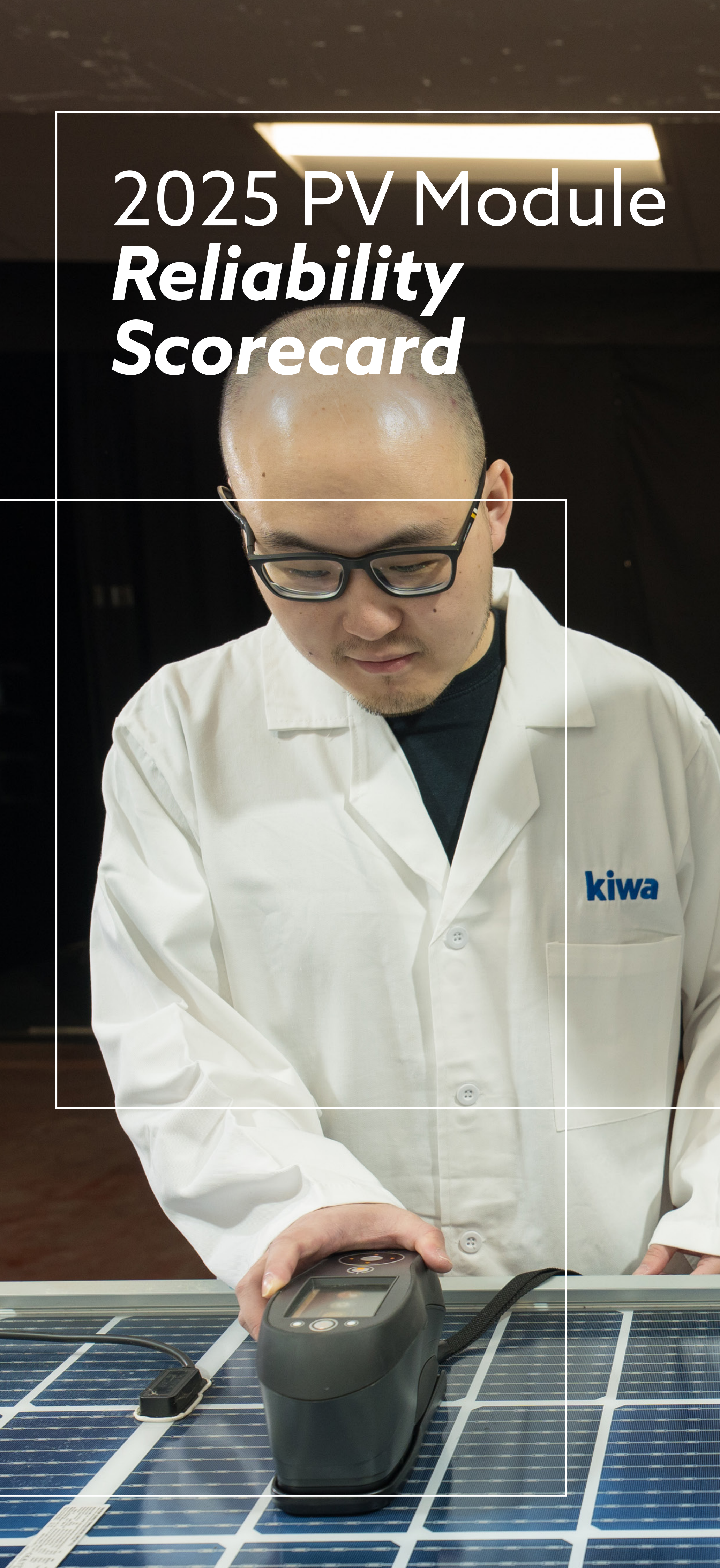
2025 PV Module ***Reliability Scorecard***



Executive Summary

Welcome to the 11th Edition of Kiwa PVEL's PV Module Reliability Scorecard, ***featuring the latest insights in module reliability*** and ***performance and this year's list of Top Performers.***

kiwa

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Welcome to Kiwa PVEL's 2025 scorecard ***executive summary***

Kiwa PVEL's Product Qualification Program (PQP) and Scorecard are the global solar industry's trusted resources for PV module reliability and performance data. In this 11th edition of the Scorecard, Kiwa PVEL is proud to showcase a broad range of Top Performer manufacturers and module model types.

The 2025 Scorecard also provide several exciting updates, such as refreshed Key Takeaways and Test Result Spotlights with new insights on the industry's hottest reliability topics, including module breakage, UVID, and n-type reliability and performance.

As always, the Scorecard provides important insights, but managing the complexities of module procurement requires careful consideration. Reviewing the full PQP test reports and specifying top performing BOMs are critical aspects of Kiwa Solar's procurement best practices. Achieve more informed and effective module sourcing by becoming a Kiwa PVEL Premium Partner. Learn more at kiwa.com/pvel/ppp

Executive Summary Contents

This Executive Summary offers readers a brief overview of Kiwa PVEL's Product Qualification Program (PQP) methodology, tests and Scorecard scoring. Key takeaways from each of the PQP tests are also included, which provide an overview of the latest test findings and trends. The Historical Scorecard is also presented, showing all of the 2025 Top Performer manufacturers and their history of Scorecard appearances, as well as the Top Performers Per Test table showing for which tests each manufacturer achieved Top Performer status.

