2023 PV Module Reliability Scorecard

EXECUTIVE SUMMARY

The 9th Edition of PVEL's PV Module Reliability Scorecard features Top Performers from 35 manufacturers and is the solar industry's essential resource for PV module reliability and performance insights.

Welcome to

PVEL's 2023 Scorecard Executive Summary

Over the last year the solar industry has experienced unprecedented growth, and some significant challenges, as PV module demand and production have exploded across the globe. In 2023, Bloomberg New Energy Finance forecasts that we will surpass 300 GW of solar deployments globally. At this scale of project development and investment, understanding how to procure high-performing, reliable modules has never been more critical. As module buyers seek the guidance they need to navigate the latest technology trends and new market entrants, we are pleased to share with you the 9th Edition of PVEL's PV Module Reliability Scorecard.

Over 35,000 unique users from more than 100 countries leveraged the 2022 Scorecard data to make better purchasing decisions and mitigate risk in their module procurement process. This year's report will build off of that success with more manufacturers and module models listed as Top Performers than ever before.

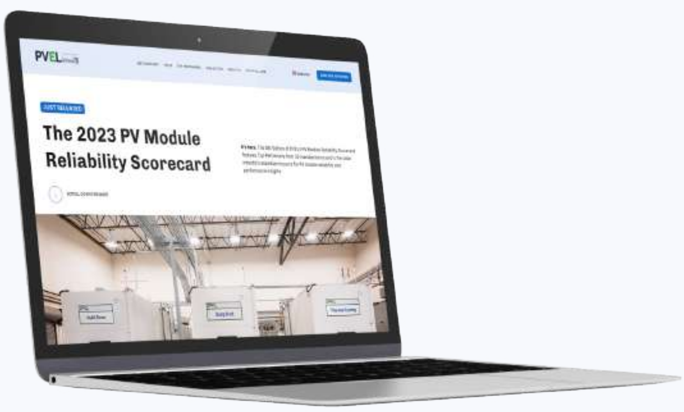
Executive Summary Contents

This Executive Summary offers readers a quick overview of PVEL's Product Qualification Program (PQP) methodology, tests and Scorecard scoring. Key takeaways from each of the highlighted PQP tests are also included, many of which focus on comparing glass//glass and glass//backsheet, results for different cell technologies, and insights into failures that occurred for that specific test. The Historical Scorecard is also presented, showing all of the 2023 Top Performer manufacturers and their history of Scorecard appearances.

Scorecard Website Contents

scorecard.pvel.com provides much more than the Executive Summary, including:

- A searchable database of Top Performer model types, which can be filtered by PQP test, manufacturer name, module power class, and more. Search results are exportable as CSV files.
- Go inside a PV module and see which materials impact which tests.
- Case studies from the field related to each PQP test.
- Test procedures, graphs of yearly results and test result spotlights.
- Data and insights on PQP failures.



Methodology

PVEL's approach to testing and benchmarking PV module reliability has been our key focus for more than a decade. The PQP results enables data-driven solar procurement and investments for developers, financiers, and asset owners.

