

2025

PV Module Index Report

RETC
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VDE



“Though some recent bankability test results are alarming, these are also issues that the technical due diligence community has successfully eradicated in the past or can resolve with improved test standards.”

Securing a sustainable future



As RETC, part of the VDE Group, publishes its seventh annual *PV Module Index Report,* established solar photovoltaic (PV) module manufacturing landscapes and supply chains are shifting. The factors driving these changes present both tailwinds and headwinds that affect progress.

The tailwinds include exciting technological advancements and enlightened policy changes that generally advance climate risk mitigation goals, such as the rise of perovskite PV and regional efforts to reduce the solar industry's carbon footprint. The headwinds include market disruptions and geopolitical tensions that seemingly undermine collective efforts to accelerate the global energy transition, such as the steep tariffs that are fanning the flames of a simmering trade war.

Instability in supply chains, manufacturing locations, and commercial technologies tends to introduce opportunities for deviation from quality. This tendency is not unique to this moment but rather walks hand in hand with periods of accelerated market disruption and change. Most importantly, this issue is evident only upon close inspection.

Based solely on product certification test results, today's highly diversified solar manufacturing landscape is virtually indistinguishable from the more consolidated and stable pipelines of years past. Unfortunately, testing product samples to International Electrotechnical Commission (IEC) qualification standards for terrestrial PV modules sheds little to no light on the ways in which commercial products tend to fail or wear out prematurely under real-world conditions of use.

Differences in performance and reliability only become apparent when we intentionally apply additional stresses with the goal of separating the wheat from the chaff. Subjecting today's PV modules to RETC's tried-and-true Thresher Test program—the industry's first consensus reliability and durability test standard for PV modules—tells a different story.

In recent rounds of bankability testing, RETC has noted an increase in issues related to humidity, thermal cycling, potential-induced degradation, and metastability. This resurgence in PV cell-related issues, many of which we have not seen in our bankability testing for the better part of a decade, suggests that solar project stakeholders must remain vigilant about risks associated with shifting solar manufacturing supply chains.

We also continue to see the structural issues highlighted in last year's report. Specifically, we have observed PV module frame and glass failures during mechanical loading, cyclical loading, and ballistic-impact testing that may be evidence of inadequate certification test standards. These laboratory-observed trends are disconcerting because they align with in-field failures reported by our operations and maintenance partners and project developer customers.

Though some recent bankability test results are alarming, these are also issues that the technical due diligence community has successfully eradicated in the past or can resolve with improved test standards. So long as we have eyes to see them, we can solve these problems.

Thank you for joining us as partners and collaborators in the collective effort to de-risk the critical energy infrastructure of the future, ensuring sustainable investment returns, insurable assets, and a worthwhile future.

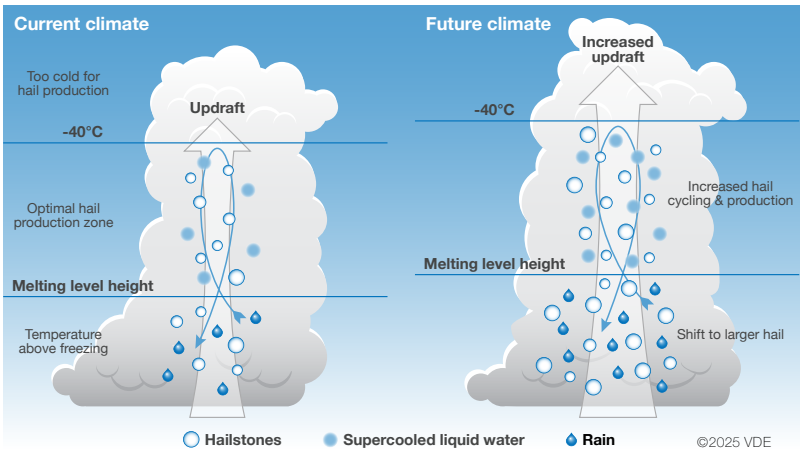
—Cherif Kedir, CEO, RETC

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About RETC

RETC (Renewable Energy Test Center), part of the VDE Group, is a leading provider of engineering services and certification testing for renewable energy products. Since its founding in 2009, RETC has partnered with manufacturers, developers, and investors to test a wide range of products, including solar photovoltaic (PV) modules, racking, trackers, power electronics, and battery energy storage system (BESS) components. At our accredited laboratories around the world, we evaluate products using the latest testing standards and industry-accepted methods. Headquartered in Fremont, California, RETC puts customers at the forefront by bringing value to research and development, bankability assessments, and market-entry activities. We are united with our customers in the belief that providing a foundation for energy security and effective decarbonization ensures a safer and more sustainable world.



About VDE

VDE, one of the largest technology organizations in Europe, has been regarded as a synonym for innovation and technological progress for more than 130 years. VDE is the only organization in the world that combines science, standardization, testing, certification, and application consulting under one umbrella. The VDE mark has been synonymous with the highest safety standards and consumer protection for more than 100 years. Within the VDE network more than 2,000 employees at over 60 locations worldwide, more than 100,000 honorary experts, and around 1,500 companies are dedicated to ensuring a future worth living: networked, digital, electrical. The VDE (VDE Association for Electrical, Electronic & Information Technologies) is headquartered in Frankfurt am Main, Germany. For more information, visit www.vde.com



Cherif Kedir

CEO and President

Cherif is a solar industry veteran of 18-plus years, with experience in product engineering and development, yield and performance enhancement, test site development, and durability, bankability and certification testing. He also has an extensive background in semiconductors, specifically with product engineering, testing, and failure analysis. Cherif leads an RETC team dedicated to helping the renewable energy industry thrive.



Dick Bayangos

Chief Financial Officer

Dick oversees finance and human relations at RETC. Dick was the Regulatory Manager of Verizon in Virginia and earned the "CFO Recognition Award – Accountability Without Excuses" for researching, resolving, and saving the company over $50M in Federal Universal Service Fund discrepancies. He also developed a new remittance model to minimize over remittance to the Federal Communications Commission.



Zennia Villanueva

VP Quality

Zen is the main liaison between customers and partner NRTLs for certification projects, creating test plans, construction evaluation, and technical reports. Zen is a certified quality engineer licensed under the American Society for Quality. She also contributes to international and local PV standards and specifications. Before joining RETC, Zen led product quality, global supplier qualification, and subcontractor quality management at Solaria.



Saeed Arash Far

Vice President of Engineering and Operations

Saeed has over 22 years of people management, product architecture design, patent, hands-on product development, and quality engineering experience. He is a seasoned architect and developer of utility-, industrial-, commercial-, and consumer-grade solutions, and sensor technologies. Before joining RETC, Saeed held a variety of executive engineering and board member roles for technology startups.



Camille Sherrod

Head of Sales and Project Management

Camille has been with RETC since the start of her solar career in 2016. She first joined as RETC's laboratory operations manager and has since managed the company's internal sales and project management resources. In these roles, she has worked directly with different customers across the renewable industry, allowing her to understand the needs of different stakeholders up and down the value chain.

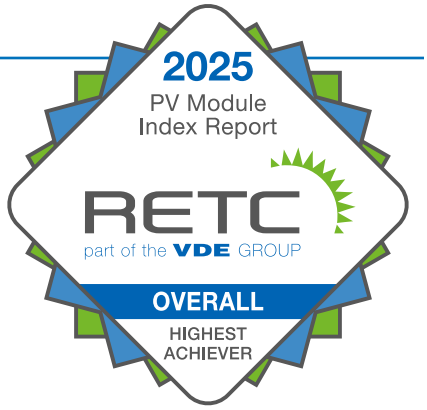


David Brearley

Product Marketing Manager

David is a strategic communications expert whose work supports the global energy transition. He joined the VDE group with more than two decades of experience working in renewables, including a decade-long tenure at *SolarPro* magazine, where he developed and published unparalleled technical content for North American solar industry stakeholders. David specializes in developing turnkey content marketing collateral.

CATEGORIES FOR HIGH ACHIEVEMENT



RETC is proud to present the ***2025 PV Module Index Report.*** By sharing annual performance distribution data for highly accelerated stress tests, this publication empowers industry stakeholders to mitigate technical risks in solar assets and portfolios.

As part of the VDE Group, one of the largest technology organizations in Europe, RETC is committed to the advancement of reliable renewable energy technologies. With this goal in mind, our seventh annual *PV Module Index Report* compiles the results of beyond-certification bankability tests conducted at our highly accredited independent testing laboratories over 12 months, spanning Q2 2024 through Q1 2025.

The bankability tests published in the disciplines section of this report (pp. 26–45) are foundational to a science- and engineering-based approach to technical risk mitigation. The goal of a data-driven approach to project development is not to eliminate every risk at any cost but rather to balance risk mitigation based on a holistic cost-benefit analysis. With this in mind, industry stakeholders can use the comparative test results contained in this report to identify product or project designs best suited to a specific environment, location, or portfolio, as determined by RETC's Thresher Test results.

Thresher Test program overview

Introduced at the 2011 PV Module Quality Assurance Forum, the Thresher Test is the solar industry's first-ever commercial reliability and durability analysis standard for PV modules. The program takes its name from a type

RETC THRESHER TEST PROGRAM

Third-party factory bill of materials verification

Module reliability

DH	TC	SDML	PID	BUDT	UVID
Damp heat	Thermal cycling	Static & dynamic mechanical load	Potential-induced degradation	Backsheet UV durability test	UV-induced degradation
2 modules	2 modules	2 modules	4 modules	2 modules	2 modules
Light-induced degradation (40 + 20 kWh/m^2)				Light-induced degradation (5 kWh/m^2)	
DH1000 ×2	TC200 ×3	SML	PID (96 hrs) ×2	DH1000	Front side (UV220 kWh/m^2)
BO-LID		DML	UV2 kWh/m^2	Rear Side ×3 (UV65 kWh/m^2)	Rear Side (UV66 kWh/m^2)
		TC50		TC50 + HF10	UVR
		HF10 ×3		Rear Side (UV6.5 kWh/m^2)	

Industry stakeholders can use the comparative bankability test results in this report to identify product or project designs best suited to a specific environment, location, or portfolio.

of farm equipment used to separate high-quality seed and grain from low-quality straw and chaff. Much as a threshing machine beats plants to separate organic materials according to utility and desirability, the Thresher Test uses highly accelerated stress sequences to separate high-quality PV module designs from low-quality ones.

