THE 2020 PV MODULE RELIABILITY SCORECARD

PV Evolution Labs (PVEL)

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PVEL is the Independent Lab for the Downstream Solar Market

Global

400+ downstream partners worldwide with 30+GW of annual buying power

Comprehensive

Testing for every aspect of a PV project from procurement to O&M

Experienced

Pioneered bankability testing for PV products nearly a decade ago

Market-driven

Continuously refining test programs to meet partner needs

Problem: How Does One Select Reliable PV Modules?

- **No long-term field data for current products:**
  - Large increase in new module and cell designs
- **Certification testing is insufficient:**
  - Scope limitations
  - Golden samples
  - Slow advancement
- **Challenges of warranties:**
  - Solvency and responsiveness
  - Imprecise measurement
  - Coverage limitations

Modules Tested for 2020 Scorecard

- 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)

Solution: PVEL's Module Product Qualification Program (PQP)

We launched our PQP 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.

Our Process

- All Bills of Materials (BOMs) of modules submitted to PQP testing are witnessed in production
- All BOMs of modules are tested using the same equipment and in the same environment to enable a leveled comparison.
- To date, we have tested over 360 BOMs from over 50 module manufacturers

PVEL's Module Product Qualification Program (PQP) Test Sequences

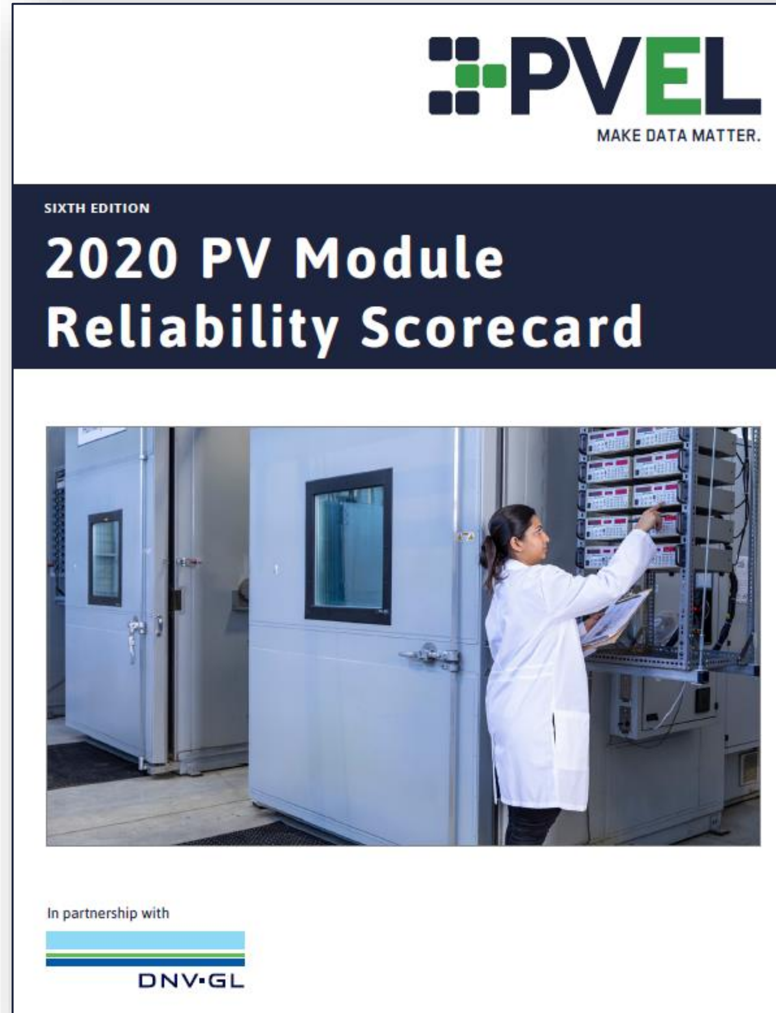
Factory Witness, Characterizations and Light-Induced Degradation Measurement

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/m^2	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/m^2	HF 10				
		Characterization	Characterization				
		TC 50 + HF 10					
		Characterization					
		UV 65 kWh/m^2					
		Characterization					
		TC 50 + HF 10					
		UV 6.5 kWh/m^2					
		Characterization					

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

PVEL’s PV Module Reliability Scorecard

www.pvel.com/pv-scorecard


PVEL
MAKE DATA MATTER.

