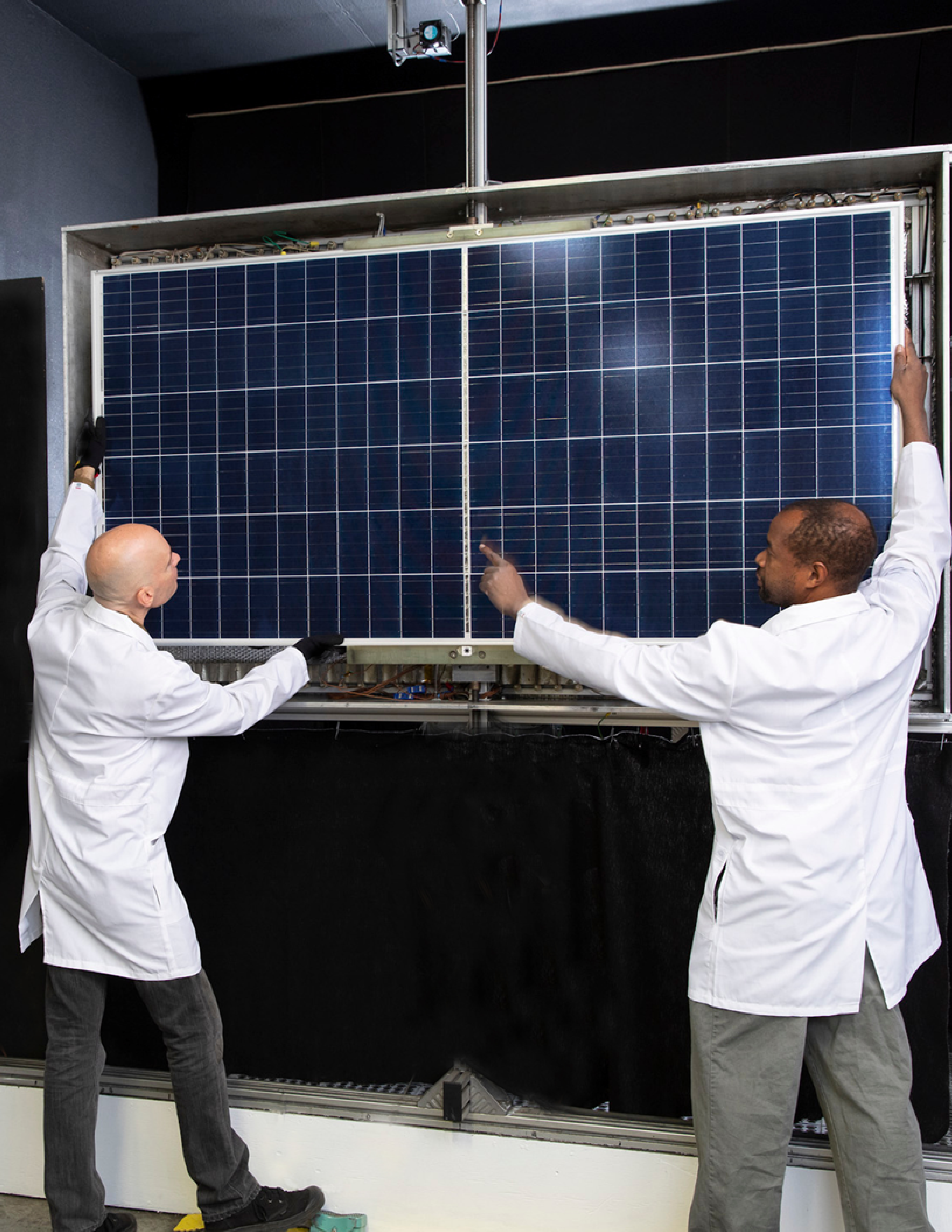
Power Degradation from PID Test Sequence for Each Module Model



Results in Context: Key Takeaways

The industry's understanding of PID is relatively advanced, so one could say that this failure mode has been "solved." There are more Top Performers for PID than any other PQP test, with a maximum degradation of 5.16% for the 2019 dataset compared to many historical data points with higher degradation levels. However, as discussed on page 8, just 3-6% power degradation is enough to cause a PV site to become unprofitable. Installing the module type in the example shown here in a system design that is susceptible to PID would result in significant energy generation losses; therefore, testing each module BOM for PID is necessary.