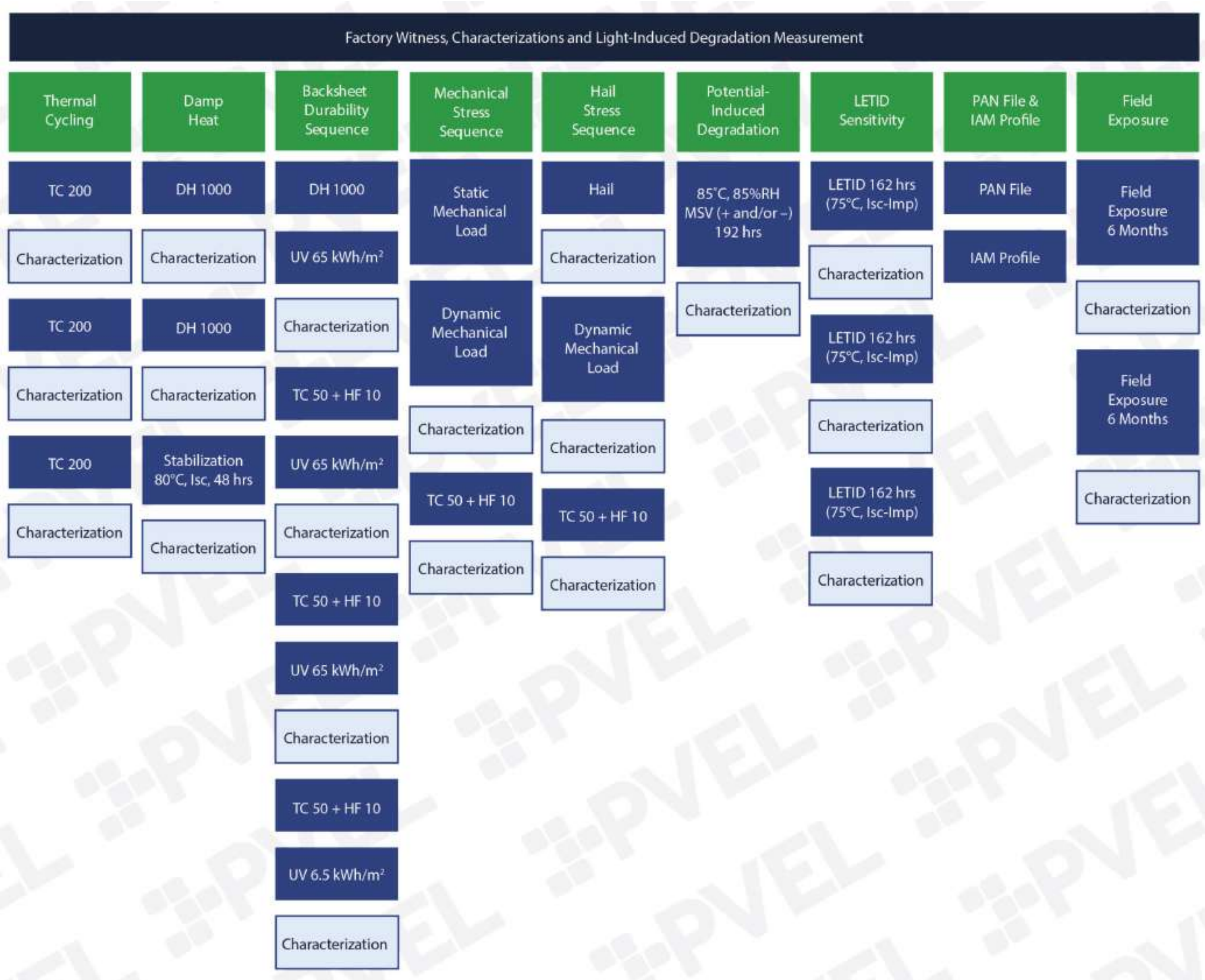
Why BOM-Level Testing is Important
PV modules with the exact same model type can be manufactured from completely different bills of materials (BOMs). PVEL's test results from the lab and field demonstrate that individual PV module components can dramatically affect product quality. Suppliers are free to mix-and-match integral materials – even cells – as long as all the components are listed in the manufacturer's IEC certification report. PVEL's extended testing results have repeatedly shown that IEC certification testing is not sufficient to differentiate levels of long-term module reliability for project investors.

How BOMs are Scored
To be eligible for the Scorecard, manufacturers must have:

- Completed the PQP sample production factory witness within 18 months of 2023, and
- Submitted at least two factory-witnessed PV module samples to all PQP reliability tests, as per PVEL's BOM test requirements.

The 2023 PV Module Reliability Scorecard shows Top Performers for six PQP test categories. Top Performers in each of the reliability tests appearing in the Scorecard must have < 2% power degradation following the particular test, a consistent Top Performer threshold since the 2018 Scorecard. For that reliability test they must not have experienced a wet leakage failure, a 'major' defect during visual inspection, or a diode failure. PAN Performance Top Performers must place in the top quartile for energy yield in PVEL's PVsyst simulations.

PVEL's PV Module PQP



2023 Top Performers - Key Takeaways

1. 250 Top Performer module types from, 35 manufacturers, including eight manufacturers new to the Scorecard.
2. Modules tested for the 2023 Scorecard were manufactured in 12 countries by module manufacturers with worldwide sales.
3. 11 manufacturers had one or more model types that are Top Performers in every reliability test (TC, DH, MSS, PID and LID+LETID).
4. 37 TOPCon model types are listed as Top Performers, up from just one in 2022. Nine HJT model types are also included this year, up from two last year.

Thermal Cycling

PVEL's Thermal Cycling (TC) test assesses a PV module's ability to endure changes in temperature. While ambient temperatures vary daily and seasonally in most solar markets, top-performing TC results are most critical in locations where temperatures are much lower at night than during the day, typically the very places that have high solar resource.