Having served as the development program coordinator, RETC was the first testing laboratory in the world to offer the Thresher Test. While many of the basic test sequences are similar to those required for product qualification, our bankability test program exposes modules to much longer cycles and times. Product that appear very similar on paper may perform very differently in the real world. By exposing product design or manufacturing vulnerabilities and deficiencies, beyond-qualification testing captures these differences.

In the years since its adoption as the de facto standard for comparative PV module testing, RETC has adapted or added testing sequences to better align outcomes with the latest field-failure data. By evolving to meet the needs of a dynamic industry, RETC's Thresher Test remains the gold standard for identifying product- or technology-specific design vulnerabilities, wear-out mechanisms, failure modes, and long-term degradation patterns.

<table>
<tr><th colspan="3">Module performance</th></tr>
<tr><th colspan="2">PAN file</th><th>LETID</th></tr>
<tr><td colspan="2">Third-party PAN file characterization for PVSyst</td><td>Light & elevated temperature</td></tr>
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<tr><td>3 modules</td><td>1 module</td><td>LeTID (162 hrs) ×3</td></tr>
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</table>

Notes

Pre/post tests for reliability tests include: EL, IV, wet leakage, visual inspection with bypass diode functionality testing at the end of a sequence.

BUDT sequence includes yellowness index measurement. Polymeric substrates only.

PID sequence conducted for positive and negative maximum system volatge at 85°C and 85% relative humidity.

Pre/post tests for LeTID and UVID include: EL, IV, visual inspection.

Abbreviations

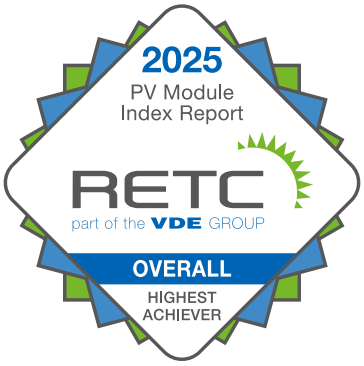
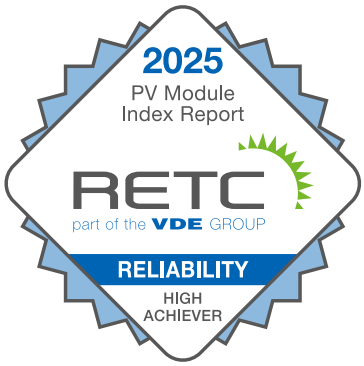
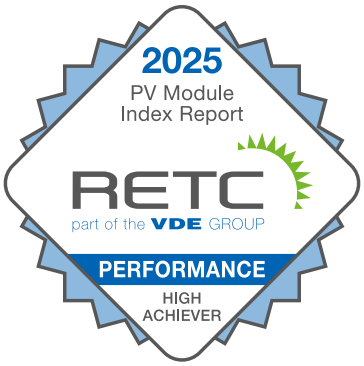
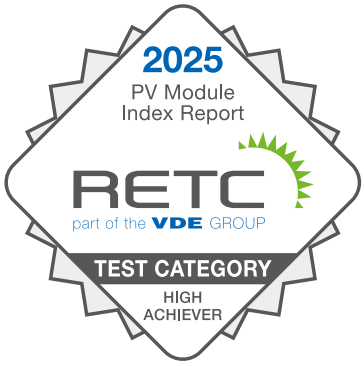
IAM: incidence angle modifier
BO-LID: boron-oxygen light-induced degradation
BUDT: Backsheet ultraviolet durability test
DH: damp heat
DML: dynamic mechanical load
HF: humidity freeze
LID: light-induced degradation
LETID: light- and elevated temperature–induced degradation
PID: potential-induced degradation
SDML: static and dynamic mechanical load
SML: static mechanical load
TC: thermal cycling
UVID: ultraviolet-induced degradation

Criteria for recognition

To be recognized as an "Overall Highest Achiever" in the *PV Module Index Report,* manufacturers must successfully complete RETC's rigorous Thresher Test program and excel across multiple tests within the reliability and performance disciplines. Moreover, manufacturers must demonstrate a commitment to quality control and assurance by allowing an independent third party to randomly select PV modules from inventory for Thresher Testing.

RETC reserves "Overall Highest Achiever" recognition for manufacturers of bills of material (BOMs) that excel across three interrelated and equally influential disciplines: module reliability, performance, and quality. A step down from this top honor, we recognize manufacturers of products that excel across multiple testing sequences within one specific discipline for "High Achievement in Reliability" or "High Achievement in Performance."

2025 PVMI AWARD CATEGORIES

Award	Criteria for Recognition
	• Complete RETC's full Thresher Test program • Meet BOM-level high achievement requirements in both the reliability and performance disciplines • Meet criteria for recognition in the quality discipline (p. 42)
	• Meet BOM-level high achiever requirements for at least three of the seven tests sequences within the reliability discipline only*
	• Meet BOM-level high achiever requirements for at least three of the seven tests sequences within the performance discipline only
	• Meet BOM-level high achiever requirements for one or more individual test sequences only

*Glass-on-backsheet module models must meet high achiever requirements for BUDT plus at least three additional test sequences within the reliability discipline.


CAUTION
PALLET™
Patent Pending



HAIL RESILIENCY CURVE TESTING FOR PV MODULES

Testing to failure is standard practice for glass reliability engineering. By applying these principles to solar panels, RETC and its sister company, VDE Americas, aim to solve a Texas-sized hail vulnerability problem.

Recent experience has shown that the technical due diligence community must do a better job of adapting solar farms to withstand the severe weather risks associated with a warming climate. In a review of claims data, climate insurance provider kWh Analytics has estimated that hail accounts for 6% of solar project insurance claims but more than 72% of losses by dollar amount. Moreover, hail-related solar project losses incurred since 2018 have exceeded $600 million—in the state of Texas alone.

As the leading state solar market in the most hail-exposed country in the world, Texas has emerged as the ultimate proving ground for PV technology climate resiliency. Solar project hail loss events in the Lone Star State have reached an unsustainable frequency and scale, putting a roadblock in the path of our collective efforts to avert a global climate crisis. However, if industry stakeholders can design PV modules and power systems capable of weathering severe convective storm environments in Texas, these resilient assets will provide a solid foundation to support power sector decarbonization as part of a global energy transition.

To prevent catastrophic hail losses in Texas, utility-scale solar farms must be able to withstand the ≥45-mm (≥1.77-in.) hail events likely to occur within an asset's operational lifetime. Survival under these extreme conditions of use not only requires climate-adapted operational strategies—such as state-of-the-art hail monitoring and tracker stow capabilities—but also the availability of proven hail-hardened PV modules. To support the development and procurement of truly differentiated product designs, RETC and VDE Americas have partnered to introduce the Hail Resiliency Curve Test program—the industry's first true measurement system dedicated to the development of hail-hardened solar assets.

Why pass/fail testing is failing now

In 1975, U.S. government-sponsored work began in earnest to develop cost-competitive PV module designs capable of supporting a large-scale terrestrial solar market. As part of the Flat-Plate Solar Array (FSA) Project, which ran from 1975 to 1986, the Jet Propulsion Laboratory (JPL) and the California Institute of Technology developed ballistic-

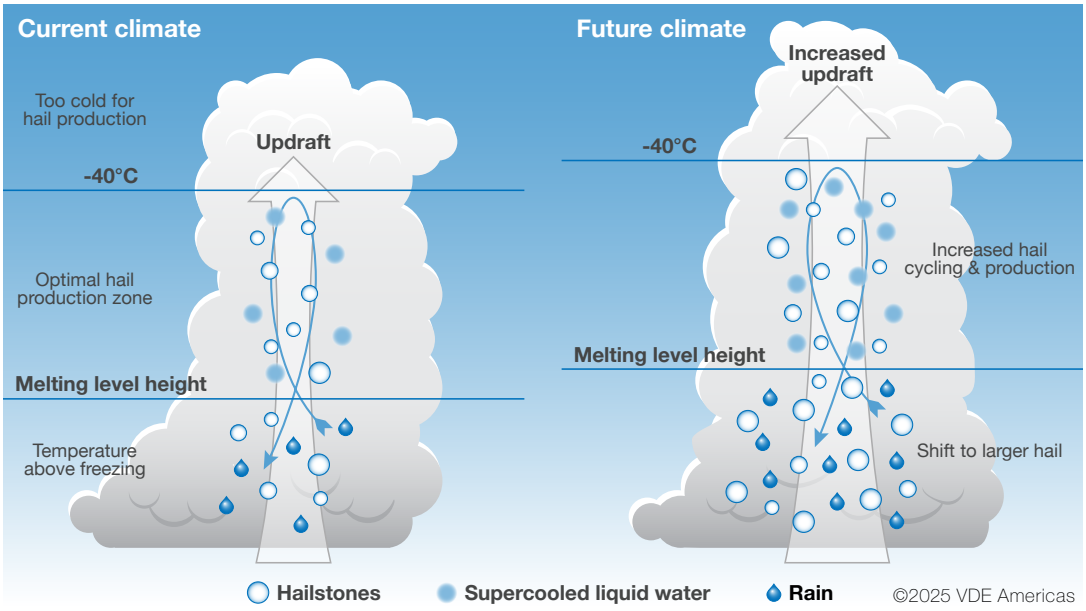
impact testing techniques still used today to simulate and study the effect of hail on solar panels. As early as April 1978, these researchers described the process of subjecting commercially available PV modules to 25-mm (1-in.) simulated hailstones, identified in conference proceedings as "frozen ice spheres projected at terminal velocity," and steel balls applied by gravity drop.

JPL's groundbreaking work on the FSA Project was foundational to the development of the durability tests and performance standards that enable modern PV modules to withstand decades of field exposure. Analyzing probabilistic failure modes, the project's reliability engineers

introduction of ever-larger PV modules, often made with the thinnest possible front glass to control weight. With regards to markets, utility-scale solar project development activities have increased exponentially in the most hail-exposed region of the world—specifically, a distinct "hail alley" that extends north out of Texas along the eastern flank of the Rocky Mountains.