Note: 44% of the historical data (in blue) extends to 600 hours of PID testing, which was the terminus for this test in past PQPs.



> PVEL's PV Module Reliability Scorecard is the starting point for updating our Approved Vendor Lists. It helps us save time by identifying suppliers to prioritize for in-depth diligence. The next step is digging into the data behind the Top Performer rankings to identify BOMs that meet the performance, reliability and financing requirements of our project pipeline.

CHRIS JACOBS Asset Engineering Manager- Cubico Sustainable Investments

HISTORICAL SCORECARD

Consistent top performance in the PV Module Reliability Scorecard demonstrates a manufacturer's commitment to product quality. As new products are introduced and older models are retired, manufacturers must adhere to strict quality control standards to maintain high levels of reliability and performance of their products.

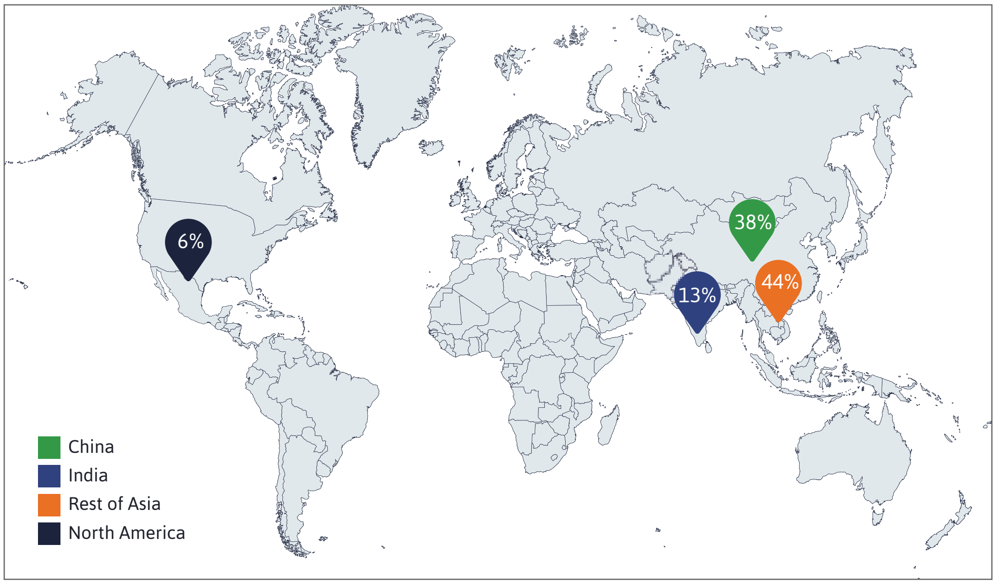
The Historical Scorecard below shows the 2019 Top Performers and their history of top performance in previous editions. Manufacturers are listed by the number of years they have been designated a Top Performer, in alphabetical order.

2019 TOP PERFORMER PVEL | DNV·GL PV MODULE RELIABILITY SCORECARD

	2019	2018	2017	2016	2014
Jinko	●	●	●	●	●
Trina Solar	●	●	●	●	●
Hanwha Q CELLS	●	●	●	●	
JA Solar	●	●		●	●
REC Solar	●	●	●	●	
GCL	●	●	●		
LONGi	●	●	●		
Phono Solar	●	●		●	
Suntech	●	●			●
Adani/Mundra	●	●			
Seraphim	●		●		
Silfab	●		●		
Vikram Solar	●		●		
ZNShine	●			●	
Boviet	●				

FACTORY LOCATIONS

The equipment, processes and quality control procedures used in manufacturing all impact PV module quality. Factory witness reports that document every step of the manufacturing process are available to PVEL's Downstream Partners. PVEL Top Performers operate in factories all over the world. The map and table below show the specific locations of 2019 PQP Top Performers.