SIXTH EDITION

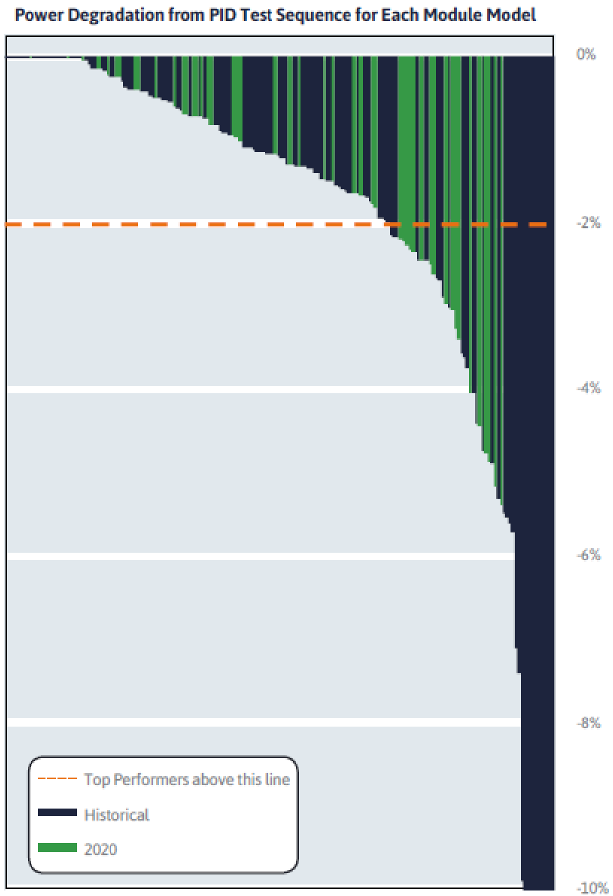
2020 PV Module Reliability Scorecard

In partnership with

DNV·GL

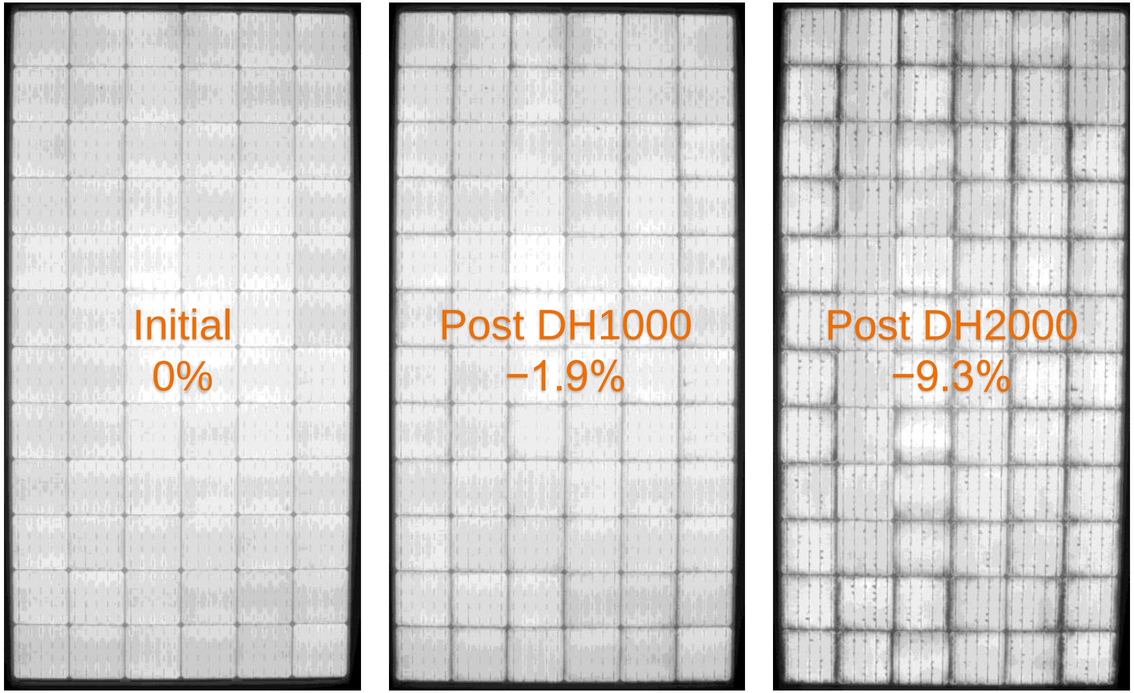
2020 Scorecard: Reliability Test Results - PID

- There were many PID Top Performers, yet susceptibility to this degradation mode remains a concern.
- Median PID degradation result was higher for this Scorecard than at any time in PVEL's 10-year history.
- **PID is not a "solved problem."**



2020 Scorecard: Reliability Test Results – Damp Heat

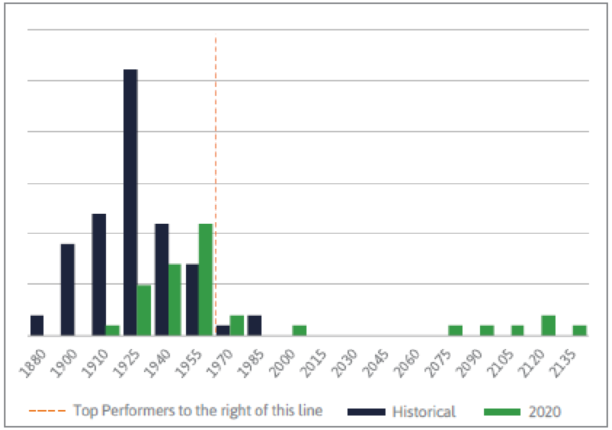
› Damp heat issues persist, with up to >9% degradation.



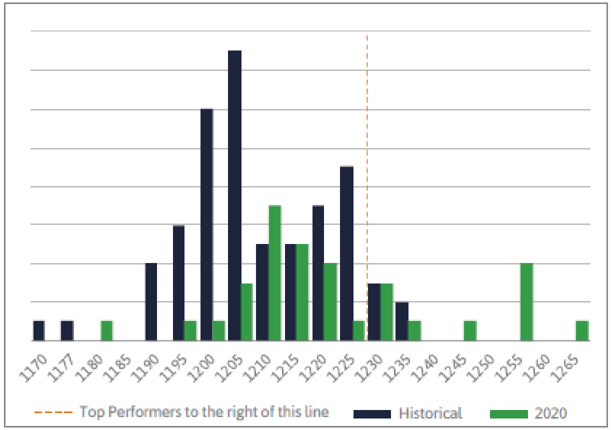
2020 Scorecard: PAN Performance

- **2020 is the first Scorecard with Top Performers for PAN performance.**
- Each PVEL PAN report includes two site simulations:
  - A 1 MW site in a temperate climate (Boston, USA)
  - A 1 MW site in a desert climate (Las Vegas, USA)
- Top Performers had at least one simulation that resulted in a kWh/kWp energy yield within the top quartile of all eligible results.

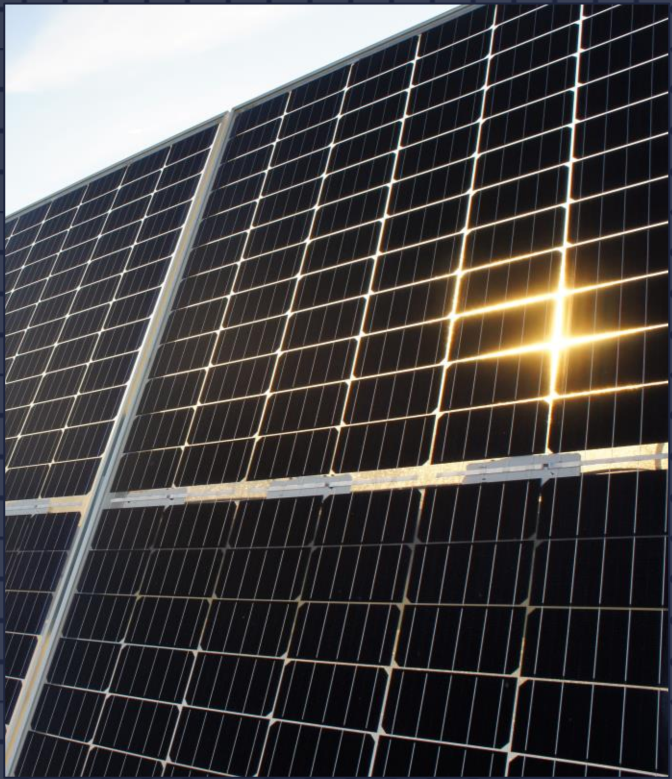
kWh/kWp for 1 MW project in Las Vegas, USA