As if these intersecting trend lines were not enough cause for concern, climate scientists believe the effects of human-caused climate change have generally increased severe convective storm risk over the decades since JPL's reliability engineers developed the industry's

Current versus modeled future hail climate



Climate models generally point to an increase in the annual number of hail days favorable to very large hail over the central and eastern United States.

defined many design qualification and product safety tests still relied upon today. To this day, we can still see JPL's imprint on PV module ballistic-impact testing standards in the 50-mm (2-in.) steel ball drop test in IEC 61730 and the 25-mm (1-in.) freezer ice ball test in IEC 61215.

The fact that simulated hail testing standards derived from the FSA Project have largely served the industry well for more than 40 years speaks to the quality of the reliability engineering work done in the process of bringing a space-age technology down to Earth. Cracks in this foundation emerged only recently due to a perfect storm of solar technology and market trends.

On the technology front, solar panels have gradually become less hail resistant over time as manufacturers have pushed the value-engineering envelope with the

prototypical PV module hail testing standards. This is the stage upon which the now-infamous $70 million Midway Solar Farm catastrophic hail loss event took place in May 2019, the shock waves of which still reverberate in solar insurance markets.

Genesis of financial hail loss modeling

After the Midway Solar Farm made headlines, resetting the solar insurance market almost overnight, Wells Fargo engaged VDE Americas, a technical advisory firm that has supported the financing of over $15 billion in operating solar and energy storage assets, to help the tax-equity investor quantify its portfolio-level hail risk exposure. "At the time, I thought this was a two- or three-week project," recalls John Sedgwick, co-founder of VDE Americas. "Instead, it has been a five-plus-year Ph.D.-led voyage of discovery."

Under the direction of Dr. John T. Allen, one of the world's foremost authorities on severe hail climatology, and Dr. Peter Bostock, an expert in solar engineering, physics, and financial modeling, VDE Americas developed science- and engineering-based meteorological and financial models that allow for site- and technology-specific hail risk assessments. RETC's beyond-qualification ballistic-impact testing data was critical to these efforts.

"Because our companies are both part of the VDE Group, one of the largest technology organizations in Europe, RETC was able to share with us anonymized hail test data," explains Jon Previtali, vice president and senior principal engineer at VDE Americas. "This hail-impact test data provides comparative hail resiliency curve profiles for common types of PV module that feed into our financial loss models.

"Looking at RETC's published hail resiliency curves, you can see that a PV module package with 3.2-mm [0.13-in.] front glass and a polymeric backsheet is roughly twice as strong—twice as resistant to hail damage, in other words—as compared to a typical bifacial PV module with a 2.0-mm [0.08-in.] dual-glass package. You can also see that the uncertainty bars associated with these comparative hail resiliency curves are quite large, which is an opportunity for improvement. If we can reduce uncertainty, we can improve the accuracy of VDE's Hail Risk Intelligence."

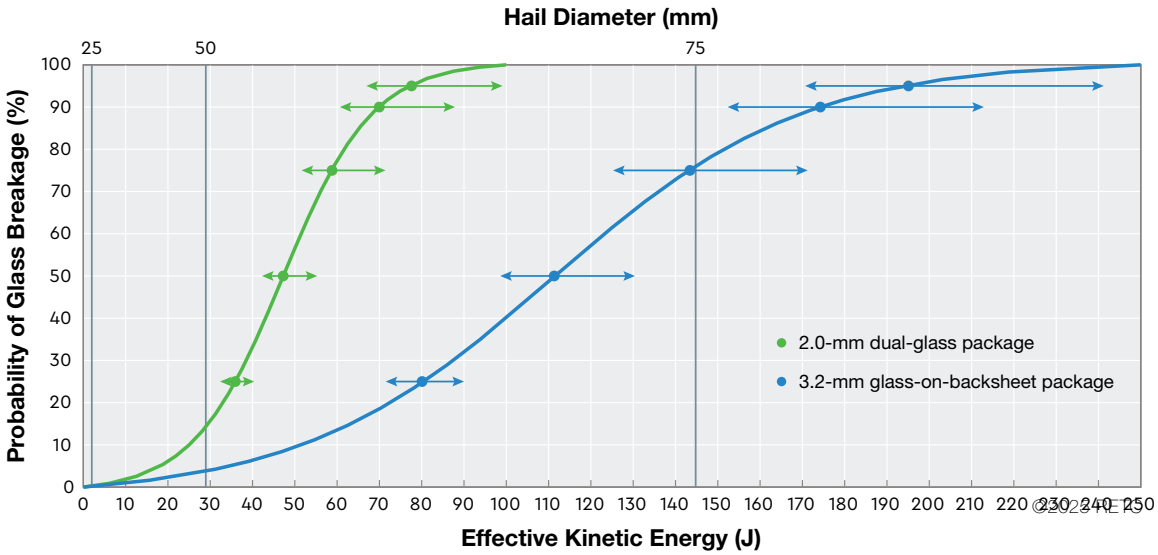
Break glass in case of emergency

In 2023, Previtali's team determined that the industry's growing hail vulnerability problem could only be solved by a return to fundamental reliability engineering principles. With this in mind, VDE Americas enlisted a glass reliability expert with experience supporting advanced product development efforts at Fortune 500 companies, including Apple and Tesla, to support the development a low-cost, high-accuracy hail resiliency curve testing program for PV modules.

"What really interests me as a glass reliability engineer," says Mike Pilliod, president and chief technical officer at Central Tension, "are measurement systems that provide a statistically representative probability of failure. The use case doesn't really matter. Automotive glass, cellphone displays, architectural glass, you name it. If you're not breaking glass—and not testing a representative number of samples to failure—you're not doing your job as a reliability engineer.

"After I started working with VDE's hail team, I quickly realized that the solar industry has effectively relied on a one-size-fits-all type of product qualification test. You put a sample PV module in front of a hail gun, fire an ice ball at it, see what happens. If nothing breaks, which is almost always the case, the product has passed the test and is considered good to go all in all operating environments and conditions of use."

Hail resiliency curves for common PV module packages



RETC originally published the comparative hail resiliency curves shown here in the 2023 edition of kWh Analytics' *Solar Risk Assessment.* The relatively large error bars associated with these Weibull curves are a reflection of the fact that the source data are based on pass/fail testing data, with large steps in effective kinetic energy. By comparison, the new Hail Resiliency Curve Test Program captures more granular test-to-failure data, which will significantly reduce statistical uncertainty.

According to Pilliod, the simulated hail tests in IEC 61215-2 are not a rigorous measurement system. The problem with pass/fail testing paradigms, he explains, is that they stop too soon, "Okay, one module passed. But why did you stop? Keep going. Figure out where the sample fails. If you gradually increase kinetic impact energy and test a meaningful number of samples to failure, you can generate Weibull distribution curves that plot the probability of glass failure on a product- or bill of materials-specific basis with low uncertainty. Now you can stack these Weibull curves and compare them. Do the curves overlap? If not, you can be reasonably certain that there is a statistical difference in resiliency."



"If you're not breaking glass—and not testing a representative number of samples to failure—you're not doing your job as a reliability engineer."

MIKE PILLIOD
Central Tension

Pilliod continues, "Using a robust test-to-failure measurement system, you can evaluate differentiated product designs and support market segmentation. Big floppy modules, to borrow a term from NREL [National Renewable Energy Laboratory], are a great solution for many solar markets, but these products are probably not designed with hail resilience in mind. PV modules intended for deployment in hail-exposed locations benefit from use of stronger, more advanced glass. Evaluating the value proposition associated with these advanced products requires a more advanced measuring system."

Testing to failure leads to understanding

At the 2024 PV Reliability Workshop, hosted by the National Renewable Energy Laboratory, VDE's Bostock first described the conceptual framework for a Weibull-based, test-to-failure program capable of informing solar project financial loss models and property damage mitigation efforts. Over the next 12 months, a VDE Americas-led product durability dream team—made of scientists and engineers with expertise in glass reliability, manufacturing quality, statistical analysis, and laboratory testing—developed, drafted, and successfully piloted a new PV module hail resiliency test protocol.

Earlier this year, RETC became the first testing laboratory in the world to offer VDE Americas' aptly named Hail Resiliency Curve Test to customers. Designed to evaluate solar panel resilience to hail damage, the test-to-failure program uses calibrated air guns to shoot progressively larger ice balls, a laboratory proxy for naturally occurring hail, at progressively higher speeds and impact energies until glass breakage occurs. Importantly, the test program provides a robust statistical representation of what happens during real-world events.

During a severe hailstorm, individual PV modules are subjected to a range of hail sizes and impact velocities. These numerous and varied impacts occur across different module areas—namely, center, edge, and corner regions—that have different resiliency characteristics. Basic pass/fail tests invariably characterize PV module hail resiliency as a simple step function, which cannot capture the complexities of a real-world hailstorm event.

"A primary benefit of VDE's Hail Resiliency Curve Test program is that it smooths out the steps in the hail resiliency characteristics the technical due diligence community relies upon," explains Previtali. "Risk advisers, insurers, and others need to understand the relationship between glass fracture and kinetic impact energy as a continuous probability distribution function. Our new testing program accomplishes this by testing a full pallet of samples to failure, with randomized impact locations across different module regions, enabling statistically meaningful comparisons between different module designs and installation configurations."

"The solar industry has long required a more sophisticated approach to hail testing, one that goes beyond legacy pass/fail techniques," says Cherif Kedir, RETC's president and CEO. "The Hail Resiliency Curve Test fills a critical knowledge gap by providing our customers with actionable data to support the design or procurement of hail-hardened products suitable for deployment in hail-exposed locations."



"Extensive third-party testing can improve customer and insurer confidence in our technology by validating its unique value proposition."

CHAD MEDCROFT
Erthos

Proven hail resilient by design

As the first testing laboratory to offer VDE's Weibull-based, test-to-failure protocol for hail, RETC is uniquely positioned to help manufacturers develop and validate differentiated PV module designs prior to market entry. Early adopters of VDE's ground-breaking Hail Resiliency Curve Test program range from well-established publicly traded companies to insurgent venture-backed startups, representing every segment of the PV module manufacturing landscape.

The Hail Resiliency Curve Test provides manufacturers with unprecedented visibility into solar panel performance in parts of the world exposed to high hail risk. Specifically, this testing program allows companies to optimize hail-hardened PV module designs, while providing downstream customers, insurers, and technical advisors with reliable risk assessment and mitigation data.