Manufacturer Name	Factory Location
Adani (Mundra Solar PV Ltd)	Gujarat, India
Boviet Solar Technology Co., Ltd.	Song Khe-Noi Hoang Industrial Zone, Vietnam
GCL System Integration Technology Co., Ltd.	Zhangjiagang, China; Van Trung Industrial Park, Vietnam
Hanwha Q CELLS Co., Ltd.	Jincheon-gun, South Korea
JA Solar Technology Co.	Shanghai, China; Van Trung Industrial Park, Vietnam
Jinko Solar Co., Ltd.	ShangRao, China
LONGi Solar Technology Co., Ltd.	Taizhou, China; Kuching, Malaysia
Phono Solar Technology Co., Ltd.	Nanjing, China
REC Solar	Tuas, Singapore
Seraphim Solar System Co., Ltd.	Changzhou, China
Silfab Solar Inc.	Mississauga, Canada
Wuxi Suntech Power Co., Ltd.	Wuxi, China
Trina Solar Co., Ltd.	Changzhou, China
Vikram Solar Ltd.	Kolkata, India
ZN Shine PV-Tech Co., Ltd.	Changzhou, China

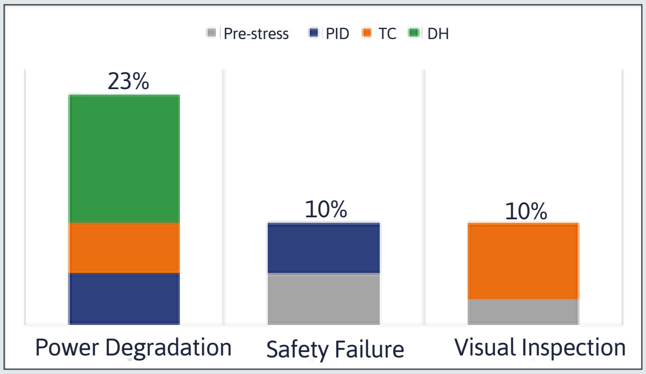
PART 4

CASE STUDIES

CASE STUDY: PQP FAILURES

Throughout PQP testing, modules undergo various characterizations including visual inspection, safety testing and electrical performance testing. The results of these characterizations are included in the PQP reports for each tested module.

PVEL does not assign pass/fail thresholds to power degradation; however, module manufacturers are able to remove their products from testing when visual anomalies, EL images, or power degradation do not meet their expectations. These instances, along with safety test failures, are considered by PVEL to be PQP “failures.” **Over 30% of all 2019 Scorecard-eligible BOMs exhibited one or more failures during PQP testing.**



For the PQP testing period represented in the 2019 Scorecard, power degradation was the largest category of recorded PQP failures, with **23% of eligible BOMs experiencing power loss above the manufacturer’s acceptable threshold.** Of eligible BOMs, 10% had at least one safety failure and 10% had at least one visual inspection defect.

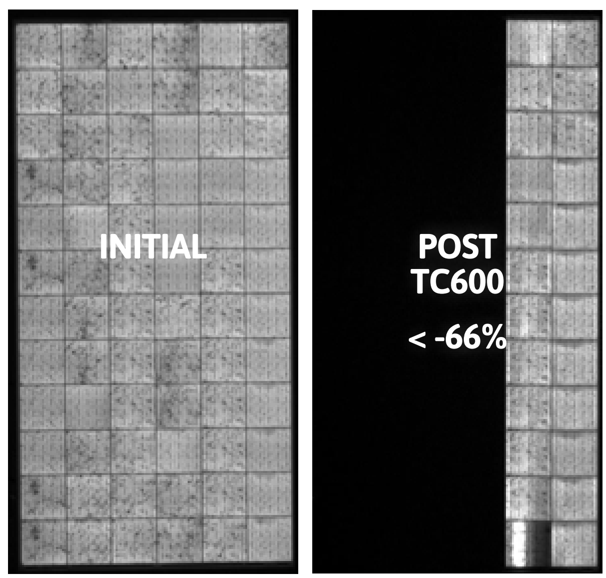
The chart on the left shows the breakdown of failures per test that occurred in 2019 Scorecard-eligible PQPs. The Pre-Stress category encompasses failures detected during incoming inspection and after light-soaking.

