Reliability Failures in the Field

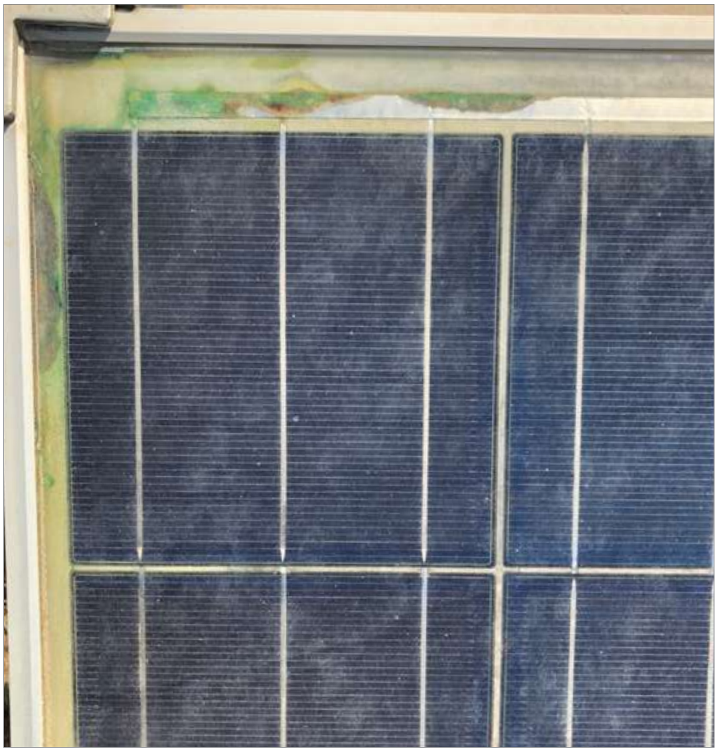
PV module failure and warranty case study

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.**

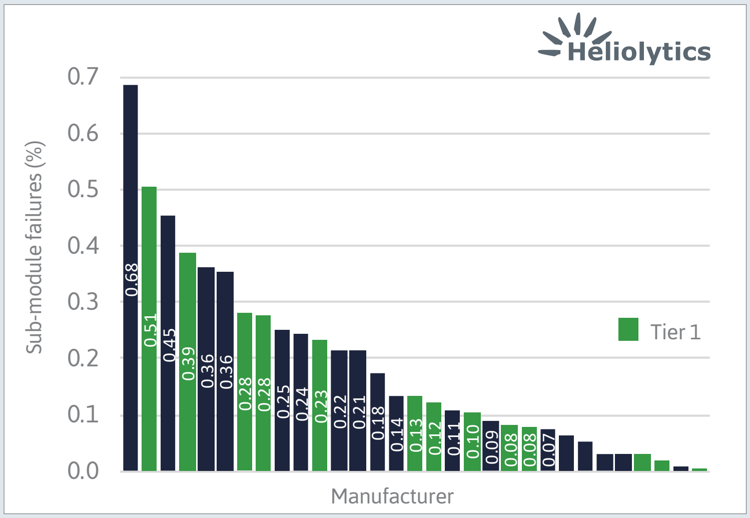


Damaged PV module from the field with evidence of busbar corrosion and delamination.

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.