"We are using the Hail Resiliency Curve Test to qualify potential glass suppliers and evaluate the business case for standardized versus differentiated product designs," says Chad Medcroft, vice president of products at Erthos. "As the inventor of Earth-mounted solar, we believe the best way to mitigate hail risk is to focus on module resilience rather than rely on tracker operation, which runs counter to convention. Extensive third-party testing can improve customer and insurer confidence in our technology by validating its unique value proposition."

The solar industry's collective response to catastrophic loss events is one of the silver linings associated with an increase in severe weather damage. "Six years ago, virtually all solar trackers were designed to stow flat in response to high-wind events," recalls Brian Grenko, president and CEO of VDE Americas. "That all changed after the technical due diligence community started working with manufacturers and asset owners to more accurately quantify hail damage potential and mitigate risk via product design and system operation improvements. Today, more and more trackers are designed to stow at a maximum tilt angle for both hail and wind, and more and more module companies are developing and commercializing hail-hardened solar panels."

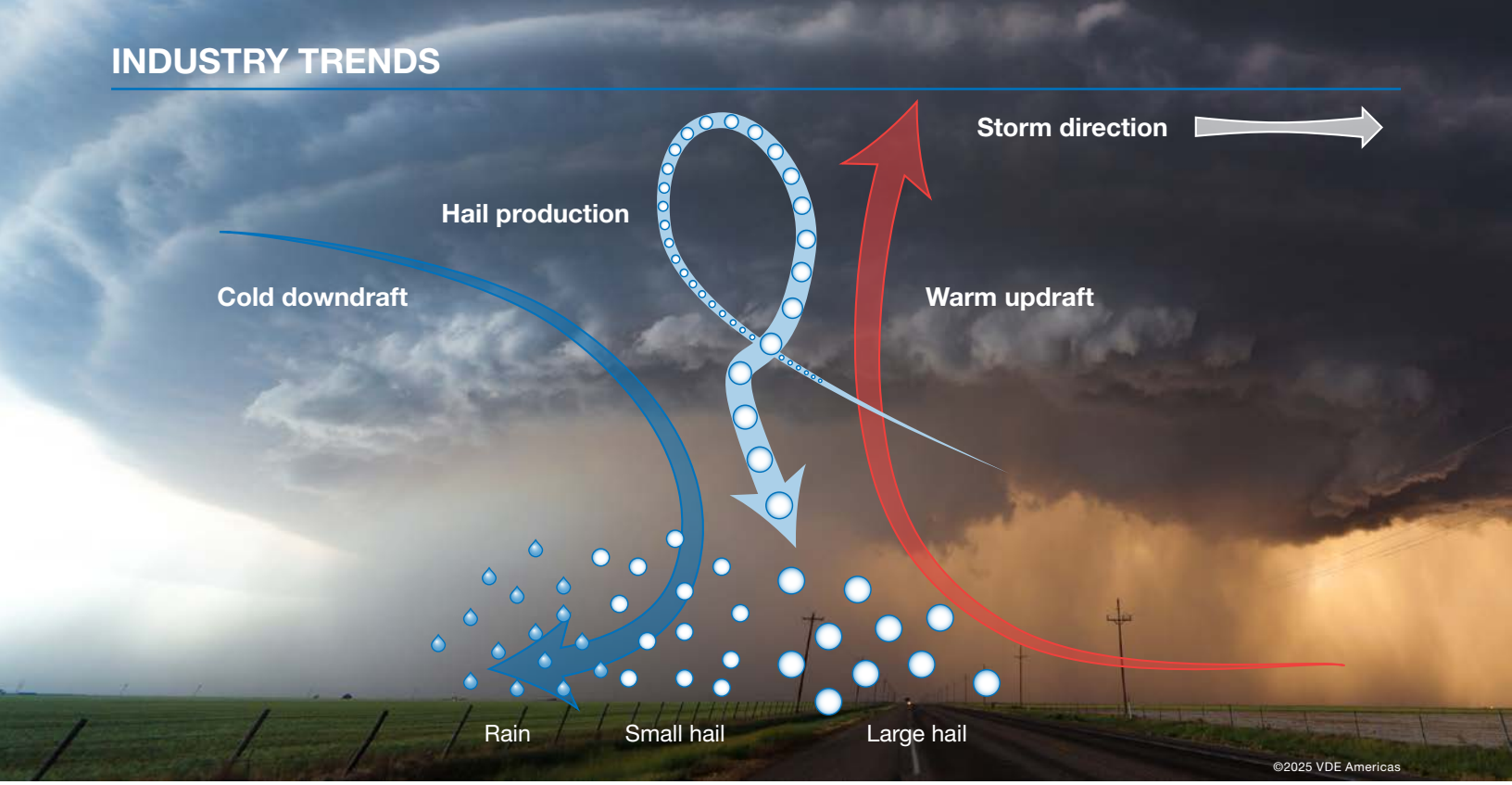
Though large-diameter hail is inevitable in some regions, large project losses are not. Informed by beyond-qualification testing data and calibrated radar-observed meteorological data, solar project financial hail loss models and forensic investigations consistently indicate that properly designed and operated solar farms can withstand the expected conditions of use in even the world's most hail-exposed locations. The margin of design safety will only increase over time, as project stakeholders learn how to automate reliable hail monitoring and stow defenses and module companies master the art of cost-effectively hardening solar modules against hail.



"Today, more and more module companies are developing and commercializing hail-hardened solar panels."

BRIAN GRENKO
VDE Americas





CONVECTIVE STORM GENERATION AND HAIL FORMATION

Scientists predict that large hail will become more common in future climate scenarios. To understand why, we spoke to a meteorologist who has researched and helped map the societal impacts of hail risk.

RETC: What are the key ingredients of a severe convective storm?

DW: Severe convective storm generation requires four primary ingredients. The first key ingredient is high moisture content in the air. Higher dewpoints are more conducive to thunderstorm formation. Another key ingredient is lift, which is a forcing mechanism of some sort that pushes air upward. The lift mechanism could occur at a convergence boundary where large air masses meet, such as along a warm or cold front, or at a physical feature, such as a mountain range that forces air vertically upward. A third key ingredient is atmospheric instability. In the meteorological context, instability refers to a state where the relative temperature of a pocket—or parcel—of air is warmer, less dense, and more buoyant than its surroundings, meaning it can rise freely. The fourth key ingredient is vertical wind shear, which is a change in wind direction or speed with height. Imagine you have 35-mph [56-kph] surface winds out of the west and 100-mph [161-kph] winds out of the north at a height of 10,000 ft [3,048 m]. That wind shear is not only relevant to tornado genesis but also impacts thunderstorm longevity. Wind shear separates the updraft region of a severe convective storm from the downdraft, where the precipitation is happening. Without wind shear, sinking cool air in the downdraft effectively knocks energy out of the vertically moving upward air, resulting in a short-lived storm event.



DENNIS WEAVER is a staff meteorologist for VDE Americas, a technical advisory firm that has supported the financing of over $15 billion in solar and energy storage assets. Dennis began his meteorology studies at Central Michigan University, researching hail damage reports alongside severe hail characteristics alongside Dr. John T. Allen. His master's thesis at Villanova University examined projected changes in climatological hail risk exposure across the United States.

RETC: How does hail form in a severe thunderstorm environment?

DW: When you have these four ingredients, conditions are favorable for the formation of longer-lived supercell storm systems. As these storms are growing, there's a region within the cloud where you find supercooled liquid water—water that remains in a liquid state even though its temperature is below freezing. Supercooled liquid water is crucial for hail formation and usually occurs at an altitude where temperatures range from around 0°C [32°F] to -20°C [-4°F]. Hail forms when supercooled liquid water collides with other small particles, which could be dust, sand, or small ice pellets, and freezes upon contact. If you have enough of that supercooled liquid water and increasing numbers of collisions within the cloud, hail will continue to grow. Moisture content is important to hail growth because it supplies the supercooled liquid water. Stronger updrafts, associated with high levels of atmospheric instability, can hold growing hail embryos in the primary growth region for longer and lead to large hail formation.

RETC: Is there scientific consensus about the impact of anthropogenic warming on hail?

DW: Part of what makes this area of study so interesting is that climate scientists and models need to account for competing effects. On the one hand, a warming climate will increase convective instability. For many locations across the United States, climate models highly project an increase in warm moist air near the Earth's surface. Because stronger updrafts support the transport of moisture into the cloud and increase supercooled liquid water content available for hail formation, this is a recipe for stronger storm systems and larger hail. On the other hand, increasing the depth of the warm surface air layer raises the melting layer height—the height below which hail starts to melt. If you increase the depth of the warm surface air layer by a couple thousand feet, falling hail will spend more time traveling through the melting layer, increasing the degree to which it melts as it falls. Interestingly, larger hailstones are less impacted than smaller ones by an increase in melting potential because larger hailstones have greater mass and fall through the melting layer more quickly. Accounting for these competing effects, future climate scenarios generally predict a decrease in small-diameter hail events but an increase in the probability of large-diameter hail. It's important to note that these are general predictions, and specific changes will vary on a regional basis.

RETC: Can solar project stakeholders screen sites based on hail meteorology?

DW: Yes, but all hail maps are not created equal. As an example, FEMA [Federal Emergency Management Agency] publishes maps that characterize hail risk across the continental United States, ranging from very low hail risk to very high hail risk. If you look at these maps, you see a patchwork of colors rather than smooth contours. The problem with patchwork-patterned hail risk maps is that these invariably exhibit population bias, meaning the exposure values are influenced by the availability of actuarial data or in-field hail spotter reports. Mapping hail risk based only on hail claims and observations, which tend to be concentrated around population centers and areas with agricultural activities, misrepresents risk exposure in remote or undeveloped locations. In other words, hail severity maps with population bias tend to underestimate meteorological risk in prime locations for utility-scale solar development.

"Future climate scenarios generally predict a decrease in small-diameter hail events but an increase in the probability of large-diameter hail."