kWh/kWp for 1 MW project in Boston, USA



2020 Scorecard: Bifacial Results



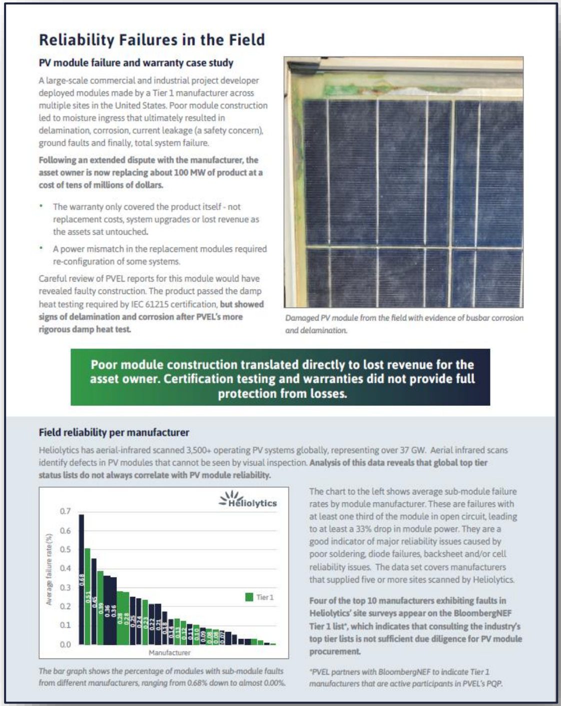
- **26% of eligible BOMs were bifacial.**
- Bifacial modules dominated the PAN Top Performers.
- TC – strong performance for bifacial BOMs, both for front-side and rear-side degradation.
- DH – similar results for glass-glass and glass-backsheet.
- DML – range of results, like monofacial modules; over 20 bifacial BOMs queued for MSS.
- PID – up to 30% rear-side degradation after PID testing.

2020 Scorecard: Failures

- **20% of eligible BOMs had at least one failure.**
- The highest amount of failures were safety-related from wet leakage testing.
- One in five manufacturers tested for the 2020 Scorecard period experienced at least one junction box-related failure.


2020 Scorecard: Case Studies

Field Issues



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, 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.**

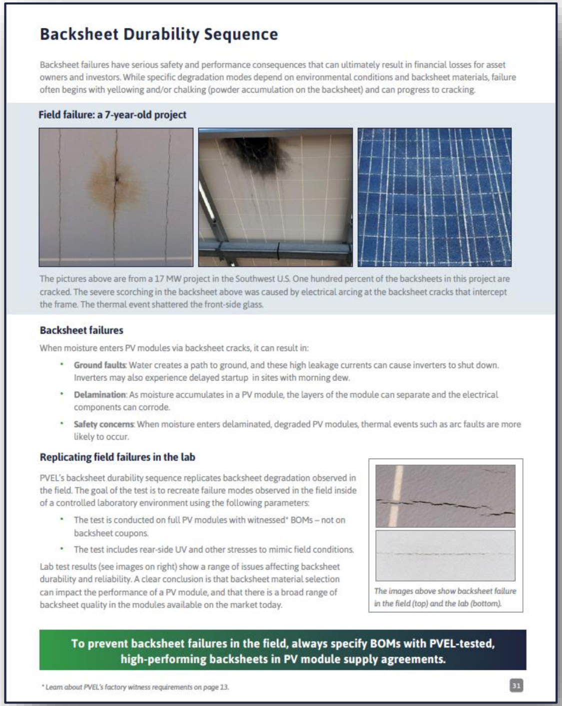
The bar graph shows the percentage of modules with sub-module faults from different manufacturers, ranging from 0.68% down to almost 0.00%.

The chart to the left shows average sub-module failure rates by module manufacturer. These are failures with at least one third of the module in open 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.*

Backsheets



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 7-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

PVEL's backsheet durability sequence replicates backsheet degradation observed 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.
- 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.*

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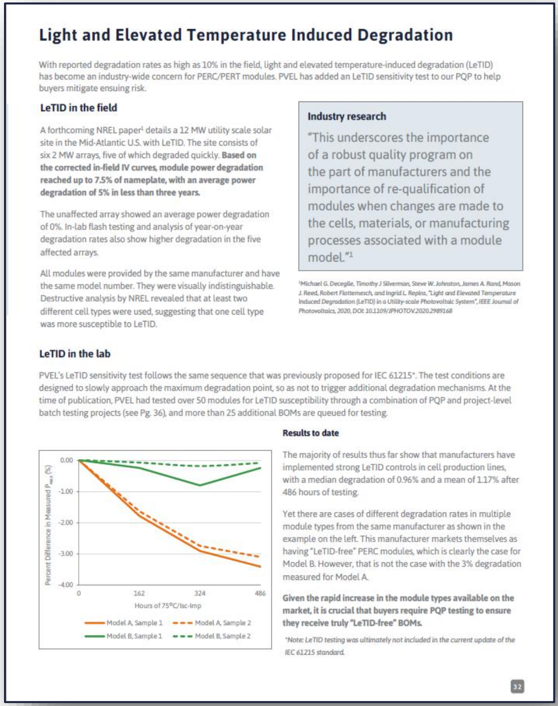
LeTID



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.*

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2020: Historical Scorecard

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

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

Best Practices for PV Module Procurement & Quality Management

Vendor Selection

PVEL Product Qualification Programs (PQPs)

- Validate product reliability and performance
- Provide modeling inputs (ie: PAN, IAM, LeTID)
- Include BOM exhibits for supply agreements

Pre-production factory audits

- Evaluate factory QA/QC processes

1. Know the product.

Project-level Manufacturing

Production oversight

- Verifies use of correct BOM and QA/QC processes

PV module batch testing

- Assesses LeTID susceptibility
- Validates performance
- Identifies serial defects

Inverter factory acceptance testing

- Verifies use of correct BOM
- Checks performance and reliability

2. Trust the process.

Installation and Commissioning

Project acceptance testing

- Quantifies operating capacity
- Analyzes system performance

Field EL imaging

- Ensures minimal damage and cell cracks for EPC hand-off
- Provides baseline data for future insurance claims
- Monitors system health when conducted periodically