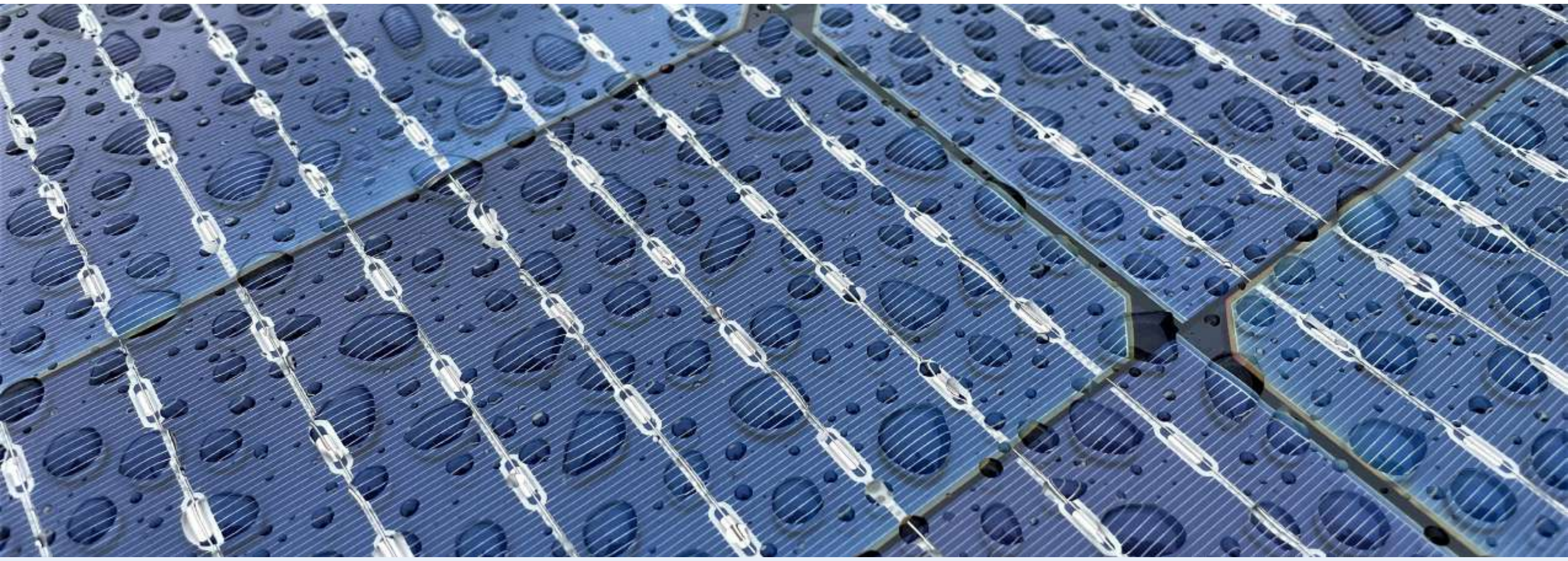
Key Takeaways

1. 84% of BOMs tested degraded by < 2% after TC600, with a median degradation of 1.0%; however, this is an increase in degradation from the 0.7% median reported in the 2022 Scorecard.
2. Glass//glass performed better than glass//backsheet with a 0.5% median degradation for glass//glass versus 1.8% for glass//backsheet.
3. TC results for PERC and TOPCon were generally aligned with low degradation. Meanwhile, the necessary low-temperature soldering for HJT modules remains a challenge for some.
4. Almost 12% of BOMs experienced one or more failures during TC testing, including failed diodes, melted connectors, exposed wires and no output due to open solder bonds in the junction box.

Go to scorecard.pvel.com/TC to see test procedure, field case study, Top Performers, and more.

Damp Heat

PVEL's Damp Heat (DH) test simulates long-term degradation and failure modes that are typical in high temperatures and high humidity conditions where moisture and heat can weaken the materials binding the PV module together. When the adhesiveness of these materials weakens due to low-quality components and/or substandard lamination processes, moisture can enter the laminate and corrode internal materials. The result is potential performance loss and safety issues.