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.
- Test result spotlights for each test, highlighting a recent finding or trend.
- Graphs of yearly power degradation for most tests and additional details on key takeaways.
- Pages dedicated to all sections shown in the executive summary.
- Direct links to test-specific pages on kiwa.com for field case studies, test procedures and more.

2025 scorecard ***key takeaways***

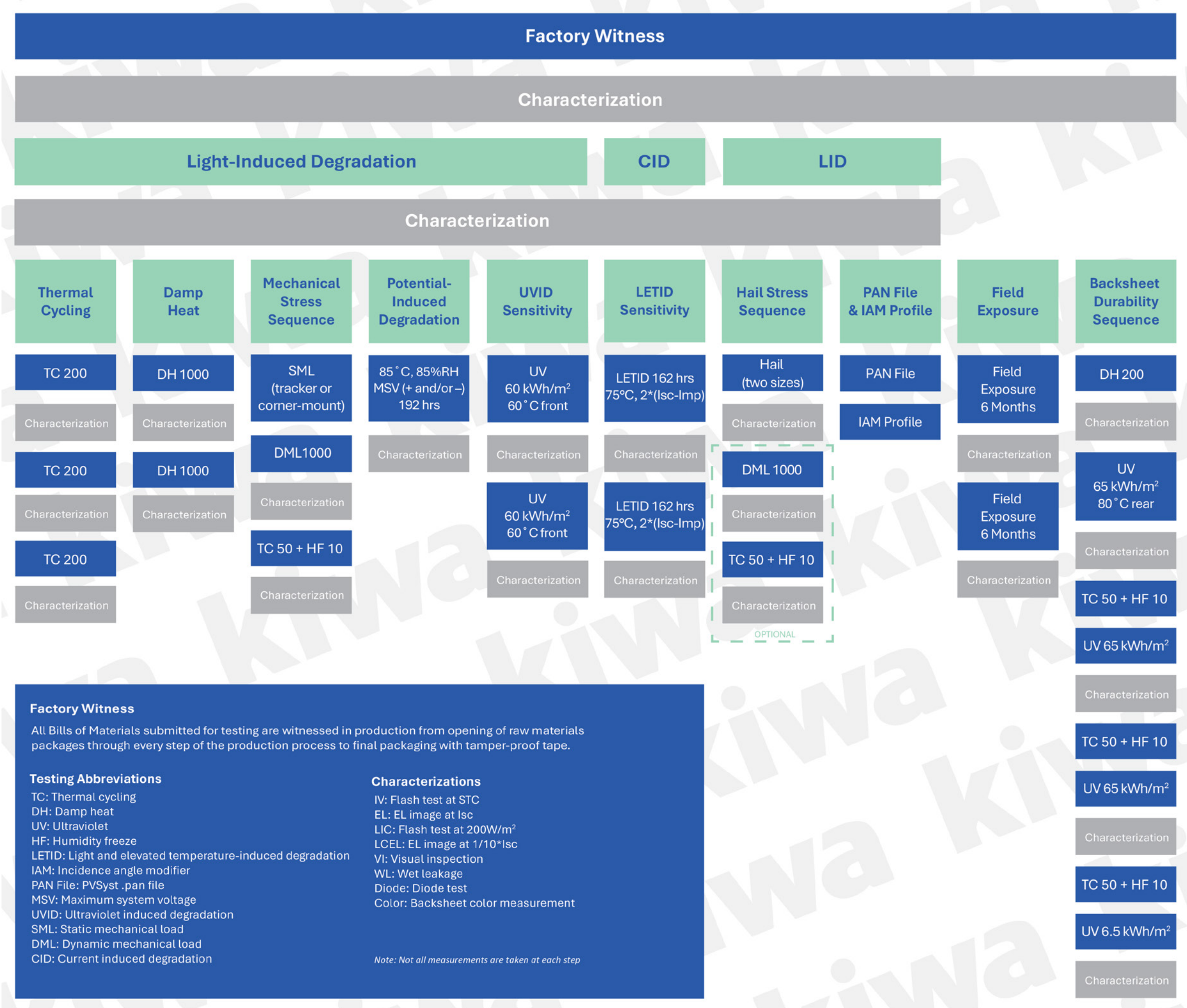
• 50 manufacturers are included in the 2025 Scorecard as Top Performers. Nine of them have at least one model type listed as a Top Performer in each of the seven tests.

• Only 21 models achieved Top Performer status in all reliability tests (TC, DH, MSS, HSS, PID and LID+LETID). Of those, only three were Top Performers in those tests plus PAN performance.

• PID and PAN results improved and MSS, HSS and LID+LETID power loss continues to be minimal. But TC and DH have worsened and the module breakage rate for MSS and HSS has increased. UVID remains a source of concern for some BOMs, but has improved for others.