3. Verify performance.

THANK YOU

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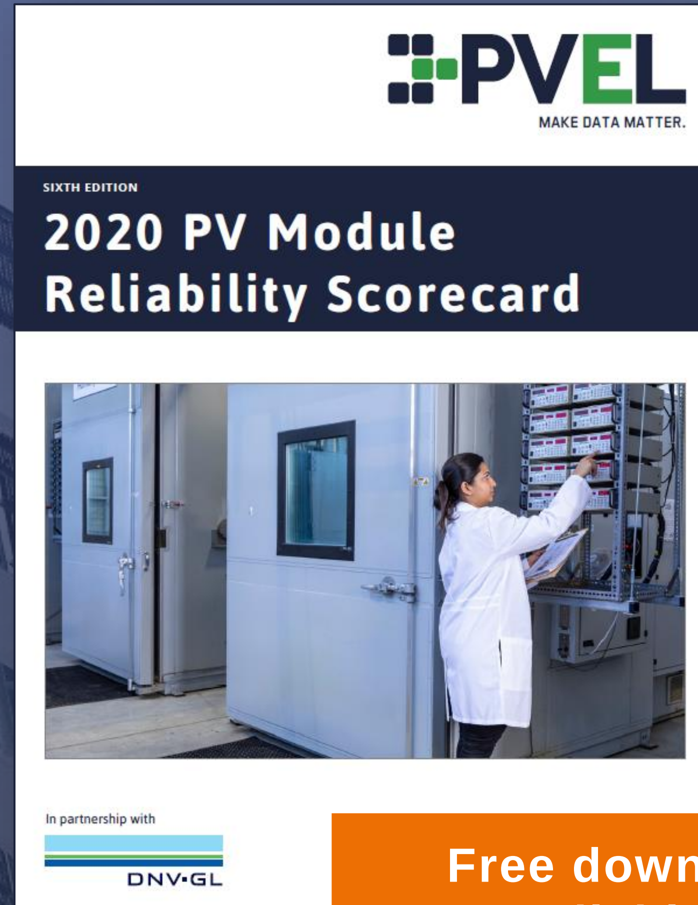
May 28, 2020



Free download available at pvel.com

Analysis of Historical PQP Module Test Data & Extending Useful Life

Dana Olson, PhD

Global Solar Segment Leader

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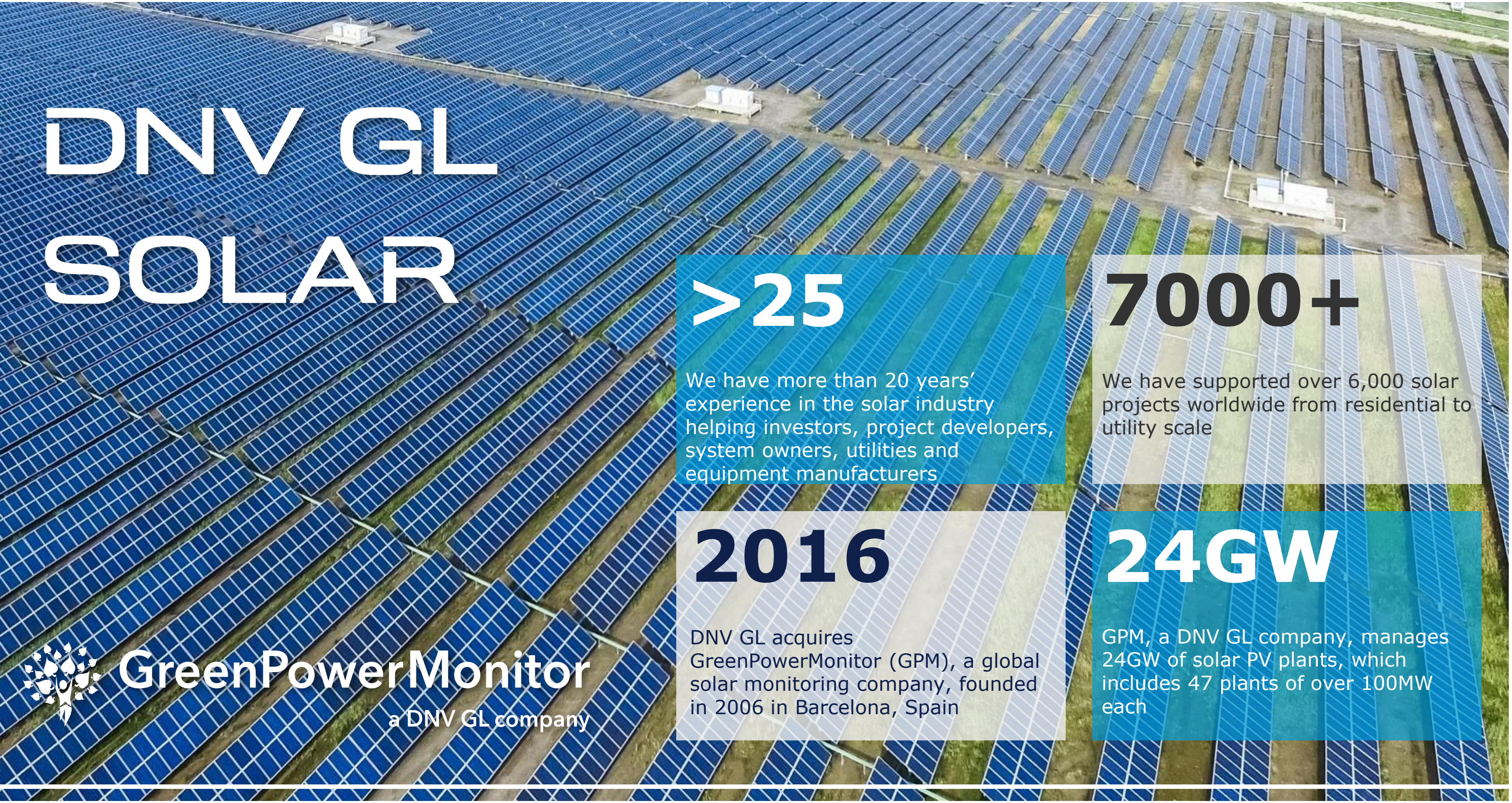
SAFER, SMARTER, GREENER



DNV GL SOLAR

>25

We have more than 20 years' experience in the solar industry helping investors, project developers, system owners, utilities and equipment manufacturers

7000+

We have supported over 6,000 solar projects worldwide from residential to utility scale

2016

DNV GL acquires GreenPowerMonitor (GPM), a global solar monitoring company, founded in 2006 in Barcelona, Spain

24GW

GPM, a DNV GL company, manages 24GW of solar PV plants, which includes 47 plants of over 100MW each

GreenPowerMonitor
a DNV GL company

*Our testing, certification and advisory services are independent from each other

DNV·GL

DNV GL – Global Expertise Across Solar PV Project Lifecycle

FEASIBILITY

- Feasibility studies
- Market & regulatory intelligence
- Utility grid integration and interconnection studies
- Environmental permitting
- Siting, technology selection, and use case modelling
- Technology & controls review and verification