Key Takeaways

1. **DH results showed a notable improvement, with 72% of BOMs exhibiting less than 2% degradation versus only 50% in the 2022 Scorecard.**

2. **Glass//glass outperformed glass//backsheet with 1.0% median degradation for glass//glass versus 1.9% for glass//backsheet.**

3. **No technology-specific outliers were seen in DH results. Average degradation was 1.2 to 1.7% across CdTe, HJT, PERC and TOPCon.**

4. **DH-related power loss failures dropped to zero following 4% of BOMs having a DH-related power loss failure in the 2022 Scorecard.**

Go to scorecard.pvel.com/DH to see test procedure, field case study, Top Performers, and more.

Mechanical Stress Sequence

PVEL's Mechanical Stress Sequence (MSS) has two primary objectives: determining whether cells in PV modules are vulnerable to cracking and determining if cell damage is likely to cause power loss in the field. Strong MSS results are most important for project locations with extreme weather events and conditions, including heavy snow and high winds.

Key Takeaways

1. **Multi-busbar (9BB or greater) results in less opportunity for inactive areas to form across cracked cells, leading to the lowest average and median MSS degradation rates in PVEL's history.**
2. **With cells in the neutral plan, no glass//glass module experienced cell-level damage following MSS, resulting in lower average and median power loss than glass//backsheet modules.**
3. **During load testing the glass in glass//glass modules was over twice as likely to break than forglass//backsheet modules.**
4. **While PVEL reports the best ever MSS results when modules were mounted using traditional two-rail mounting, some modules experienced breakage during load testing when tracker-mounted.**

Go to scorecard.pvel.com/MSS to see test procedure, field case study, Top Performers, and more.

Potential-Induced Degradation

Potential-induced degradation (PID) is triggered by high PV system voltages on ungrounded installations. PID is more likely to occur in projects that use transformerless inverters, and is further accelerated by high-temperature and high-humidity environments. While PID is sometimes reversible, severe and permanent PID can lower energy yield by as much as 30%.

Key Takeaways

1. **79% of BOMs tested were PID Top Performers, but 5% of BOMs had over 5% power loss.**
2. **The average and median degradation rates for glass//glass and glass//backsheet BOMs were indistinguishable.**
3. **PVEL also saw very strong PID results for CdTe. PERC, HJT and TOPCon median degradation all ranged from 1.1 to 1.6%.**
4. **Four manufacturers experienced higher than expected PID power loss. In one case, a change in encapsulant changed the PID power loss from less than 1% to almost 4.5%.**

Go to scorecard.pvel.com/PID to see test procedure, field case study, Top Performers, and more.

LID + LETID

Light-induced degradation (LID) and light-and-elevated temperature-induced degradation (LETID) are cell-based phenomena triggered by light exposure that are often incorporated in energy yield models. LID rates vary by cell technology and typically stabilize within a few days or weeks of field operation. LETID mainly affects PERC cells and may be an unintended consequence of certain LID-reduction techniques applied in manufacturing. LETID is most severe in hot climates.

Key Takeaways

1. **97% of BOMs tested had less than 2% power loss. LID + LETID results had a 0.8% median and 0.7% average, with 71% of BOMs having less than 1% degradation after LID and LETID.**

2. **100% of PERC BOMs in the 2023 Scorecard test population were doped with gallium, with a 0.7% median and average degradation following LID and LETID.**

3. **The average LID + LETID power loss across CdTe, n-type TOPCon and n-type HJT BOMs was 0.0% and the median was 0.2%.**

4. **Placing modules outdoors for light-soaking during LID testing led to a surprising amount of failures including power labels peeling off and junction box lids dislodging.**

Go to scorecard.pvel.com/LID-LETID to see test procedure, field case study, Top Performers, and more.

PAN Performance

PVEL's PAN files simulate PV module performance in different temperature and irradiance conditions and are essential data inputs for energy models. Using empirical performance data improves energy yield forecast accuracy for all projects, but it is most impactful for high-temperature or low-irradiance conditions that may be poorly represented by default performance assumptions.

Key Takeaways

1. **With the higher energy yields of TOPCon and HJT, the top quartile specific energy yield threshold was raised by a relative 0.8% over the 2022 PAN Top Performer threshold.**

2. **Every bifacial TOPCon and bifacial HJT module completing PAN testing in time for 2023 Scorecard inclusion was a PAN Top Performer due to higher bifaciality and better temperature coefficients.**