• 83% of module manufacturers and 59% of BOMs had at least one test failure, up from the 66% and 41% reported in the 2024 Scorecard, respectively.

Kiwa PVEL ***product qualification program***



Methodology

Since 2012, Kiwa PVEL's Product Qualification Program has focused on benchmarking PV module reliability and performance. Our PQP reports and results support informed solar procurement and investment decisions.

Why BOM-Level *testing is important*

PV modules with the exact same model type can be manufactured from completely different bills of materials (BOMs). Changes in PV module components can have big impacts on reliability and performance, and the industry's certification tests are typically not rigorous enough to identify these potential issues. Module warranties also often have shortcomings that leave site owners exposed to significant financial losses. Kiwa PVEL's PV Module PQP is a comprehensive protocol of tests focused on addressing these concerns and helping module buyers achieve better procurement.

Scorecard *eligibility*

To be eligible for the 2025 Scorecard, manufacturers must have:

• Completed the PQP sample production factory witness after October 1, 2023, and, for each BOM shown, have at least one new Top Performer-achieving result that was not included in the 2024 Scorecard.

• Submitted at least two factory-witnessed PV module samples to all PQP reliability tests, as per Kiwa PVEL's BOM test requirements.

How BOMs *are scored*

The 2025 PV Module Reliability Scorecard lists Top Performers for seven PQP test categories. To be listed as a Top Performer in a particular test, the modules must not have experienced a wet leakage failure, a 'major' defect during visual inspection or a diode failure during that particular test.

• Top Performers for TC, DH, MSS and PID must have < 2% power degradation. For MSS, the mounting used during mechanical load testing is shown in the Top Performer list. For PID, the BOM must have < 2% power degradation in PID(+) and PID(-).

• Top Performers for HSS must not have experienced glass breakage during hail testing using 40 mm hail or larger. The actual hail size is shown in the Top Performer list, as well as the BOM glass thickness.

• Top Performers for LID + LETID must have < 1% power degradation when combining the LID and LETID test results.

• Top Performers for PAN performance must place in the top quartile for energy yield in Kiwa PVEL's PVsyst simulations. If IAM testing was included for that BOM, the IAM results are included in the PAN analysis. If no IAM testing was included, the PVsyst default IAM for AR coated glass is used.

In some cases, results for some test categories were not available at the time of Scorecard publication. Kiwa PVEL's Premium Partners access the detailed PQP results on a quarterly basis rather than waiting for the next Scorecard. Find out more about subscribing here.

Thermal ***cycling***

The PQP's Thermal Cycling (TC) test extends the IEC/UL certification test from 200 to 600 cycles, more accurately simulating a PV module's lifespan of temperature fluctuations. TC's extreme temperature swings stress module components, degrading interfacial bonds within the module and junction box that could substantially reduce performance. This test is crucial for environments with significant day-to-night temperature differences.

TC key ***takeaways***

- 71% of BOMs tested degraded by < 2% following TC600. This has decreased from 83% of BOMs degrading by < 2% reported in the 2023 and 2024 Scorecards.

- Over the past year of TC testing, the median degradation rate for TOPCon and PERC was 1.1% and 3.6%, respectively, showing TOPCon technology's advantage over PERC.

- For the 2025 Scorecard dataset, 90% of all glass//glass BOMs tested had < 2% degradation following TC600, versus 0% of glass//backsheet BOMs.

- 32% of manufacturers experienced at least one failure during TC testing, which was up from 20% for the 2024 Scorecard. These included power loss, delamination, broken glass, failed bypass diodes and exposed wires.

Go to scorecard.pvel.com/TC to see more.

Damp *heat*

The PQP's Damp Heat (DH) test is 2000 hours, double the duration of the IEC/UL certification test. For susceptible modules, this test instigates 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 module together.

DH key *takeaways*

• 62% of BOMs tested degraded by < 2% following DH2000. This has continued the decreasing trend from the 2024 and 2023 Scorecards, where 69% and 72% of BOMs had < 2% degradation, respectively.

• 67% of TOPCon BOMs tested over the past year had degradation < 2% following DH. This dropped to 33% for PERC BOMs and 0% for HJT BOMs, but the sample sizes for PERC and HJT were significantly lower than TOPCon.

• The median power degradation for TOPCon glass//glass BOMs tested over the past year was 1.6% compared to 4.0% for TOPCon glass//backsheet BOMs.