DENNIS WEAVER
VDE Americas

Growth of a hailstone

Seed

Small suspended particles like dust, sand, or ice crystals

Spherical embryo

Droplets of supercooled liquid water freeze around seed

5mm

Hailstone formation

Held in updraft, one side persistantly faces down; accretion on bottom only

Maximum size for conditions

Random tumbling, accretion on all sides until heavy enough to overcome updraft



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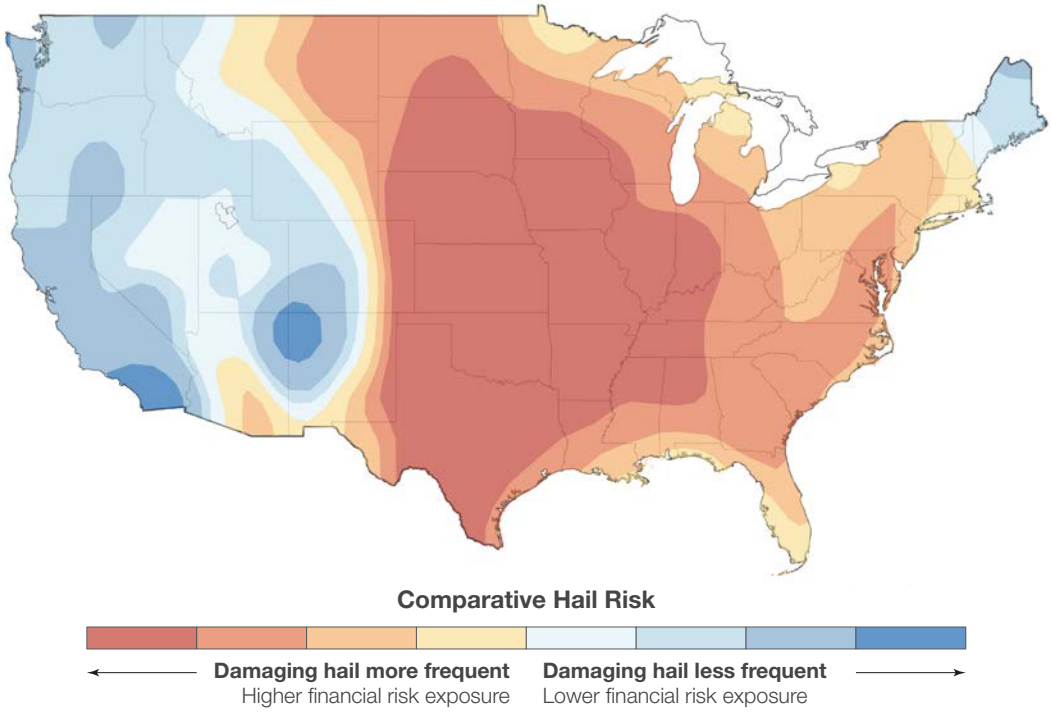
RETC: What is the best practice for mapping hail risk during project development?

DW: To eliminate population bias, you need to map hail risk based on models that fully account for atmospheric phenomena. For the VDE Hail Risk Atlas, a set of ArcGIS-based maps that I help develop and maintain, we map hail risk across the continental United States based on a strategic distribution of approximately 2,500 grid points. At each of these locations, we compute the probability of hail at different sizes based on historical hail observation datasets that include both NEXRAD [Next Generation Weather Radar] and ground observations. The benefit of using the NEXRAD network is it allows for hail identification in these remote areas where we may not be capturing a full set of hail events from ground observations alone. Once we have the full distribution of naturally occurring hail for each of these locations, we use spatial interpolation to estimate risk at unsampled areas of the map. This process allows us to map hail risk as a series of smooth contours. The data sets that VDE offers via subscription in Esri's ArcGIS environment include both meteorological hail risk maps, which characterize the return interval in years for different hail sizes, and financial hail risk maps, which estimate probable maximum loss and average annual loss values based on fielded technology. These advanced ArcGIS maps are very powerful tools for supporting early-stage solar project development activities.



WeatherVideoHD.TV / stock.adobe.com

Hail risk in the continental United States



The hail return interval metric characterizes the estimated amount of time between discrete severe weather events based on hailstone diameter.





SHEDDING LIGHT ON ULTRAVIOLET-INDUCED DEGRADATION

Recent testing to better understand power degradation during highly accelerated UV exposure indicates that laboratory-observed UVID is real, partially reversible, and—perhaps most importantly—entirely preventable.

In the *2024 PV Module Index Report,* RETC flagged UV-induced degradation (UVID) as a potential field reliability issue for some newer high-efficiency PV cell technologies—most notably, n-type tunnel oxide passivated contact (n-TOPCon) devices. Specifically, we not only noted that roughly 40% of UVID test samples degraded by ≥5% but also observed double-digit degradation rates in some mass-produced PV modules.

Since market analysts predict that TOPCon devices could account for 80% of total solar cell shipments in 2025, it is imperative that the technical due diligence community understand UVID causes and effects, especially the extent to which laboratory observations correlate with in-field degradation. With this in mind, RETC has embarked on a series of experiments designed to help identify, characterize, and eradicate UVID risk in commercial PV products. Here, we present preliminary results of these ongoing and evolving investigations.

An encapsulated history of UVID

The solar industry has long managed the harmful effects of UV radiation on fielded PV modules. Industry veterans are undoubtedly familiar with visible module packaging problems resulting from UV exposure, such as encapsulant discoloration, internal delamination, or polymeric backsheet cracking. Module manufacturers and encapsulant suppliers have largely eradicated the UV degradation problems that once contributed to teething issues, such as ethylene vinyl acetate (EVA) browning, in legacy PV modules. UV light

can also contribute to the formation of acetic acid on the encapsulant, which can degrade electrical performance by corroding metalized contacts.

Additionally, UV exposure can damage surface passivation and antireflective coating dielectric layers, causing a degradation in solar cell performance. Though the root causes of these types of UVID appear to vary according to cell type and passivation stack, testing laboratories, researchers, and material scientists all around the world have noted that modern solar cell technologies frequently exhibit comparatively high degradation rates when subjected to accelerated UV exposure. Whereas legacy aluminum back surface field (Al-BSF) PV cells consistently exhibited excellent UV stability, laboratory testing generally indicates that n-type TOPCon PV cells are the commercial technology most vulnerable to UVID.

To test the potential for UV degradation, RETC worked with experts in the technical due diligence community to develop a rigorous beyond-certification UVID testing sequence. As early as 2022, we reported that newer PV cell technologies appeared susceptible to UVID. Other testing laboratories around the world have reported similar results, warning of larger than expected efficiency and voltage losses.

Lessons from the UVID test program

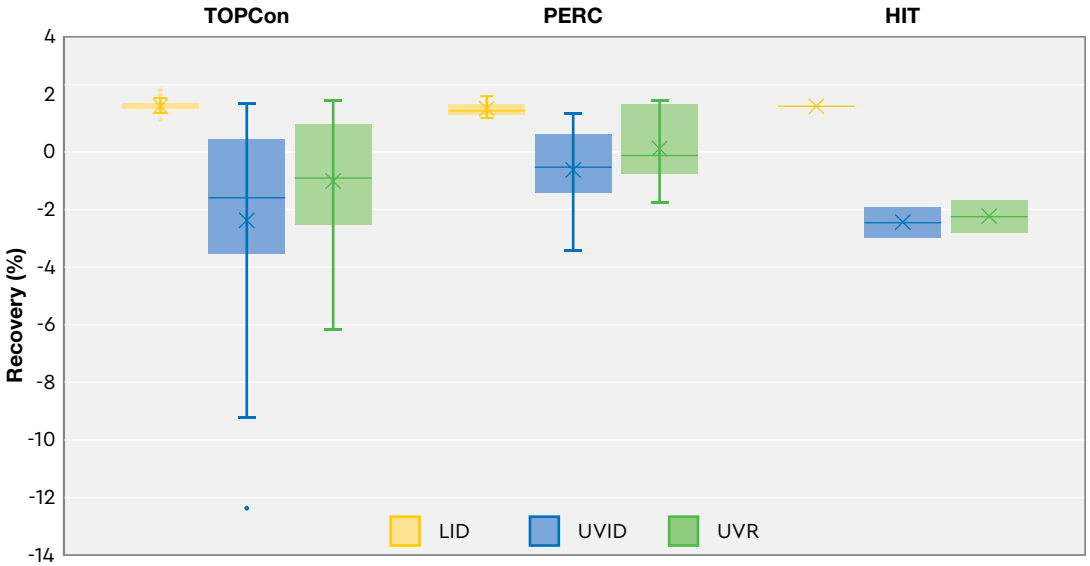
Laboratory-reported levels of UVID susceptibility not only merit industrywide discussion and dialogue but also demand immediate and collective action to ensure that UVID does not become a major reliability issue in fielded PV assets and portfolios. With this in mind, in late 2024, RETC began inviting manufacturers to participate in a series of experiments designed to answer common questions about UV degradation modes and test results. Though simulated long-term exposure testing is still ongoing, here are some preliminary observations about UVID in today's high-efficiency PV technologies based on data collected as part of our dedicated test program.

UVID is not unique to TOPCon devices. As shown in the graph below, three common high-efficiency solar technologies—namely, TOPCon, passivated emitter rear contact (PERC), and silicon heterojunction (HJT)—are all potentially susceptible to high (>2%) UVID rates after 110-hour UV exposure. In our sample set, the median UVID rate for PERC devices was approximately 2%, as compared to nearly 4% for HJT and TOPCon. We observed the highest degradation rates in TOPCon devices, recording >12% degradation in outlier cases and a cluster of results in the 5%–10% range.

Light soaking reverses some UVID effects. Performance recovers in virtually all test samples after exposure to a full-spectrum light source for 1 to 2 hours. While UV recovery is most significant in TOPCon devices, it is also evident in PERC and HJT ones. Full-spectrum light soaking never recovers the full effects of UVID. Given that UV recovery in the laboratory is always partial, some UV damage could be permanent.

UVID is preventable in TOPCon devices. Even before the UV recovery stage, some TOPCon test samples effectively register 0% degradation during 110 kWh UV exposure, which is roughly equivalent to 1 years' worth of in-field exposure on a single-axis tracker. Even after they are subjected to multiple cycles of UV exposure, some bills of materials do not experience high degradation. In other words, some manufacturers have already succeeded in designing and manufacturing UVID-resistant TOPCon modules.