TESTING

- Component technology reviews & qualification testing
- Type and component certification of PV inverters
- Battery fire safety
- Controls validation testing & development
- Battery, PV module, and inverter life estimations

ENGINEERING & DEVELOPMENT

- Owner’s Engineering: Design review and optimization
- Battery cell, module, power electronics performance testing
- Technical Specifications
- Bid selection and EPC contracting support
- Energy assessment
- Interconnection support

CONSTRUCTION & COMMISSIONING

- Independent engineering
- Degradation and warranty support
- Construction oversight
- System testing and inspection
- Grid code compliance
- Module batch testing
- Site and Factory Acceptance Tests

OPERATION

- Performance validation
- Resource and energy forecasting
- Existing asset consulting, inspections and decommissioning
- Refinancing and mergers and acquisitions advisory services
- Forensic investigations
- Monitoring, control and asset management

*Our testing, certification and advisory services are independent from each other

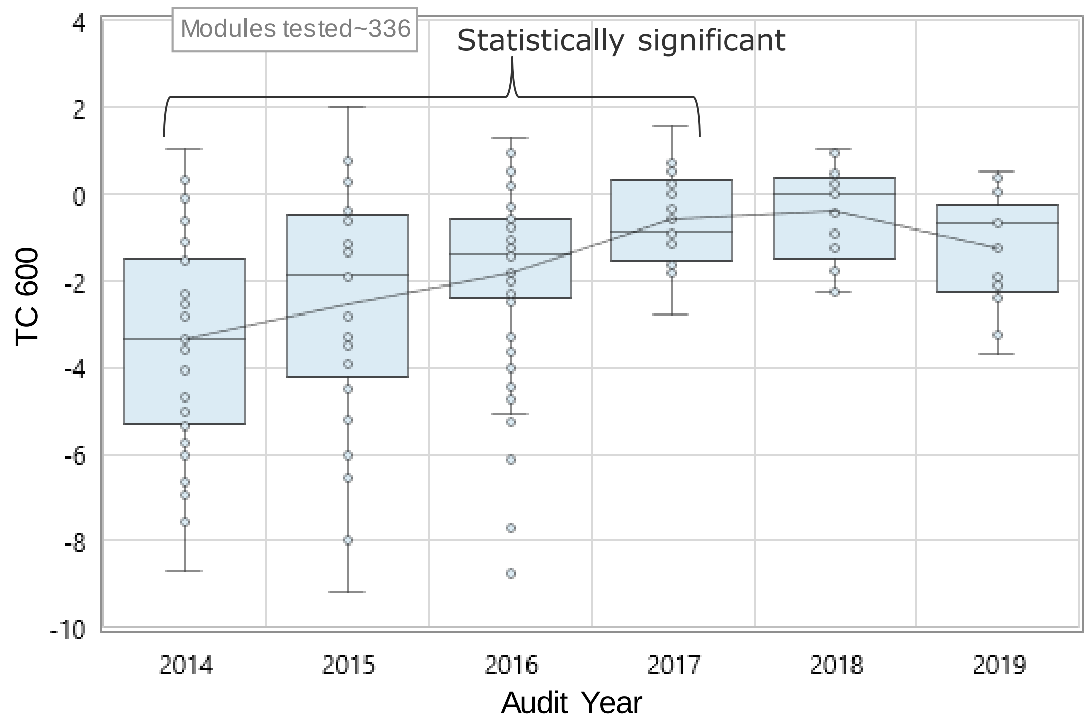
GreenPowerMonitor
a DNV GL company

Trends in PQP Tests 2014-2019 Results

- 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
  - Statistically significant trends demonstrate a $p<0.05$
- All data analysis by:
  - Henry Hieslmair, Ph.D.
  - Principle Engineer, Solar Technoloy, DNV GL

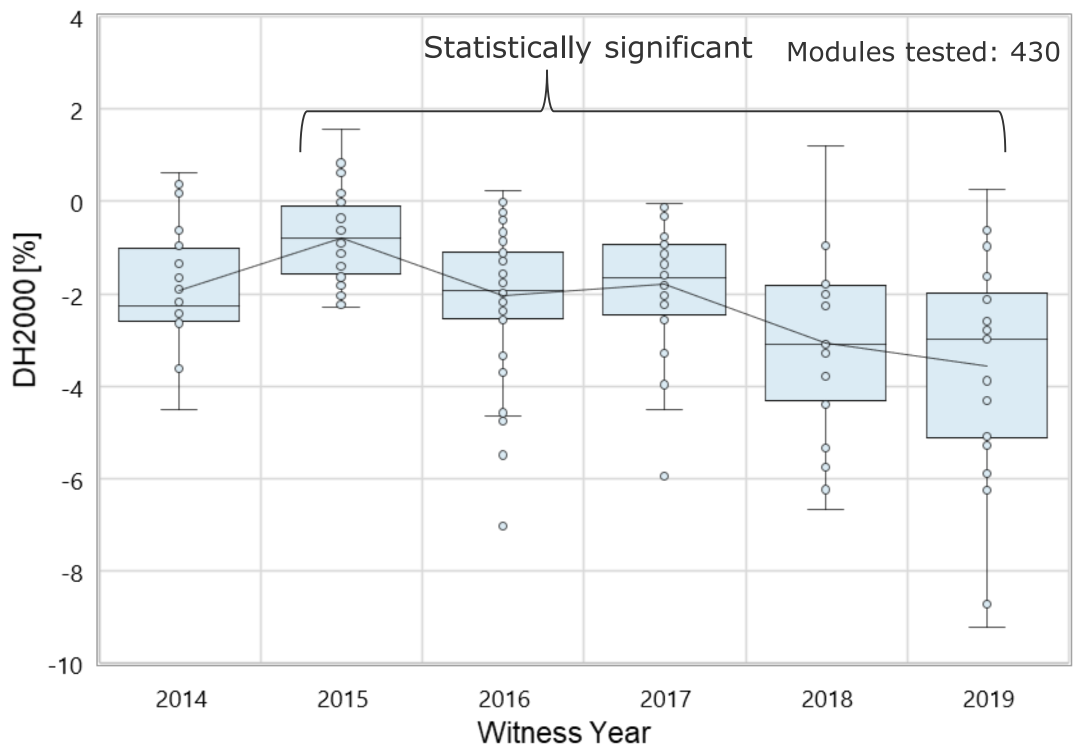
Trends in Thermal Cycling – TC600

- TC600 results improved 2014 to 2017
- Plateau with little degradation after 2017
- This improvement may be explained by:
  - Transition to monocrystalline cells
  - Increased number of busbars
  - Thicker encapsulants



Trends in Damp Heat – DH2000

- Damp heat 2000 results indicate a deteriorating trend since 2015
- This may be due to the adoption of PERC cells which may require the additional boron-oxygen LID stabilization step following DH2000
  - As highlighted in the 2020 Scorecard
- Alternatively, may reflect utilization of non-fluoropolymer backsheets or thinner screen-printed fingers, which may be more sensitive to corrosion via moisture ingress.