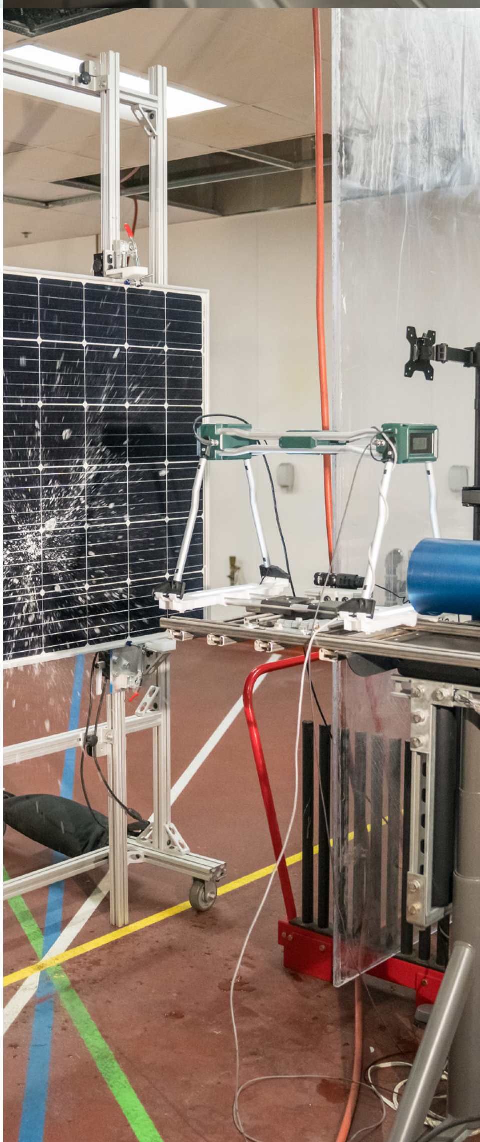
• 10% of BOMs and 19% of manufacturers experienced one or more failures during DH testing. These included delamination, junction box lids falling off, and power loss caused by corrosion.

Go to scorecard.pvel.com/DH to see more.

Mechanical stress ***sequence***

The PQP's Mechanical Stress Sequence (MSS) surpasses IEC/UL certification for more thorough module and cell durability testing. It detects potential glass and cell cracking vulnerabilities, and frame structural weaknesses through static and dynamic load testing. The subsequent climate chamber testing assesses power output reduction due to cell cracks, crucial for sites facing extreme weather such as heavy snow and high winds.

Hail stress ***sequence***



The PQP's Hail Stress Sequence (HSS) surpasses IEC/UL minimum hail requirements to rigorously test PV modules with ice balls ranging in size from 35 to 55 mm, while ensuring consistent and comparable impact energies. This test is mostly focused on glass breakage but also provides insights on cell crack susceptibility.

MSS key ***takeaways***

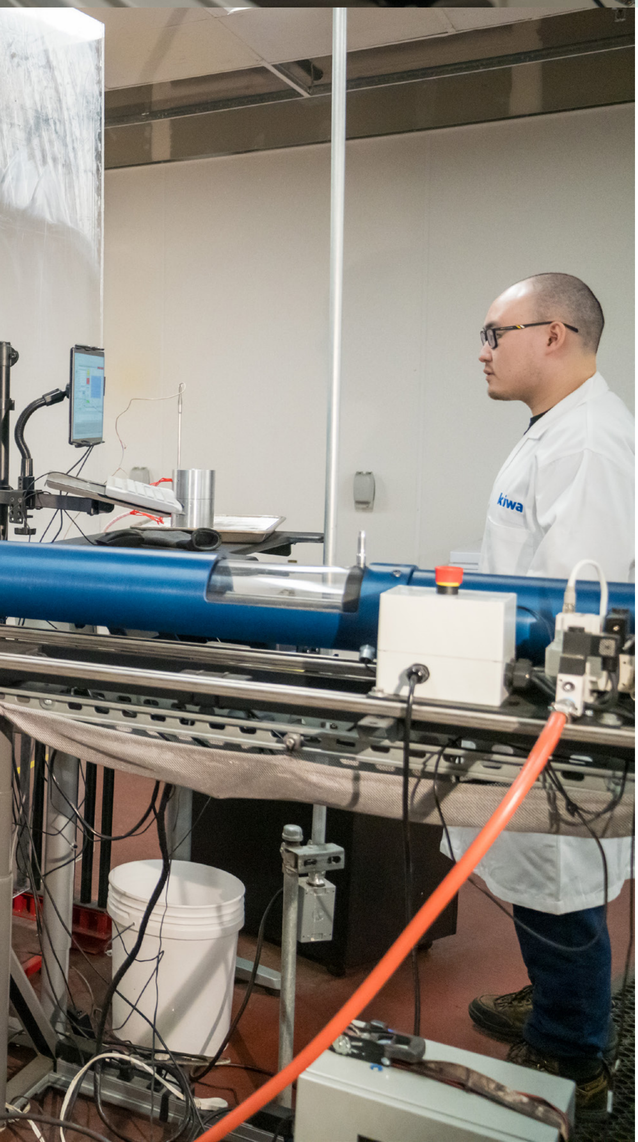
• 94% of BOMs completing MSS had < 2% power loss. This power loss has remained relatively minimal for the past three years due to glass//glass and/or multi-busbar modules.

• 20% of BOMs experienced one or more failures during MSS testing, which has increased from just 7% in the 2023 and 2024 Scorecards. Most of these failures were due to glass breakage and/or frame damage.

• The sharp increase in the rate of broken modules came after updating the static mechanical load portion of the MSS test to use 400 mm Nextracker mounting at a ±1800 Pa test load, versus the previously used two-rail mounting with 50 mm clamps at a ±2400 Pa test load.