Post-LID UV degradation and recovery for TOPCon, PERC, and HJT



This data visualization charts laboratory-observed power degradation by PV cell technology after the following test sequences: light-induced degradation (LID), ultraviolet-induced degradation (UVID), and UV recovery (UVR) light soak.

Manufacturers can solve UVID problems. The first step in solving a problem with UVID is recognizing that one exists in the first place. RETC has seen this firsthand in its work supporting manufacturers' iterative product design and continuous improvement efforts. After our beyond-qualification testing identified high UVID in a particular test sample, one of our customers decided to try modifying the bill of materials by adding a UV-blocker that shifts UV wavelengths to the blue region. When RETC tested the subsequent product samples, we were happy to report that the bill of material alteration had eliminated the UVID problem. Additional testing is required to assess the overall reliability of this design approach in terms of prolonged exposure to heat, humidity, and thermal cycling.

UVID in real-world applications

Though testing laboratories, material scientists, and researchers have thoroughly documented high UV degradation rates in newer high-efficiency PV cell technologies, it remains unclear whether a correlation exists between these laboratory observations and real-world degradation modes. In an outdoor environment, PV modules are not subject to UV irradiance only but rather to full-spectrum light, which has the ability to reverse UVID and a variety of metastability effects.

If full-spectrum light exposure ameliorates or prevents UV damage in advanced PV modules, we may one day learn that UVID is a laboratory artifact that has little to no effect in fielded projects. Given the current scale of field deployments, however, we recommend that project stakeholders err on the side of caution. After all, developers routinely report perceived instances of solar asset underperformance under real-world conditions of use. If a correlation does exist between laboratory-observed UVID and real-world production losses, it is imperative that we solve the problem as soon as possible.

Record solar capacity additions are a rare beacon of hope on the troubled seas of climate crisis coverage. In 2024, solar markets around the world added approximately 600 GW of new PV power generation capacity, resulting in a cumulative global capacity of over 2.2 TW. These newly commissioned PV power systems accounted for more than three-quarters of the renewable energy capacity installed globally last year.

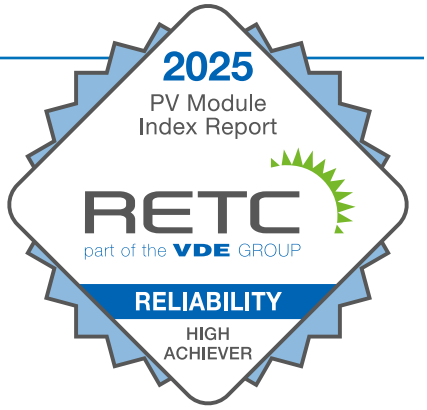
Some climate scientists are skeptical that it remains possible to keep global warming under the 1.5°C target enshrined in the 2015 Paris Agreement. However, most agree that collective efforts to avert the most severe and potentially irreversible human-caused climate impacts cannot succeed without the continued massive expansion of solar generation capacity. In other words, today's solar developments and deployments are truly the critical power generation assets required for a worthwhile future.



While light soaking reverses some UVID effects, UV recovery is always partial, suggesting that some laboratory-observed UV damage is permanent and irreversible.



MODULE RELIABILITY INDICATORS



Reliable operation over a 25- to 30-year warranty period is not a coincidence—it is predictable using highly accelerated life testing.

To characterize long-term in-field reliability, industry stakeholders—including subject matter experts at RETC and other organizations within the VDE Group—have developed enhanced testing standards, procedures, and sequences that go beyond minimum product safety and design qualification requirements. These beyond-qualification test protocols put additional stress on modules to identify areas of weakness and better predict long-term in-field reliability.

While product certification and qualification are essential first steps on the road to reliability, beyond-qualification testing data clearly shows that some PV modules are more resilient to severe hail impacts, whereas other products are more vulnerable. At the same time, products that test well for hail durability may be at an elevated risk of degradation when installed in a hot, humid location. Intelligent solar development recognizes and leverages these differences.

Success or failure in the field could come down to this simple question: What is the right tool for the job? All PV module and project installation environments are not the same. Strategic design adaptation ensures that fielded solar projects can withstand site-specific risks while optimizing investor returns and maximizing benefits to homeowners, businesses, and communities.

RELIABITY DISCIPLINE CRITERIA

Category	Evaluation Method	High Achiever
Backsheet ultraviolet durability	DH1000 + [3 x (UV65 + TC50 + HF10)] + UV6.5	No backsheet cracking
Damp heat	DH2000 + B-O LID	<2% degradation
Hail durabilty test	HDT + TC50 + Hot Spot	>20-joule impact
Potential-induced degradation	PID192 + UV2	<2% degradation
Static and dynamic mechanical load	SML + DML + TC50 + HF30	<2.5% degradation
Thermal Cycling	TC600	<2% degradation
Ultraviolet-induced degradation	UV220 (front) + UV66 (back)	<2.5% degradation

Informed by the comparative results of highly accelerated stress testing, diligent project developers, owners, and insurers can take science- and engineering-based steps to mitigate severe weather risks and prevent catastrophic loss events. By specifying appropriate technologies during the project design phase, stakeholders can avoid time-consuming warranty claims or costly litigation after the commercial operation date.

For the 2025 edition of the *PV Module Index Report,* RETC identified seven important reliability evaluation categories, summarized here in the "Reliability Discipline Criteria" table. The source data in the reliability discipline derive from either RETC's Thresher Test or Hail Durability Test programs. Within individual categories, we recognize manufacturers of products that exceed carefully calibrated reliability indicator thresholds as test category high achievers. In the year-in-review section (p. 48), we further showcase manufacturers of products that consistently exceed our high-achiever requirements in the reliability discipline.

Backsheet ultraviolet durability test (BUDT)

For PV modules with glass-on-backsheet packaging, there is a strong correlation between module reliability and backsheet durability. The polymeric backsheet's role is to protect the PV cells and interconnects from moisture intrusion, environmental contamination, corrosion, and degradation. Ultraviolet (UV) aging is a primary aging factor for polymeric backsheet materials. In a worst-case scenario, UV aging can cause backsheet cracking, compromising module performance and safety.

To probe glass-on-backsheet PV module designs for vulnerabilities to UV exposure, RETC's Thresher Test program incorporates a durability testing sequence designed to prevent backsheet-related failures in fielded PV power systems. The BUDT sequence starts with 1,000 hours of damp heat exposure to weaken polymeric bonds. Subsequently, it exposes test samples to three consecutive rounds of rear-side UV exposure, followed by 50 thermal cycles and 10 humidity-freeze cycles. The sequence closes with an additional round of UV exposure (6.5 kWh/m^2). By screening unreliable or incompatible backsheet materials out of the market before they make it into field installations, this Thresher Test sequence improves new product designs and real-world project reliability.

BUDT* HIGH ACHIEVERS
Manufacturer (in alphabetical order)
JinkoSolar
Qcells
VSUN Solar

*Applies to glass-on-backsheet models only.

For test category high achiever recognition in the *2025 PV Module Index Report,* RETC required that all glass-on-backsheet PV module models withstand BUDT exposure without cracking occurring in the polymeric material. We considered any evidence of backsheet cracking during visual inspection to be a red-flag result in this sequence because it presents a potential electrical safety hazard. For the second year running, 100% of test samples met our high-achiever requirements for BUDT. Note that glass-on-glass module designs, which provide a superior level of UV resistance and PV cell protection, are not subject to the BUDT sequence.

Damp heat (DH)

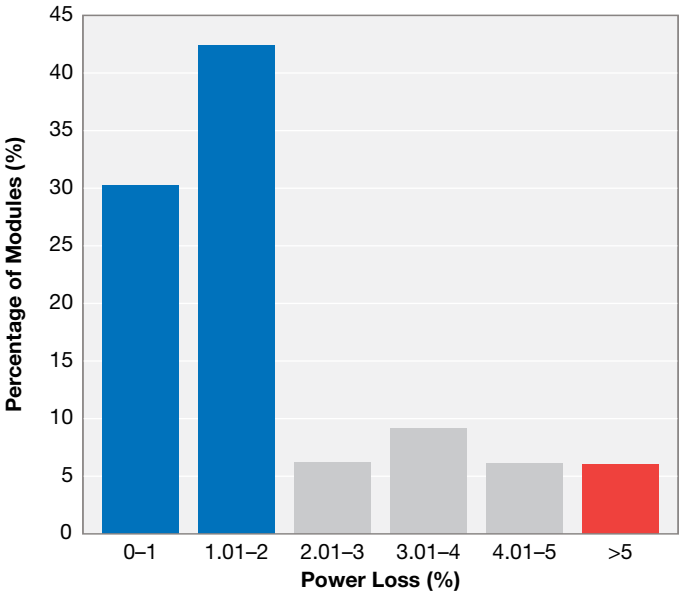
RETC's bankability test program includes a DH testing sequence that characterizes a PV module's ability to withstand prolonged exposure to hot and humid environments. This sequence takes place inside an environmental test chamber and exposes modules to a controlled temperature of 85°C (185°F) and a relative humidity of 85% for a set amount of time. Specifically, the Thresher Test's DH sequence has a 2,000-hour duration of exposure (DH2000)—twice the duration typically required for product certification (DH1000). After DH exposure, samples undergo a modified boron-oxygen light-induced (B-O LID) regeneration test, as B-O LID can impact certain advanced PV cells.

In the 2024 edition of the *PV Module Index Report,* RETC had noted that newer high-efficiency PV module technologies appeared to be more susceptible to damp heat as compared to earlier aluminum back surface field (Al-BSF) PV cell technologies. As newer high-efficiency solar cell technologies—including p-PERC, n-TOPCon, and HJT—displaced Al-BSF in the marketplace, the technical due diligence community generally observed a gradual increase in damp heart vulnerability.

However, reviewing the data aggregated in this testing sequence for the 2025 report, RETC is pleased to report that this disconcerting trend line has reversed course. In our most recent data set, we note a significant improvement in DH results on a year-over-year basis both in terms of high-achiever and red-flag results. Specifically, the percentage of model BOMs that met our test category high-achiever criteria rose from 31% to 73%. Whereas 18% of samples returned a red-flag result in this sequence one year ago, the red-flag percentage dropped this year to 6%.