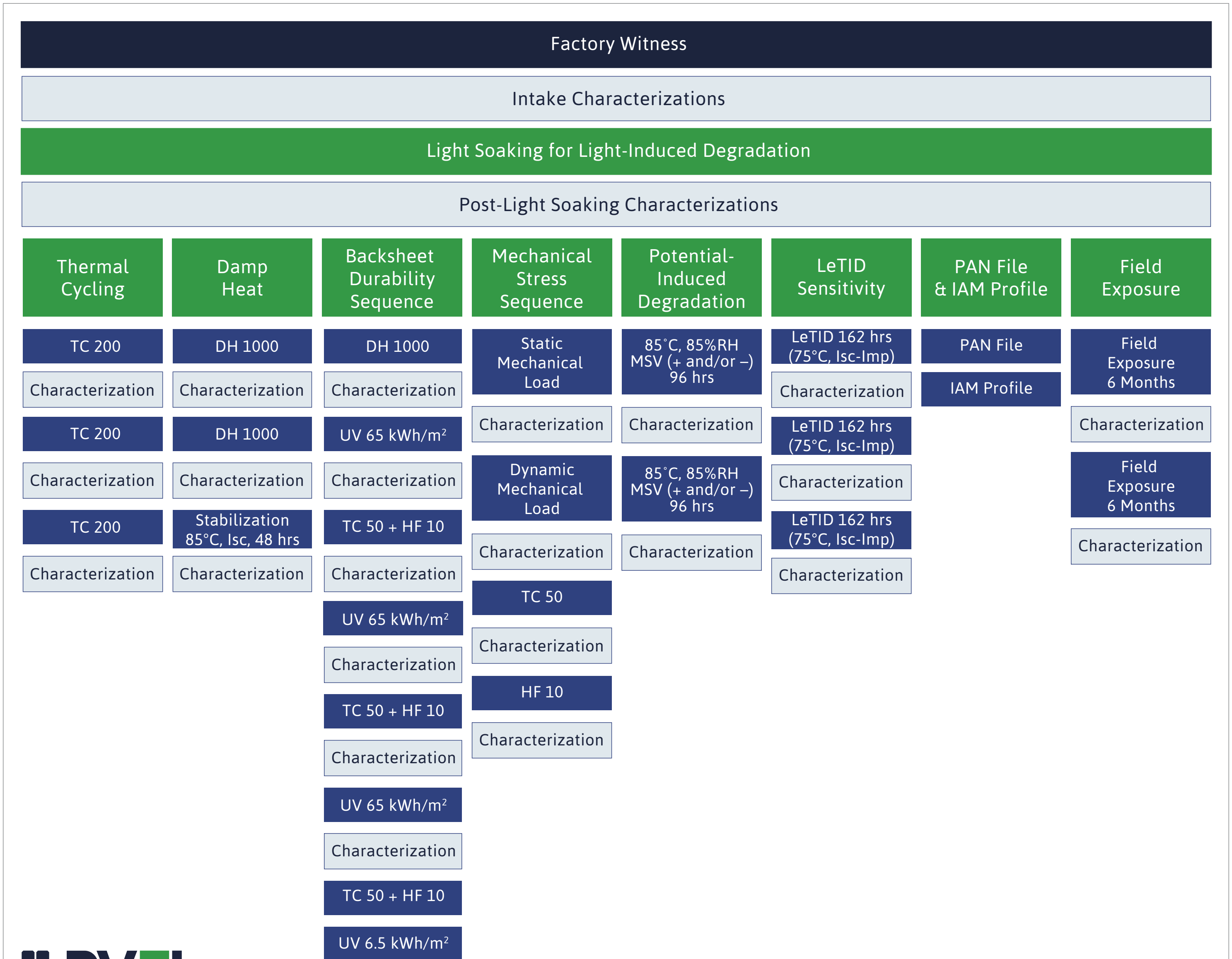
PV module buyers can ensure they receive the exact BOM combination that performed well in PQP testing by using exhibits to specify approved BOMs in their supply agreements. Free of charge, PVEL provides buyers with detailed BOM listings for inclusion in supply agreements.

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.