• A range of issues have been identified for this increase breakage including reduced glass strengthening, flaws within the glass, weaker frame designs, laminate edge pinch, larger module areas, more aggressive module mounting and contact between the glass and frame.

Go to scorecard.pvel.com/MSS to see more.



HSS key ***takeaways***

• The past year of testing continued to prove that 3.2 mm glass//backsheet modules and hail-hardened designs are significantly less susceptible to glass breakage than 2.0 mm glass//2.0 mm glass modules.

• The first BOMs of hail-hardened modules made with either 2.5 mm glass//2.5 mm glass or 3.2 mm glass//2.0 mm glass have achieved lower glass breakage rates than both 3.2 mm glass// backsheet and 2.0 mm glass//2.0 mm glass.

• There was no post-hail impact power degradation > 2% in the 2025 Scorecard dataset. Current module designs suffer relatively little hail-induced power loss due to the use of half-cut, multi-busbar (MBB) cells.

• 15% of BOMs experienced a failure, defined here as when there are broken modules from both hail sizes, or when the manufacturer requests a hail retest.

Go to scorecard.pvel.com/HSS to see more.

Potential induced ***degradation***

The PQP's Potential Induced Degradation (PID) test doubles the IEC/UL certification test duration to 192 hours. There are multiple forms of PID. PID-shunting occurs when sodium ions from the glass travel to pinholes in the anti-reflective coatings on the cells, permanently lowering performance. PID-polarity is static charge build-up due to internal circuit voltages and is possibly reversible.

PID key ***takeaways***

• 72% of BOMs produced in 2024 degraded by < 2% following PID(-). This is an increase from the 57% of BOMs produced in 2023 that degraded by < 2%. Two PID(-) outliers with 11.9% and 17.6% power loss drove down the average for 2024 BOMs.

• While there was a wider range in TOPCon results compared to PERC and HJT, there were no statistically significant differences in the PID(-) susceptibility for TOPCon, PERC and HJT cell technologies, nor for glass//glass versus glass//backsheet.

• PID is typically lower for PID+, but 9% of BOMs with < 2% degradation for PID(-) had ≥ 2% degradation for PID(+). Conversely, 32% of BOMs with < 2% degradation for PID(+) had ≥ 2% degradation following PID(-).

• 9% of BOMs experienced a failure during PID testing. Most of these failures were due to power degradation caused by PID-polarization, which is often reversable with a UV exposure, but there have been reports of PID-polarization occurring in the field.

Go to scorecard.pvel.com/PID to see more.

LID + ***LETID***

The PQP's Light Induced Degradation (LID) and Light and Elevated Temperature Induced Degradation (LETID) tests quantify these cell-based phenomena that are often incorporated into energy yield models. LID varies by cell technology but primarily impacts boron-doped cells and stabilizes shortly after module deployment. Degradation from LETID reaches its maximum point after months or years.

LID + LETID key ***takeaways***

- 93% of BOMs tested had < 1% power loss in the combined LID plus LETID, with the median and average results virtually identical for BOMs produced in 2023 and 2024.

- The median LID power loss for 2025 Scorecard eligible BOMs was 0.4% for TOPCon, 0.4% for PERC, and 0.3% for HJT. The average power loss was 0.4% for TOPCon, 0.3% for PERC and 0.4% for HJT.

- The median LETID power loss for 2025 Scorecard eligible BOMs was 0.0% for TOPCon, 0.0% for PERC, and 0.2% for HJT. The average power loss was 0.1% for TOPCon, 0.2% for PERC and 0.1% for HJT.

- 5% of BOMs experienced one or more pre-stress testing failures, down from 11% in the 2024 Scorecard. In the worst example of pre-stress testing failure, one BOM had multiple broken glass modules during LID testing.

Go to scorecard.pvel.com/LIDLETID to see more.

PAN ***performance***

Kiwa PVEL's PAN testing and .pan file generation enhances PV module performance simulations by using empirical data across a range of temperature and irradiance conditions. This is an essential input for accurate energy models, reflecting real-world conditions more accurately and supporting better decision-making in module procurement and project development.

PAN key ***takeaways***

- Energy yields improved due to an increase in TOPCon and HJT BOMs included in the PAN dataset, resulting in the Top Performer threshold for PAN increasing by 0.95% and 0.59% for Kiwa PVEL's modelled sites in Las Vegas and Boston, respectively.

- HJT's average Pmp temperature coefficient of -0.25%/°C was better than that of both TOPCon (at -0.29%/°C) and PERC (at -0.32%/°C). The HJT and TOPCon values are slightly better than what was reported in the past two Scorecards.

- The average bifaciality was 85.5% for HJT, 76.3% for TOPCon and 68.7% for PERC. Compared to what was reported in the 2024 Scorecard, these averages were slightly lower for HJT and PERC and slightly higher for TOPCon.

- Low light performance has been fairly aligned across PERC, TOPCon and HJT BOMs for the past three years, with average low light performance of -3.2% for HJT, -3.8% for TOPCon and -4.2% for PERC.