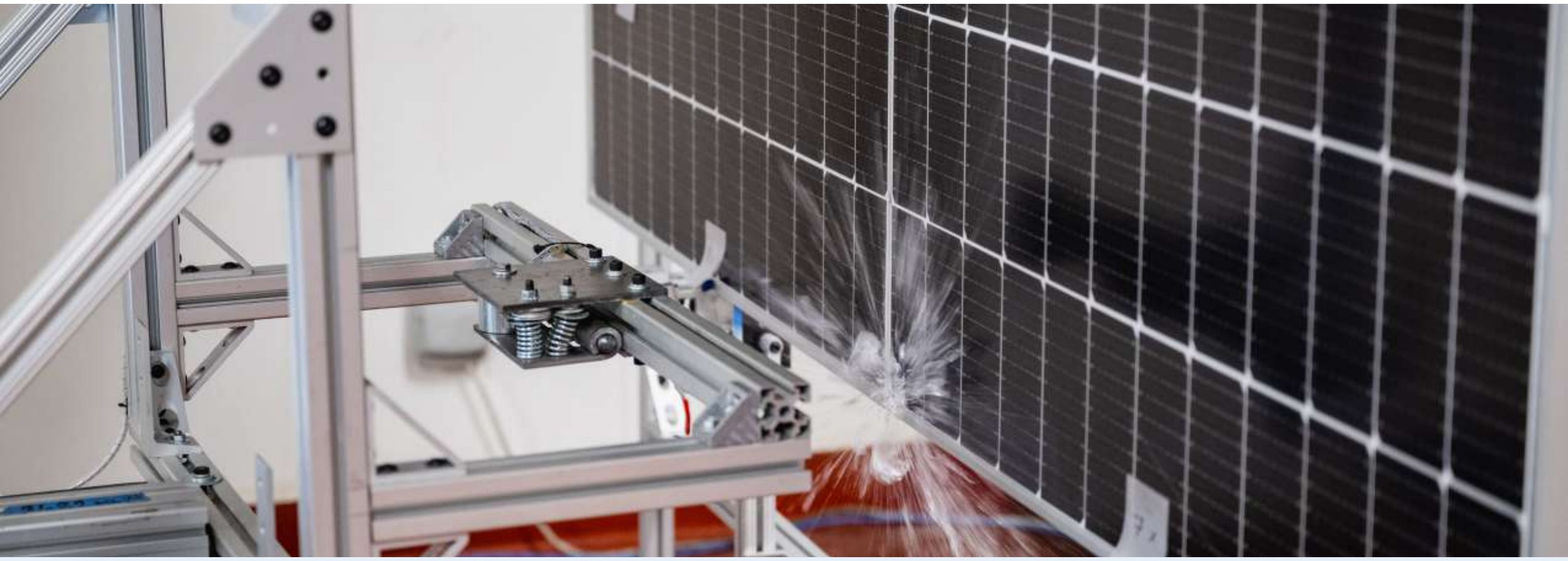
3. **Across the 2023 Scorecard test population, the median Pmax temperature coefficient was –0.26%/°C for HJT, –0.30 %/°C for TOPCon, and –0.33 %/°C for PERC.**

4. **Thus far there is no correlation to any crystalline cell technology having substantially better low light performance than others.**

Go to scorecard.pvel.com/PAN to see test procedure, field case study, Top Performers, and more.

Hail Stress Sequence

PVEL's Hail Stress Sequence (HSS) subjects modules to the equivalent impact energy of extreme natural hail and simulates post-hail impact field conditions to assess potential power loss. Strong performance in hail testing is important for projects deployed to hail-prone regions. HSS results allow PV module buyers to benchmark the hail resistance of different PV modules.



Key Takeaways

1. **During 50 mm hail testing, 89% of 2.0 mm glass//glass modules experienced broken glass compared to 39% for 3.2 mm glass//backsheet modules.**

2. **For both glass//glass and glass//backsheet modules, the first impact directed at a module corner yielded the highest breakage rate.**

3. **The glass//glass breakage rate decreased to 57% with 40 mm hail and 18% with 35 mm hail.**

4. **While very important for some locations, many regions do not experience extreme hail. As such PVEL is not naming Top Performers in the HSS category.**

Go to scorecard.pvel.com/HSS to see test procedure, field case study, and more.

Backsheet Durability Sequence

PVEL's Backsheet Durability Sequence (BDS) assesses vital reliability risks for backsheets including yellowing and polymer cracking. While backsheet cracking is certainly more concerning, yellowing can be a sign of material degradation that may ultimately lead to backsheet failure in extreme cases. UV exposure is the primary driver of polymer degradation, so backsheet durability is most important in high irradiance and high albedo conditions.