Example 1: Diode Failure During Thermal Cycling

According to Heliolytics, more than 80% of the >1 MW sites they have scanned using aerial infrared (IR) imagery show sub-module defects with at least one-third of the module affected. Many of these sub-module failures are due to one or more bypass diodes in the module junction box failing in open- or short-circuit condition.

For typical crystalline modules, bypass diodes are necessary in order to prevent module hot spots during shading conditions – an issue that can severely damage a module and render it unsafe. Despite the critical role they play, bypass diodes can fail for a variety of reasons such as poor component selection, weather events, or a lack of robust process and quality control during junction box and/or module manufacturing. When a module bypass diode fails in short-circuit condition, one third of the module will no longer generate energy. When a module bypass diode fails in open-circuit condition, it increases hot spot risk.

PVEL’s PQP testing uses extended thermal cycling to thermally stress module components. Diodes prone to failure can yield disastrous results for a module’s performance during this test, such as in the case to the right where two diodes failed after 600 thermal cycles and **the module power output decreased by 66%.**



Over the past five editions of the Scorecard, a general trend of improved module performance and reliability can be observed, yet these failures provide a stark reminder of the need for module buyers to perform due diligence when purchasing PV modules, since even “proven” technologies can exhibit unexpected issues.

CASE STUDY: PQP FAILURES CONTINUED

Example 2: Wet Leakage Failures

While module performance risk is certainly of great concern, module safety is paramount. One way the PQP assesses safety is through wet leakage testing during the PQP characterization stages. This test evaluates the electrical insulation of the module under wet operating conditions such as those that occur in the field due to rain, fog, dew, humidity or melting snow.

While performing this test, the module is immersed in a conductive water solution and the junction box, cables and connectors are wetted with the same solution. Then 1,000 or 1,500 volts is applied between the module's electrical circuit and the liquid for two minutes. During this time the insulation resistance is measured and must equal or exceed 40 MΩ·m^2 in order to pass the test according to IEC 61215-2:2016.

One of the most prevalent PQP failures observed in the past 18 months is that of wet leakage faults, where the module's insulation resistance measured less than the IEC-defined pass threshold. **Failure of the wet leakage test signifies that the module may present a safety hazard in the field, especially while operating when wet.**

Over 30% of BOMs tested had at least one failure.

CASE STUDY: KNOW YOUR BOM

A top tier module manufacturer submitted modules to PQP testing that were made with two different Bills of Materials (BOMs). Both BOMs:

- Had the same model number, label and datasheet
- Were visually indistinguishable
- Were manufactured in the same facility
- Passed IEC 61215 (<5% degradation after TC200)

One BOM had TC800 results that were PVEL PV Module Reliability Scorecard "Top Performer"-level (< 2% degradation). The other BOM had TC800 results that were within the lower ranking of historical PQP results with 7% degradation.

Same Manufacturer. Same Model Number. Different Performance.