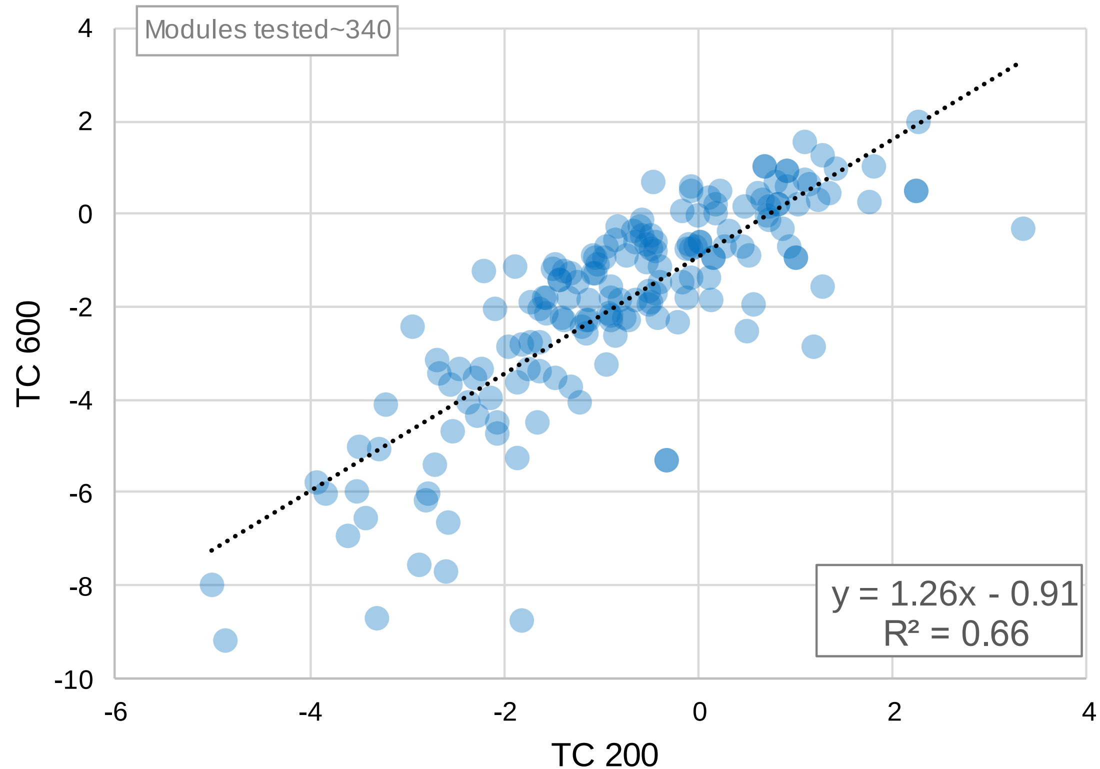
Ideal Test Duration

- 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.

DNV·GL

Ideal Test Duration – TC 600 vs. TC 200

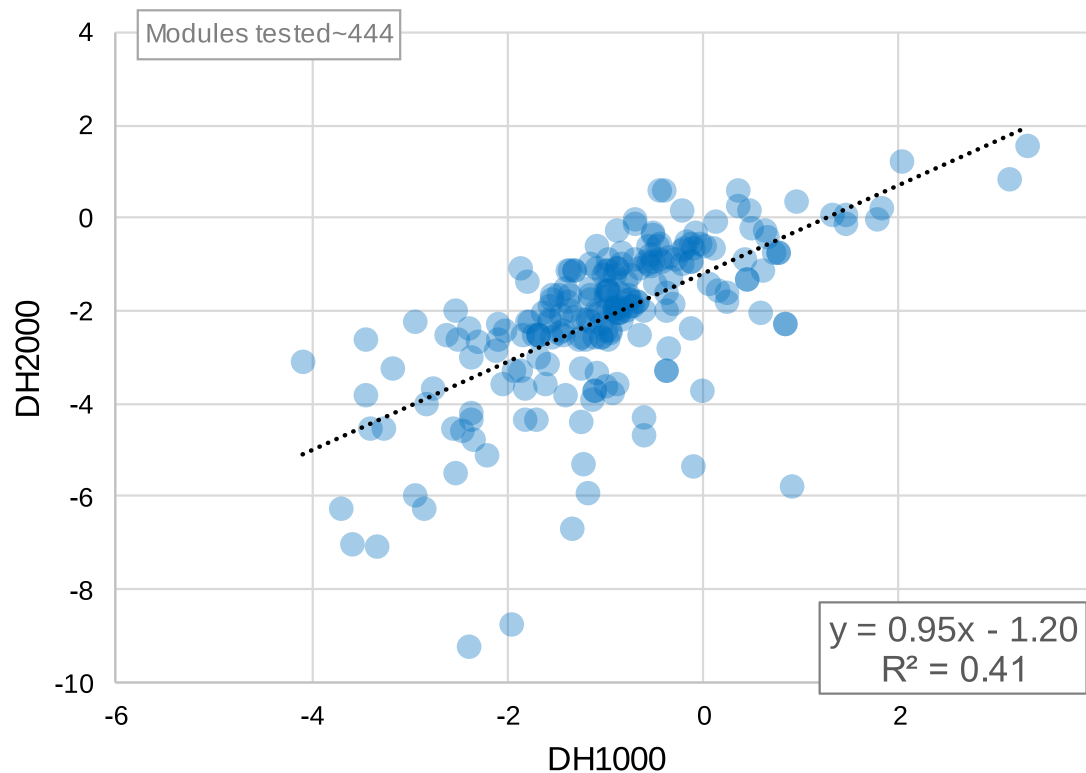
- Thermal cycling test
- Correlation between 200 cycles and 600 cycles indicates no new mechanisms introduced by the 600 cycle test
  - Data show stopping at 200 cycles might be premature
- Reviewing the historical 600 cycle and 800 cycle
  - Correlation indicates that TC600 is a sufficient test duration with very good agreement