Key Takeaways

1. **PVEL's historic BDS testing has not revealed any backsheets that have suffered from backsheet cracks. This covers backsheets with a range of outer layer materials including coatings, PVF, PVDF and PET films.**

2. **These BDS results represent less than half of the 130 backsheets available on the market according to ENF's solar backsheet directory.**

3. **While no cracking has been observed, PVEL has detected wet leakage/electrical insulation failures during BDS that were traced to the junction boxes.**

4. **Legacy and perhaps newer modules continue to experience backsheet cracks in the field. Repairs are often the suggested remedy, the reliability of which remains unclear.**

Go to scorecard.pvel.com/BDS to see test procedure, field case study, and more.

Historical Scorecard

The table below shows the history of top performance for all manufacturers featured in the 2023 Scorecard. Manufacturers are listed by the number of years they have been designated a Top Performer, in alphabetical order.

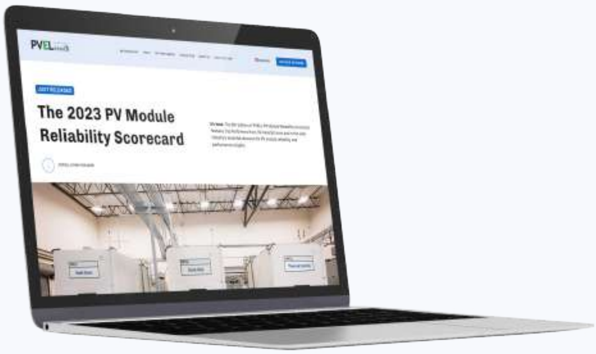
	2023	2022	2021	2020	2019	2018	2017	2016	2014
Jinko	•	•	•	•	•	•	•	•	•
Trina Solar	•	•	•	•	•	•	•	•	•
JA Solar	•	•	•	•	•	•		•	•
Qcells	•	•	•	•	•	•	•	•	
REC Group	•	•	•	•	•	•	•	•	
Astronergy	•	•	•	•		•	•		•
Adani Solar	•	•	•	•	•	•			
Maxeon	•	•	•	•		•	•		
Phono Solar	•	•	•		•	•		•	
Vikram Solar	•	•	•	•	•		•		
Boviet Solar	•	•	•	•	•				
First Solar	•	•	•	•		•			
HT-SAAE	•	•	•	•		•			
Silfab Solar	•		•	•	•		•		
Yingli Solar	•					•	•	•	•
ZNShine Solar	•	•		•	•			•	
Talesun	•	•	•				•		
DMEGC Solar	•	•	•						
ET Solar	•	•	•						
Heliene	•	•		•					
HD Hyundai	•		•				•		
Risen Energy	•	•	•						
VSUN	•	•	•						
Canadian Solar	•			•					
Jolywood	•		•						
SEG Solar	•	•							
Waaree	•	•							
AE Solar	•								
Aiko Solar	•								
Akcome	•								
EGing PV	•								
Emmvee	•								
Huasun	•								
Premier Energies	•								
SolarSpace	•								

Go to scorecard.pvel.com/top-performers to see the list of Top Performer model types.

Go Online for More!

Go to scorecard.pvel.com to access:

- A searchable database of Top Performer model types, which can be filtered by PQP test, manufacturer name, module power class, and more. Search results are exportable as CSV files.
- Go inside a PV module and see which materials impact which tests.
- Case studies from the field related to each PQP test.
- Test procedures, graphs of yearly results and test result spotlights.
- Data and insights on PQP failures.
- Kiwa's best practices for module procurement.



About PVEL

PVEL, a member of the Kiwa Group, is the leading reliability and performance testing lab for downstream solar project developers, financiers, and asset owners around the world. For over a decade, PVEL's flagship Product Qualification Program has replaced assumptions about PV module performance with quantifiable metrics, and connected manufacturers with a global network of 400+ downstream partners. Learn how PVEL makes data matter though PQP testing, field services and market intelligence at pvel.com.

About the Kiwa Group

Kiwa, PV Evolution Labs (PVEL) and PI Berlin have joined forces to offer world class expertise in laboratory testing, material and manufacturing oversight to create trust in the performance, reliability, and safety of your investment. The Kiwa Group offers a comprehensive portfolio of quality assurance, testing, inspection and certification services for the solar industry. We support investors, developers, EPC contractors and asset managers, while also helping manufacturers demonstrate compliance to the requirements of numerous markets. To learn more, visit www.kiwa.com/solar.

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