Go to scorecard.pvel.com/PAN to see more.

Incidence angle *modifier*

Incidence Angle Modifier (IAM) coefficients evaluate the response of a PV module to light coming from various angles. Kiwa PVEL has improved upon the IEC 61853-2:2016 test method to capture IAM profiles for both glass//backsheet and glass//glass modules. This unique indoor IAM testing method has demonstrated world-leading results for precision and repeatability.

IAM key *takeaways*

• Measurements over the past year using Kiwa PVEL's method continued to show that the IAM values for commercial modules are relatively aligned. This may contradict manufacturer provided IAM curves.

• Kiwa PVEL can accurately measure differences in IAM performance between BOMs. The highest performer's modelled energy yield was 0.60% higher than the lowest performer for a simulated single-axis tracker site in Las Vegas, USA.

• For that simulated single-axis tracking system, the typical module Kiwa PVEL measured over the past year had a 0.12% higher energy yield compared to PVsyst's Fresnel ARC default. This difference is more pronounced in fixed tilt and cloudier conditions.

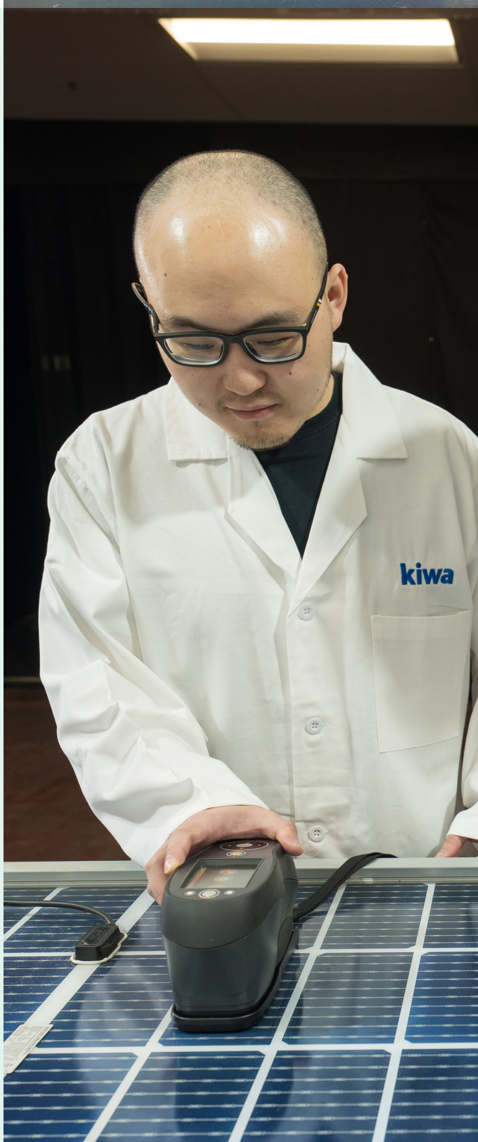
• While the sample size was lower for HJT, Kiwa PVEL's IAM measurements indicate that HJT modules on average have a lower IAM than TOPCon and PERC modules. This is likely due to the blue light absorption in the amorphous silicon for HJT cells.

Go to scorecard.pvel.com/IAM to see more.