Ideal Test Duration – DH2000 vs. DH1000

- The damp heat correlation between 1000 hours and 2000 hours
  – 1000 hours is not adequate substitute for 2000 hours

- While the historical correlation between 2000 and 3000 hours indicates that less relevant failure mechanisms may be introduced at 3000 hours
  – The data shows that 2000 hours is optimal



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

- Extending system life beyond 25 years

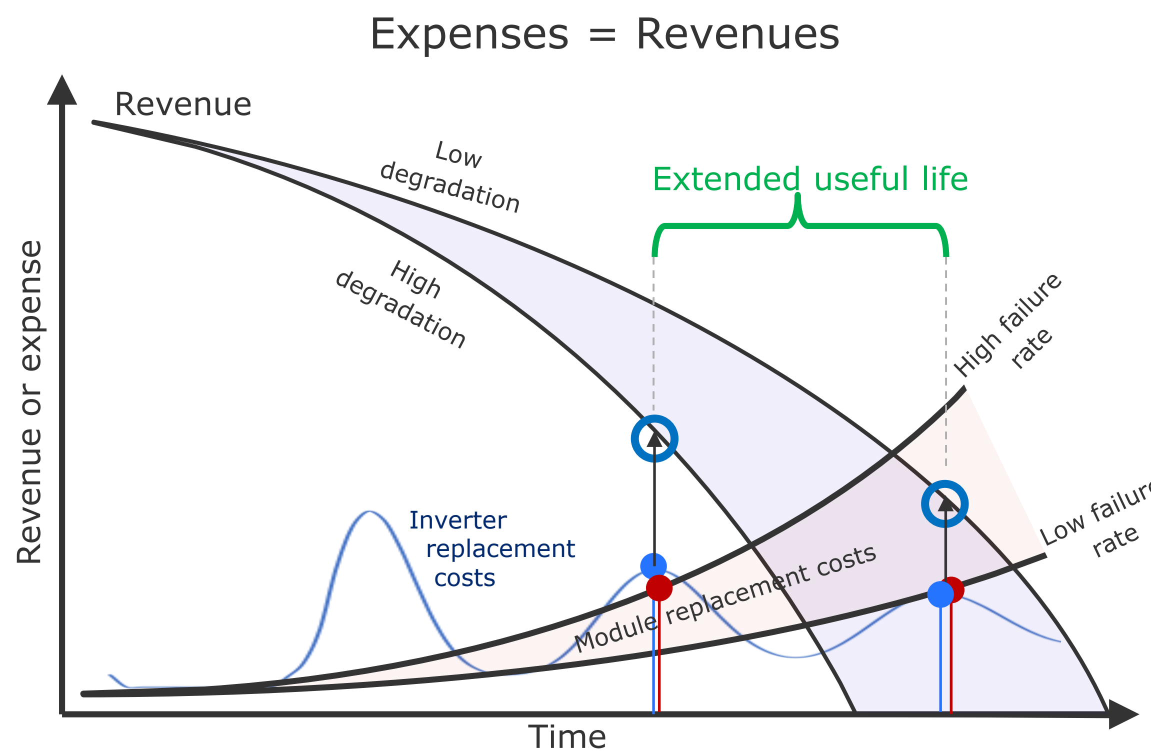
- DNV GL determines the module useful life by considering the failure rate of the module
  - Where failure is defined as a significant drop in module power in a short period of time
  - Causes could include PID, corrosion, failed backsheets, etc.

Useful Life Assessments

- Extending the useful life to 30-40 years
  - Lower levelized cost of electricity (LCOE) by 16-20%
  - Increase asset value

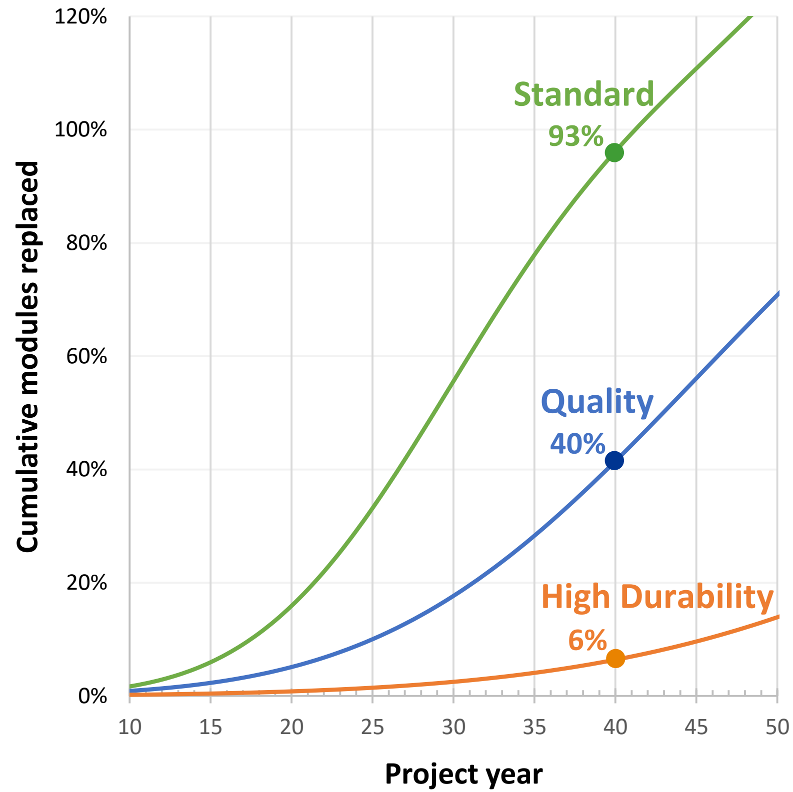
- However, system components require quality improvement and/or replacement over time

- Components and systems would need to demonstrate low failures and/or degradation rates



Module Classification and Impact on Useful Life

- DNV GL has developed a three-tier module classification:
  - Standard, Quality, and High Durability
  - With associated failure rates and replacement schedules
- PVEL's PQP enables module classifications through an extensive suite of accelerated stress tests
- Additional classifications considerations include:
  - Factory audit reports
  - Detailed BOM review
  - Historical field data
- Targeting a system life of 40 years would entail almost all of the Standard modules to be replaced
- Only 40% and 6% of the Quality and High Durability modules would be replaced, respectively.