For the test category high achiever recognition in the *2025 PV Module Index Report,* RETC required that test samples withstand DH2000 exposure with less than 2% degradation in maximum power. We considered maximum power degradation greater than or equal to 5% a red-flag result that could compromise a product's ability to perform reliably over a 25- or 30-year period. A total of 13 manufacturers met our high-achiever criteria in the DH sequence.

Damp Heat 2000



DH SEQUENCE HIGH ACHIEVERS

Astronergy, Canadian Solar, DAS Solar, DMEGC Solar, JA Solar, JinkoSolar, LONGi Solar, Runergy, SolarSpace, Trina Solar, VSUN Solar, Waaree, and Yingli Solar met our DH test category high achiever criteria.

KEY DH TAKEAWAYS

- 73% of models tested met DH high-achiever criteria.
- 6% of models tested returned a DH red-flag result.
- 13 different manufacturers were DH high achievers.

Hail Durability Test (HDT)

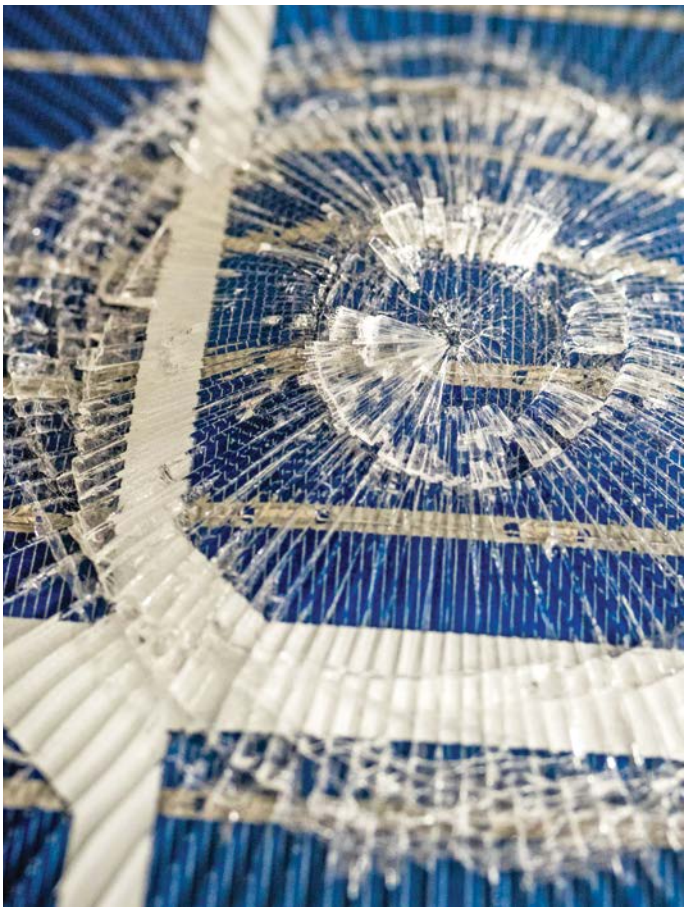
Within the context of the Thresher Test program, beyond-qualification ballistic-impact testing is an optional rather than a core sequence. However, virtually all PV module designs are unscathed by the basic ballistic-impact tests found in IEC certification standards. To pass IEC 61215-2, a module design must withstand 11 impacts of 25-mm (1-in.) ice balls traveling at their terminal velocity, which results in a modest kinetic impact energy of 2 joules.

While these minimum pass-fail test criteria served the industry well for decades, they have not prevented catastrophic loss events as solar deployments have increased in frequency and scale in hail-exposed regions. In May 2019, a severe hailstorm in West Texas damaged more than 400,000 modules at the Midway Solar farm, resulting in losses on the order of $70 million. Three years later, *Business Insurance* magazine reported that "U.S. renewable energy insurers were expected to pay out more than $300 million in claims" resulting from the 2022 hail season in Texas. Most recently, in March 2024, the Fighting Jays solar project, located 30 miles south-by-southwest of Houston, made headlines after a series of 1-in-500-year hailstorms decimated parts of the 350-MW site, reportedly resulting in $50 million hail claim.

The sudden increase in catastrophic hail loss events highlights the need for beyond-certification testing to ensure that large-scale solar projects can withstand severe weather events over a 25- or 30-year project life. This is especially true for projects deployed in hail-prone locations, such Texas and other high-growth U.S. solar markets east of the Rockies.

To address this gap, RETC's HDT sequence expands upon existing IEC standards to probe vulnerabilities to glass breakage and cell cracking and classify products based on severe hail resilience. This sequence exposes modules to 45-mm diameter freezer iceball impacts, followed by 50 thermal cycles and hot-spot endurance testing per IEC 61215. The HDT sequence's final characterization includes visual inspection, electroluminescence testing, and maximum power measurements.

To better prevent catastrophic module field failures and mitigate financial losses in new field deployments, RETC and its sister company, VDE Americas, recently introduced an enhanced commercial hail-impact testing program. As detailed previously (see pp. 12–16), the new Hail Resiliency Curve Test characterizes impact resilience according to a highly granular test-to-failure methodology. The resulting information-rich hail resiliency curves will improve the fidelity and accuracy of the financial hail risk models that industry stakeholders use to inform site selection, product specification, and insurance terms and conditions. This program is open for business now and its results will inform future editions of this report.



For test category high achiever recognition in the *2025 PV Module Index Report,* RETC required that HDT samples withstand an effective kinetic energy of at least 20 joules while achieving a Class A rating for hail durability. A Class A hail classification indicates that a test sample experienced less than 1% maximum power degradation upon completion of the hail durability test sequence without incurring significant visual abnormalities or defects. Modules with fully tempered front glass generally outperform those with heat-strengthened front glass in the HDT sequence. Because the hail durability test is an optional sequence within the Thresher Test program, RETC did not establish a red-flag threshold in this category.

HDT* HIGH ACHIEVERS

Manufacturer (in alphabetical order)
JA Solar
JinkoSolar
LONGi Solar
Runergy

*Optional test sequence.

Potential-induced degradation (PID)

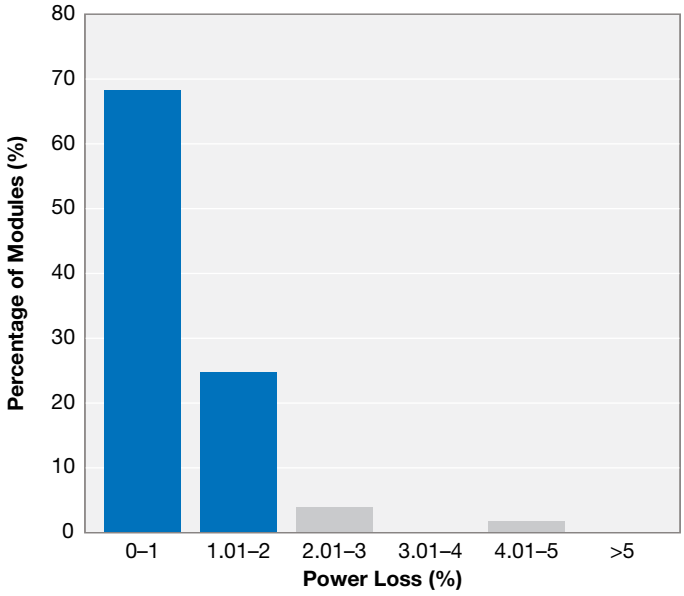
The Thresher Test includes a PID testing sequence that characterizes a PV module's ability to withstand degradation due to shunting (PID-s) or surface polarization (PID-p). This sequence places rack-mounted modules in an environmental chamber exposes them to a voltage bias of several hundred volts with respect to the mounting structure while controlling temperature and humidity. The Thresher Test PID sequence requires a 192-hour duration of exposure (PID192), which is double the exposure time required for product certification (PID96).

PID risks vary depending on the cell technology. Whereas legacy Al-BSF technologies are at risk of PID-s, newer high-efficiency p-PERC, n-TOPCon, and n-HJT cell technologies are vulnerable to both PID-s and PID-p. While some amount of PID is reversible with UV light exposure, NREL has demonstrated that this recovery is not field representative. If the technical due diligence community decides to remove the rear-side post-PID UV light soak step from the IEC 61215 standard, RETC will adapt its Thresher Test sequence accordingly.



For test category high achiever recognition in the *2025 PV Module Index Report,* RETC required that PV module models withstand PID192 exposure with less than 2% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 5% a red-flag result. Reviewing the data aggregated in this testing sequence for the 2025 report, RETC is pleased to note an improvement in PID results on a year-over-year basis, both in terms of high achiever and red flag results. Specifically, the percentage of high achievers increased from 83% to nearly 94% while the percentage of red flags decreased from 6% to 0%.

Potential induced degradation



PID SEQUENCE HIGH ACHIEVERS

Astronergy, Canadian Solar, DAS Solar, DMEGC Solar, JA Solar, JinkoSolar, LONGi Solar, Qcells, Risen Energy, Runergy, SolarSpace, Trina Solar, VSUN Solar, Waaree, and Yingli Solar met our PID test category high achiever criteria.

KEY PID TAKEAWAYS

- 94% of models tested met PID high-achiever criteria.
- 0% of models tested returned a PID red-flag result.
- 15 different manufacturers were PID high achievers.

Static and dynamic mechanical load (SDML)

RETC's Thresher Test includes an SDML sequence to characterize a PV module's ability to withstand transportation stressors, snow and ice loads, and dynamic push-pull loads associated with hurricanes, typhoons, and other high-wind events. After static mechanical loading, dynamic mechanical loading subjects PV modules to 1,000 cycles of ±1,000 pascal (Pa) loads at a frequency of three to seven cycles per minute. Subsequently, test samples are placed in an environmental chamber and undergo TC50 testing followed by HF30 testing. Measurements taken upon completion capture post-SDML performance characteristics.