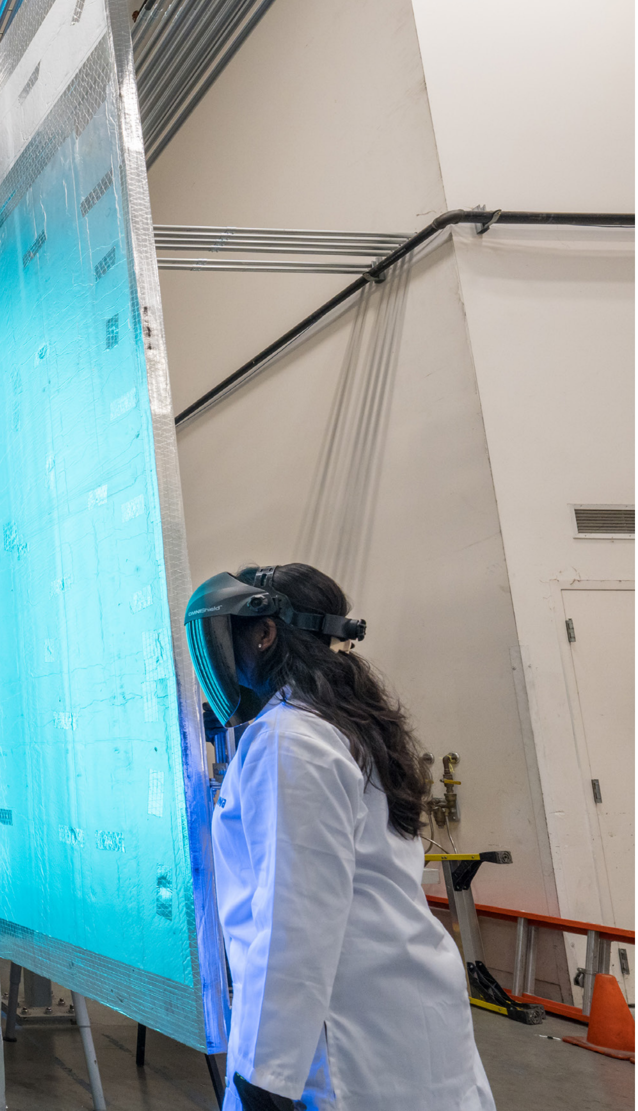
Ultraviolet induced ***degradation***

Kiwa PVEL's Ultraviolet Induced Degradation (UVID) test goes beyond standard IEC/UL certification to identify modules that are susceptible to this degradation mechanism. HJT and TOPCon modules are advertised to have improved first year and annual degradation rates, but examples of both (in addition to PERC) have shown significant UV-induced power loss.

Backsheet durability ***sequence***



The PQP's Backsheet Durability Sequence (BDS) goes well beyond IEC/UL certification requirements to effectively evaluate backsheet reliability, focusing on risks like yellowing and cracking due to polymer degradation. This test uses UV light, high temperature and humidity, and temperature cycling to simulate conditions that can lead to material degradation in the field.



UVID key ***takeaways***

- After testing more than 80 BOMs, the median power degradation was 3.1% and 4.2% for TOPCon and HJT BOMs respectively. PERC BOMs showed relatively lower degradation, with a median power loss of 2.2%.

- Dark storage degradation has been observed in some TOPCon and HJT modules after UVID and field exposure. This effect was most severe in UVID-sensitive TOPCon modules, at rates up to 1% power loss per day.

- UVID is more pronounced in modules with UV-transparent front encapsulants that have a cut-off wavelength below 340 nm. UV-blocking front encapsulants or light down-conversion encapsulation additives lower UVID power loss.

- The PQP's optional Field Exposure test has identified some BOMs with significant degradation (median: 2%, maximum: 8%) following one year of deployment in Davis, CA. This has been mainly attributed to UVID.

Go to scorecard.pvel.com/UVID to see more.

BDS key ***takeaways***

- Over the past two years, Kiwa PVEL's BDS testing for PQPs has not revealed any backsheet cracking issues. This testing covers 25 BOMs with a range of outer layer materials including CPC, PVF, PVDF and PET films. The backsheets were transparent, white and black.

- While no backsheet cracking has been observed, several modules suffered from other issues, including illegible labels (a major defect according to IEC), busbar discoloration on the rear side of bifacial modules, cable chalking, cracked connectors and backsheet discoloration.

- Bifacial modules with transparent backsheets comprise more than 56% of the test sample population in Kiwa PVEL's BDS testing. Results show that transparent backsheets suffered from similar degradation and yellowing compared to white backsheets.

- Many new module backsheets have been deployed in the field over the last few years, showing no early signs of degradation. It is possible that some of these unproven backsheets may reveal potential issues over the long term.

Go to scorecard.pvel.com/BDS to see more.

PQP ***failures***

The number of module manufacturers undergoing PQP testing who experienced at least one test failure continues to increase. The BOM-level failure rate has also steadily risen. Experiencing test failures is no longer an ‘if’, but a ‘when’, and how manufacturers learn from them is essential to ensuring long-term module reliability.

PQP failures key ***takeaways***

• 60% of all failures were detected during visual inspection. The largest source of this was module breakage during MSS testing due to the increase in tracker-mount testing from previous years combined with weaker glass and/or frames.

• The percentage of BOMs experiencing a power loss related failure increased to 19%, up from 14% in the 2024 Scorecard. This was largely due to UVID power loss being included as part of the failure statistics this year.

• 7% of BOMs experienced a wet leakage electrical insulation (or “safety”) failure. This was the same number reported in the 2024 Scorecard, which was down from the 18% reported in the 2023 Scorecard.

• One third of manufacturers had one or more junction box related failures. They include 11% of manufacturers with junction box covers falling off, 8% of manufacturers with loose cables/exposed wires, and 8% of manufacturers with bypass diode failures.

Go to scorecard.pvel.com/failures to see more.

Historical ***scorecard***

The table below shows the history of top performance for all manufacturers featured in the 2025 Scorecard. Go to scorecard.pvel.com/top-performers to see the list of Top Performer model numbers.

Manufacturers are listed by the number of years they have been designated a Top Performer, in alphabetical order.