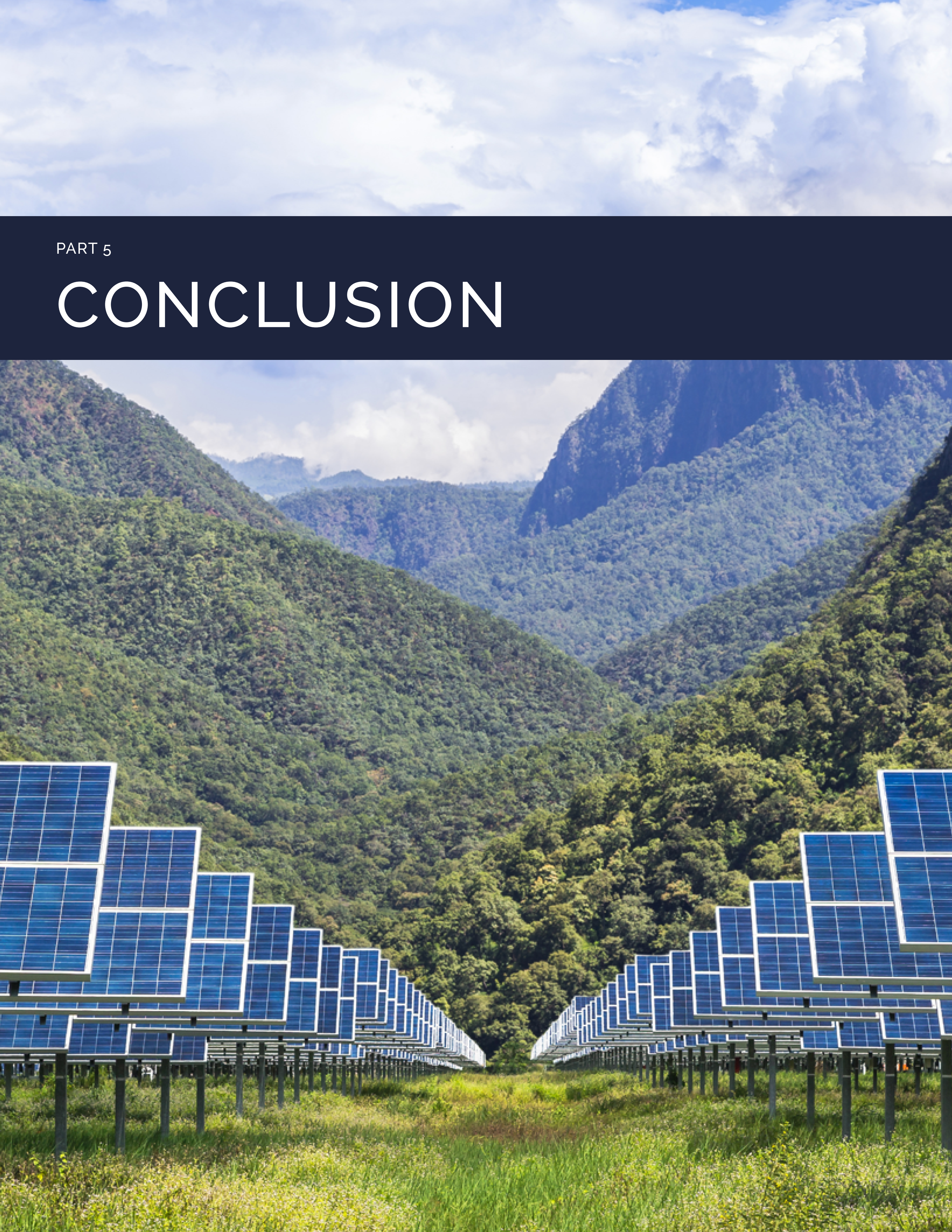
When a purchaser orders a module without specifying the BOM, the manufacturer is free to use any combination of materials that have been IEC or UL-certified for that model. One supply order could be comprised of many different BOMs that share the same model number. Some of these BOMs may have been third-party tested, some not. Module buyers and asset owners may experience differing levels of reliability and performance in the field when multiple BOMs are deployed. **Without independent testing and BOM verification, buyers cannot be certain that every module will perform as expected.**

The top performing module models named in the Scorecard represent specific, detailed BOMs that are rigorously tested in PVEL's labs. Ordering a Top Performing module model alone does not guarantee purchase of a top performing BOM. PVEL's Downstream Partners can gain access to the specific BOMs that achieved Top Performer designation. **PVEL also provides complimentary BOM exhibits to Downstream Partners for their module supply agreements. The exhibits specify the PVEL-tested BOM that must be supplied.**

Know your BOM.

PART 5

CONCLUSION



PROCUREMENT BEST PRACTICES

Asset owners expect solar power plants to generate energy safely and reliably for decades. Most PV module BOMs today have been produced for only a few years at most, which makes it challenging to understand long-term safety and reliability. Using long-term field data to verify PV module quality and forecast lifetime energy yield is not possible, especially with the rapidly evolving technology landscape.