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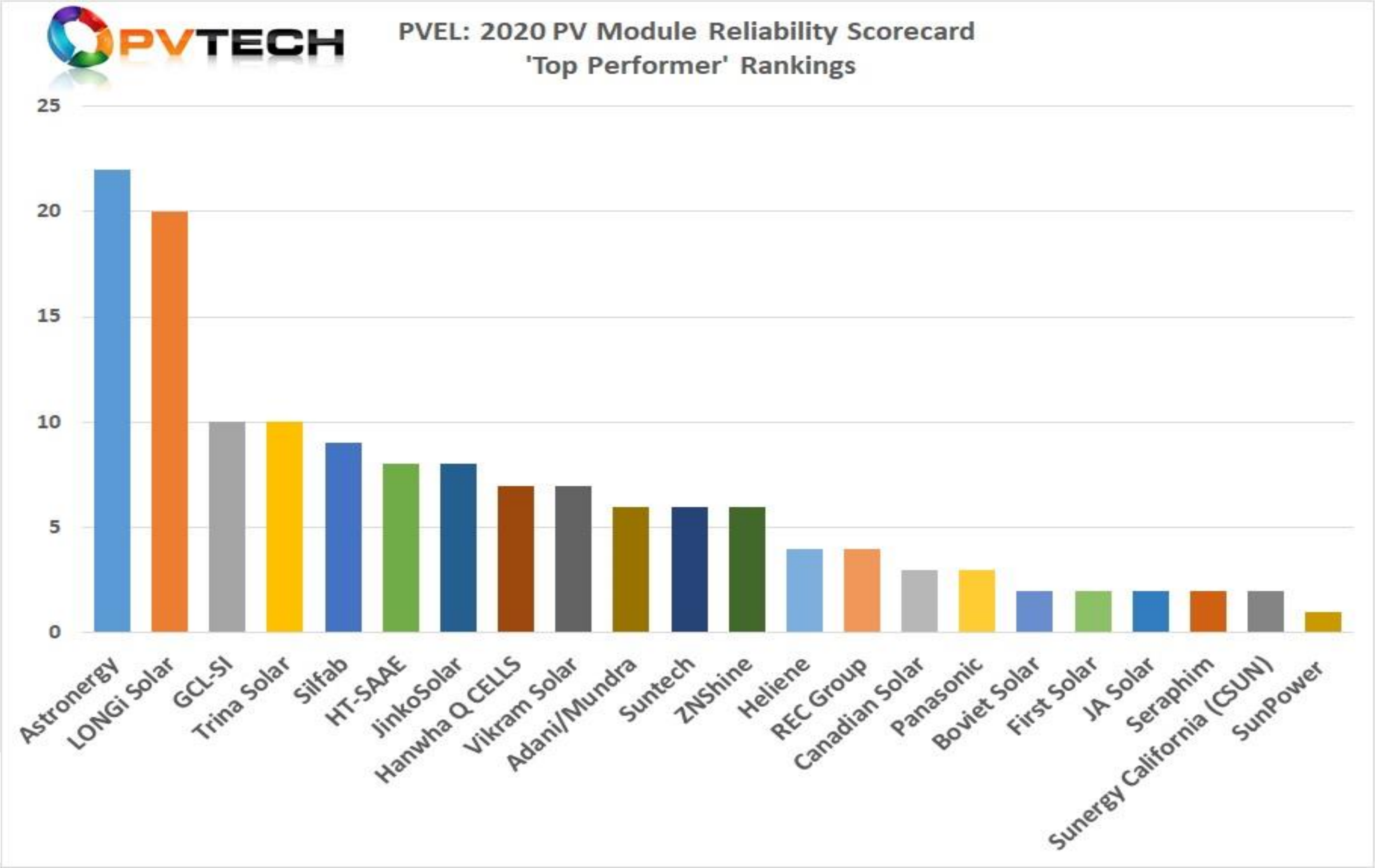
PVEL 2020 PV MODULE RELIABILITY SCORECARD ANALYSIS



PVEL 2020 PV MODULE RELIABILITY SCORECARD ANALYSIS

Module Manufacturer	Top Performer Status Total	Top Performer Status Different Modules
Astronergy	22	6
LONGi Solar	20	13
GCL-SI	10	8
Trina Solar	10	6
Silfab	9	3
HT-SAAE	8	4
JinkoSolar	8	4
Hanwha Q CELLS	7	4
Vikram Solar	7	4
Adani/Mundra	6	2
Suntech	6	2
ZNShine	6	2
Heliene	4	2
REC Group	4	1
Canadian Solar	3	1
Panasonic	3	1
Boviet Solar	2	2
First Solar	2	1
JA Solar	2	2
Seraphim	2	2
Sunergy (CSUN)	2	2
SunPower	1	1

PVTECH

PVEL 2020 PV MODULE RELIABILITY SCORECARD ANALYSIS

PV Module Manufacturer	1.Thermal Cycling	2.Damp Heat	3.Dynamic Mechanical Load (DML)	4.Potential-Induced Degradation (PID)	5.PAN File
Astronergy	CHSM72P-HC-xxx	CHSM72P-HC-xxx	CHSM72P-HC-xxx	CHSM72P-HC-xxx	
Astronergy	CHSM60P-HC-xxx	CHSM60P-HC-xxx	CHSM60P-HC-xxx	CHSM60P-HC-xxx	
Astronergy	CHSM72M(DG)-B-xxx	CHSM72M(DG)-B-xxx	CHSM72M(DG)-B-xxx	CHSM72M(DG)-B-xxx	CHSM72M(DG)-B-xxx
Astronergy	CHSM60M (DG)-B-xxx	CHSM60M (DG)-B-xxx	CHSM60M (DG)-B-xxx	CHSM60M (DG)-B-xxx	CHSM60M (DG)-B-xxx
Silfab	SLGxxxM	SLGxxxM	SLGxxxM	SLGxxxM	
Silfab	SLAxxxM	SLAxxxM	SLAxxxM	SLAxxxM	
LONGi Solar	LR6-72PH-xxxM	LR6-72PH-xxxM	LR6-72PH-xxxM	LR6-72PH-xxxM	
REC Group	RECxxxTP2M	RECxxxTP2M	RECxxxTP2M	RECxxxTP2M	

PVTECH

PVEL 2020 PV MODULE RELIABILITY SCORECARD ANALYSIS

Dynamic Mechanical Load (DML) Test

- **Smallest number of PV module manufacturers achieving 'Top Performer' score (8)**
- **Glass-glass and glass-backsheet bifacial modules show similar performance results following the DML test**
- **DML test indicates the potential susceptibility to microcrack issues**
- **DML+TC50+HF30 test has been replaced by a new mechanical stress sequence (MSS).**
- **PVEL plans to release a separate publication featuring MSS results in the coming months.**