Manufacturer	2025	2024	2023	2022	2021	2020	2019	2018	2017	2016	2014
Jinko	x	x	x	x	x	x	x	x	x	x	x
Trina Solar	x	x	x	x	x	x	x	x	x	x	x
JA Solar	x	x	x	x	x	x	x	x		x	x
Qcells	x	x	x	x	x	x	x	x	x	x	
Astronergy	x	x	x	x	x	x		x	x		x
REC Group	x		x	x	x	x	x	x	x	x	
Adani Solar	x	x	x	x	x	x	x	x			
LONGi	x	x		x	x	x	x	x	x		
Maxeon	x	x	x	x	x	x		x	x		
Phono Solar	x	x	x	x	x		x	x		x	
Vikram Solar	x	x	x	x	x	x	x		x		
GCL	x	x			x	x	x	x	x		
HT-SAAE	x	x	x	x	x	x		x			
Silfab Solar	x	x	x		x	x	x		x		
Yingli Solar	x	x	x					x	x	x	x
ZNShine Solar	x	x	x	x		x	x			x	
Seraphim	x			x	x	x	x		x		
DMEGC Solar	x	x	x	x	x						
EliTe Solar	x	x	x	x	x						
HD Hyundai	x	x	x		x				x		
Heliene	x	x	x	x		x					
Risen Energy	x	x	x	x	x						
Talesun	x		x	x	x				x		
VSUN	x	x	x	x	x						
Canadian Solar	x	x	x			x					
Jolywood	x	x	x		x						
SEG Solar	x	x	x	x							
Waaree	x	x	x	x							
Aiko Solar	x	x	x								
Emmvee	x	x	x								
Huasun	x	x	x								
Premier Energies	x	x	x								
AE Solar	x		x								
Hanersun Energy	x	x									
Leapton Solar	x	x									
Mission Solar Energy	x	x									
NE Solar	x	x									
Renesola	x										x
ReNew	x	x									
Runergy	x	x									
Tata Power Solar	x	x									
Thornova	x	x									
Tongwei	x	x									
DAH Solar	x										
Haitai Solar	x										
Jetion Solar	x										
Kalyon PV	x										
Rayzon Solar	x										
RenewSys	x										
Ronma Solar	x										

Top performers per ***test***

The table below shows for which tests each manufacturer achieved Top Performer status with one or more models. In some cases, test results for some test categories were not available at the time of Scorecard publication.

Manufacturers are listed by the number of tests, followed by the number of years they have been designated a Top Performer, in alphabetical order. Go to scorecard.pvel.com/top-performers to see the list of Top Performer model numbers.

Manufacturer	TC	DH	MSS	HSS	PID	LID+ LETID	PAN
Jinko	x	x	x	x	x	x	x
Phono Solar	x	x	x	x	x	x	x
ZNShine Solar	x	x	x	x	x	x	x
Talesun	x	x	x	x	x	x	x
VSUN	x	x	x	x	x	x	x
Jolywood	x	x	x	x	x	x	x
Waaree	x	x	x	x	x	x	x
NE Solar	x	x	x	x	x	x	x
Tongwei	x	x	x	x	x	x	x
Trina Solar	x	x	x	x	x	x	
Qcells	x	x	x	x	x	x	
Seraphim	x	x	x	x	x	x	
EliTe Solar	x	x	x	x	x	x	
Canadian Solar	x	x	x	x	x	x	
Leapton Solar	x	x	x	x	x	x	
ReNew	x	x		x	x	x	x
Kalyon PV	x	x	x	x	x	x	
JA Solar	x	x	x		x	x	
Adani Solar			x	x	x	x	x
LONGi	x		x		x	x	x
Maxeon	x	x	x	x	x		
Vikram Solar	x			x	x	x	x
Yingli Solar			x	x	x	x	x
DMEGC Solar	x	x	x		x	x	
Huasun	x		x		x	x	x
Thornova	x		x	x	x	x	
RenewSys			x	x	x	x	x
Ronma Solar	x		x	x	x	x	
Astronergy	x	x	x			x	
Silfab Solar				x	x	x	x
Heliene			x	x	x	x	
Risen Energy	x				x	x	x
Aiko Solar	x	x	x			x	
Emmvee			x	x	x	x	
Premier Energies				x	x	x	x
Hanersun Energy		x	x	x		x	
Runergy	x	x	x	x			
GCL			x		x	x	
HD Hyundai			x	x	x		
SEG Solar	x					x	x
Mission Solar Energy			x	x		x	
Renesola		x			x	x	
Tata Power Solar			x	x		x	
DAH Solar			x		x	x	
Haitai Solar	x				x	x	
Jetion Solar			x		x	x	
Rayzon Solar	x	x				x	
REC Group					x		x
HT-SAAE			x				
AE Solar				x			

About *Kiwa PVEL*

Kiwa PVEL is the leading reliability and performance testing lab for downstream solar project developers, financiers and asset owners around the world. For over a decade, Kiwa PVEL's Product Qualification Program (PQP) has been globally recognized for replacing assumptions about PV module performance with quantifiable metrics. Related data and consulting services offered by Kiwa PVEL provide vital procurement intelligence.
Visit kiwa.com/pvel for more.

About *Kiwa Solar*

The Kiwa Group offers a comprehensive portfolio of quality assurance, testing, inspection and certification services for the solar industry. This includes component certification, qualification and bankability testing, technical due diligence, factory audits and inspections, batch testing and field services at operating sites and those under construction. We support investors, developers, EPC contractors and asset managers, while also helping manufacturers demonstrate compliance with the requirements of numerous markets.
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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.

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• Pages dedicated to all sections shown in the Executive Summary.

• Direct links to test specific pages on kiwa.com for field case studies, test procedures and more.

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