As the data in this year's Scorecard demonstrates, even small changes in BOM combinations impact product reliability and performance. **While controlled laboratory testing can never fully replicate field conditions, it remains the most objective, comprehensive resource available for PV buyers to evaluate module quality.**

Independent testing not only supports strategic procurement and data-driven energy yield modeling, it can also be used to screen for defects in utility-scale orders that are produced over several weeks or months. Finally, by field-testing operating assets stakeholders can validate production models and quickly address any issues.

3 Steps for Risk Mitigation

1

Know Your BOM:
Product Qualification Program

Before PV module procurement:

- Review independent test data
- Evaluate the factory
- Specify BOMs in supply agreements

In addition to PQP reports, PVEL provides to Downstream Partners complimentary BOM exhibits for module supply contracts.

2

Verify Production Standards:
Statistical Batch Testing

During the production process:

- Verify specified BOM is used
- Conduct production oversight of the factory
- Test random samples from each production batch

PVEL offers BOM qualification, factory oversight and high throughput statistical batch testing services.

3

Confirm Real-World Performance:
Field Testing

Verify modules meet expectations:

- Quantify operating capacity
- Monitor and check system health
- Analyze system performance

PVEL offers on-site, daytime EL testing and advanced system performance analytics for operating assets as well as underperforming assets.

Beyond procurement:
PVEL's PQP adds value to energy simulations and bankability studies

DNV GL's energy simulations begin with default assumptions about the average performance of different PV module technologies. We use independent test data to validate our assumptions – and when necessary, update those assumptions to reflect changes in product performance. This test data is critical to ensuring the lowest uncertainties possible in estimating product and project performance.

When assessing bankability and reviewing technology, DNV GL always indicates if modules are PQP tested. Technology that is not tested independently is flagged for additional review, which can raise concerns with investors. When products have not been tested independently by a reputable lab, we lack objective proof that they will perform as expected. PVEL's PQP gives DNV GL the data our clients need to build confidence in their PV module selections.

DANA OLSON Solar Segment Leader, DNV GL - Energy

CONCLUSION

PVEL's 2019 PV Module Reliability Scorecard demonstrates that independent testing is critical as technology advances. As showcased by this year's damp heat results, new technologies such as PERC present potential risks. During PV plant operation, even when PV module warranty claims are successful, investors face financial losses due to periods of lost energy production and costs associated with labor to replace equipment, which are typically not covered by warranties. Due to the lack of long-term field data and the impact of equipment failure on project economics, **independent testing and technical due diligence are the best risk mitigation tools available to buyers today.**

Know your BOM.

Over 30% of the PQP results included in the Scorecard showed at least one failure. Changing a module's components or even the factory in which it was produced can render it more susceptible to accelerated degradation and early lifetime failure. PQP test reports provide buyers with the data they need to select BOMs that meet their quality standards. PVEL's BOM exhibits help ensure the correct materials are used in their orders. Statistical Batch Testing demonstrates manufacturing consistency. Field Testing validates that PV modules are performing as expected. **Buyers who follow PVEL's procurement best practices can mitigate procurement risks.**

Data drives returns.

Data-driven procurement strategies are the best way to protect a solar PV investment. With independent testing, buyers can invest in new technologies or more cost-effective products with greater confidence. By using empirical data in production forecasts and financial models, solar project stakeholders can optimize financing and obtain a stronger return-on-investment. Buyers can drive better returns with independent data that demonstrates performance and reliability.

PVEL's PQP is designed for the downstream.

When it comes to PV module testing, certification bodies, jurisdictional authorities, manufacturers and PV module buyers all have different priorities. PVEL develops its PQP sequences in close collaboration with our Downstream Partner network. Only a carefully designed qualification program can deliver the information that buyers need to make data-driven procurement decisions.

We provide the data that matters.

Interested in becoming a PVEL Downstream Partner?
Learn more about our PQPs and sign up online at:
pvel.com/PQPs

PV EVOLUTION LABS

Our PV Module Reliability Scorecard is just the beginning. With nearly 10 years of accumulated test data and reports, PV Evolution Labs (PVEL) is the leading independent lab for the downstream solar PV industry.

Learn more:

PVEL.COM | info@pvel.com