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

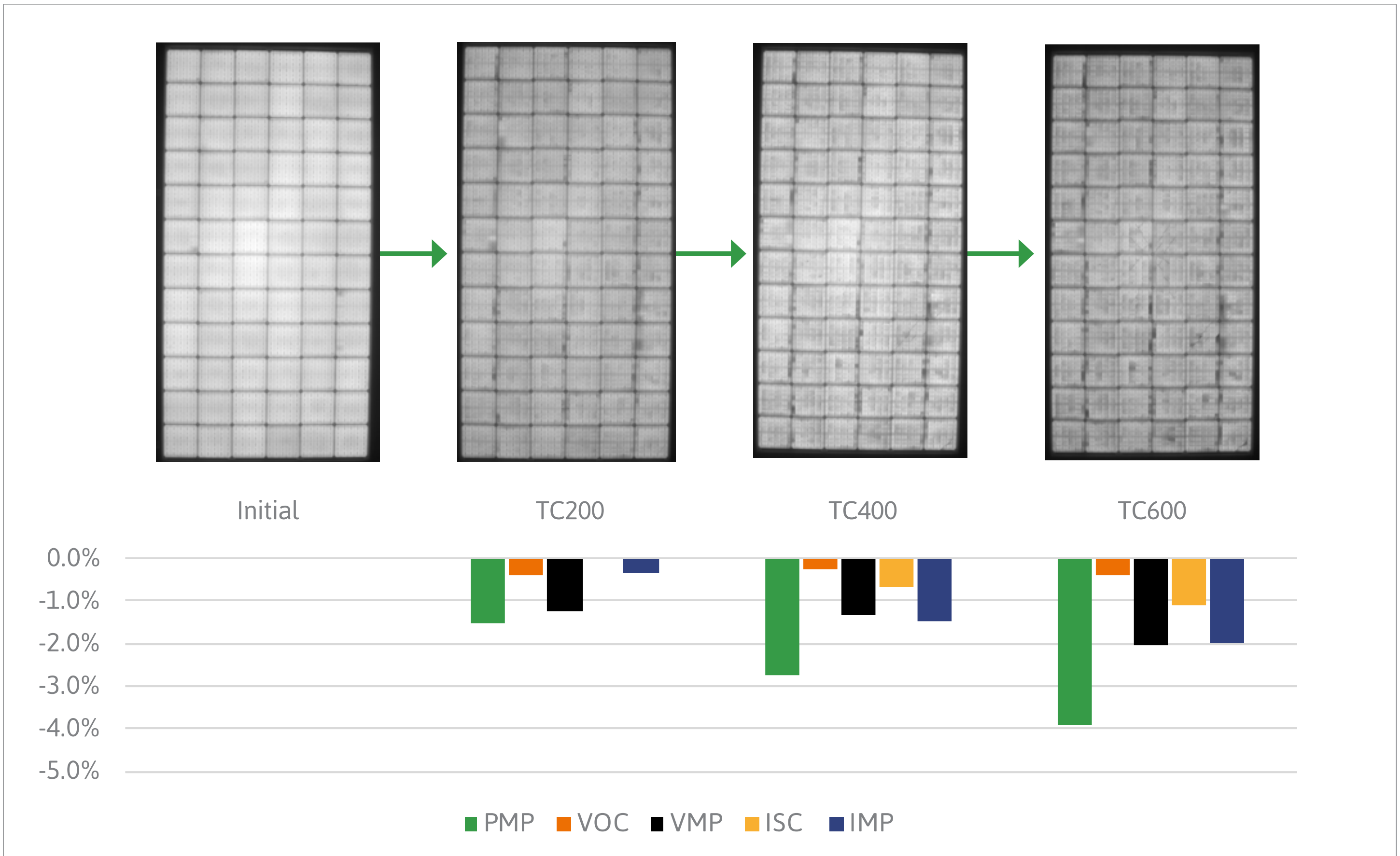
As ambient temperatures change, the components in fielded PV modules expand and contract depending on the level of heat or cold. The components have different thermal expansion coefficients, so they can expand and contract at different rates in the same environmental conditions. This results in a thermomechanical 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.

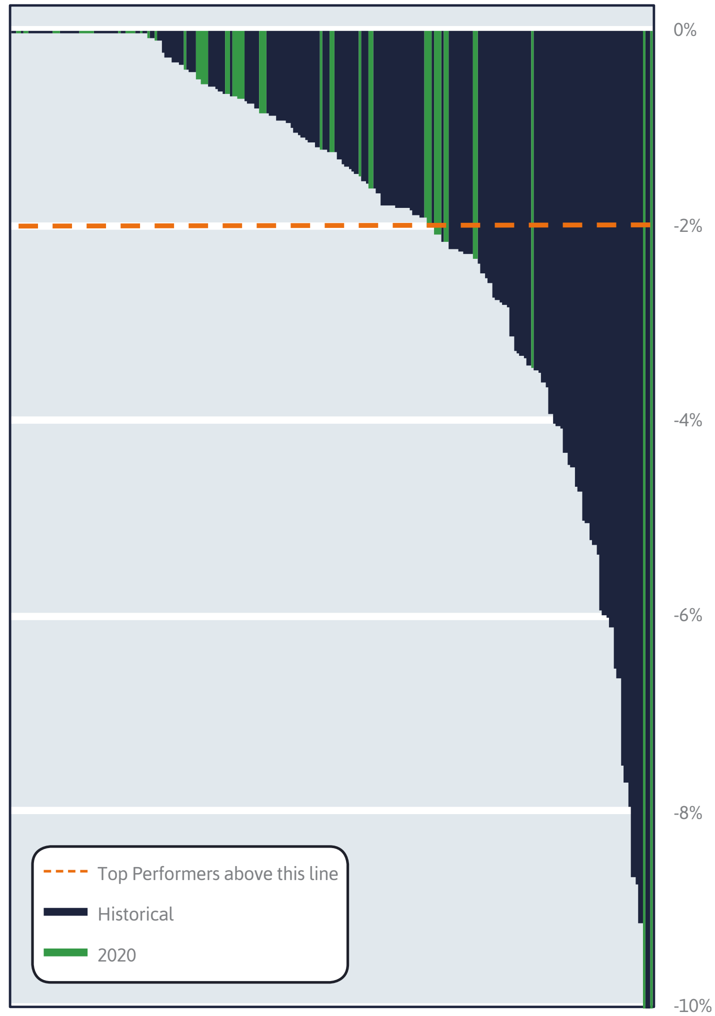
Thermal cycling procedure

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 / CHSM60-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.