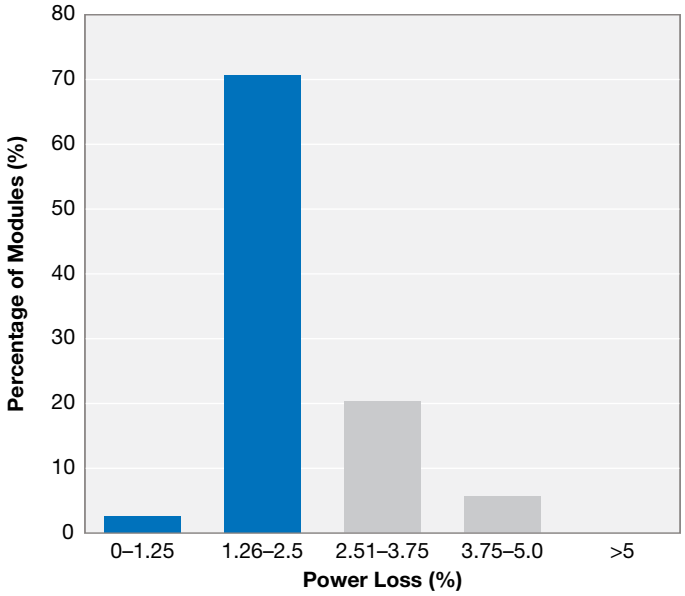
Double-glass PV modules that use two sheets of glass with the same thickness generally outperform other product designs in the SDML sequence. PV cells packaged between identical sheets of glass are effectively placed in a neutral axis, reducing cell fracture risks. Glass-backsheet module designs, which perform well in the HDT sequence, tend to underperform in the SDML sequence. This is especially true if the module junction box contacts the torque tube while the module is under load, as this can cause cell breakage.

For test category high achiever recognition in the *2025 PV Module Index Report,* RETC required that PV module models withstand SDML exposure with less than 2.5% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 5% to be a red-flag result. Reviewing the data aggregated in this SDML testing sequence for the 2025 report, RETC is pleased to report a slight a year-over-year improvement in the high achiever results and a notable reduction in red-flag results. Specifically, the percentage of high achievers increased from 72% to nearly 74% while the percentage of red flags decreased from 6% to 0%.

KEY SDML TAKEAWAYS

- 72% of models tested met SDML high-achiever criteria.
- 0% of models tested returned an SDML red-flag result.
- 13 different manufacturers were SDML high achievers.

Static and dynamic mechanical load





SDML SEQUENCE HIGH ACHIEVERS

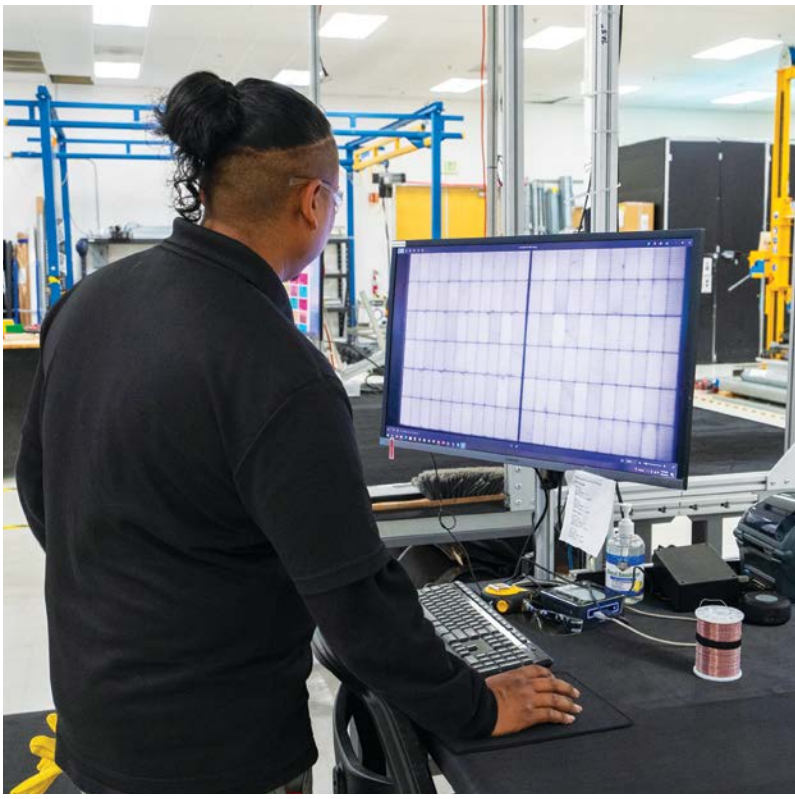
Astronergy, Canadian Solar, DAS Solar, DMEGC Solar, JA Solar, JinkoSolar, LONGi Solar, Qcells, Runergy, SolarSpace, Trina Solar, VSUN Solar, and Yingli Solar met our SDML test category high achiever criteria.

Thermal cycling (TC)

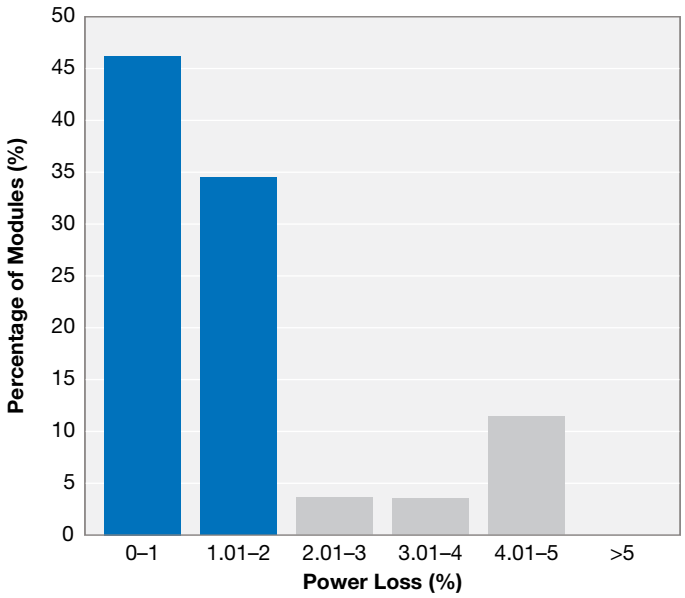
The Thresher Test includes a TC testing sequence to characterize a PV module's ability to withstand stresses associated with diurnal and annual temperature fluctuations. The TC sequence calls for cycling modules in an environmental chamber between two temperature extremes, 85°C (185°F) on the high end and -40°C (-40°F) on the low end. The Thresher Test requires a 600-cycle TC sequence (TC600), which is triple the requirement for product certification (TC200). The goal of TC testing is to probe module designs for thermal fatigue failure modes, ensuring a long operational lifetime.

Historically, a best PV module design practice for TC resilience was to use all-silver paste and lead-based soldering. As the industry transitioned from all-silver pastes to silver-aluminum ones and, in some cases, unleaded solder coatings, researchers and testing laboratories have observed some variations in TC results. Paste selection can affect the adhesiveness of the metallization layer bonded to PV cell contacts, as observed with n-TOPCon type PV cells. Meanwhile, n-HJT technologies are susceptible to TC degradation due to the relatively low-temperature soldering process required to avoid damaging the amorphous silicon layer(s).

TC sequence results are especially relevant for project deployment in operating environments characterized by wide diurnal-to-nocturnal temperature swings. All else being equal, p-PERC and n-TOPCon tend to perform reasonably well in the TC sequence, though perhaps not as well as legacy Al-BSF cell technologies. More busbars on the PV cells tends to lead to better TC results, assuming the pastes and solder coatings are robust.



Thermal cycling



TC SEQUENCE HIGH ACHIEVERS

Astronergy, Canadian Solar, DAS Solar, DMEGC Solar, JA Solar, JinkoSolar, LONGi Solar, Runergy, SolarSpace, Trina Solar, VSUN Solar, Waaree, and Yingli Solar met our TC test category high achiever criteria.

For test category high achiever recognition in the *2025 PV Module Index Report,* RETC has required that PV module models withstand TC600 exposure with less than 2% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 5% a red-flag result. Reviewing the data aggregated in TC sequence for the 2025 report, RETC is pleased to report a meaningful year-over-year improvement in both high-achiever and red-flag results. Specifically, the percentage of high achievers increased from 71% to nearly 85% while the percentage of red flags decreased from 8% to 0%.

KEY TC TAKEAWAYS

- 85% of models tested met TC high-achiever criteria.
- 0% of models tested returned a TC red-flag result.
- 13 different manufacturers were TC high achievers.

Ultraviolet-induced degradation (UVID)

RETC's Thresher Test includes a UVID testing sequence to characterize a PV module's ability to withstand ultraviolet-induced degradation. This testing sequence exposes test sample front sides to 220 kWh/m^2 of UV exposure (UV220), nearly 15 times the UV exposure required for product certification (UV15), and backsides to 66 kWh/m^2 of UV exposure (UV66), followed by a light soak phase for UV recovery. For context, UV220 equates to roughly 3 years of UV exposure in a tracker application, which is well within the wear-in period of the Weibull bathtub curve that basic certification testing aims to cover.

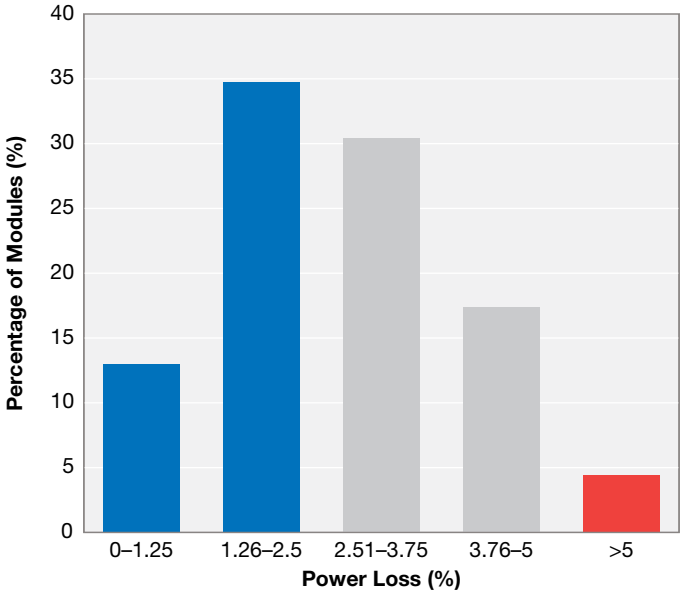
In recent years, the technical due diligence community has noted a rise in UVID susceptibility in newer, high-efficiency commercial PV cell technologies. Specifically, surface passivation and antireflective coating dielectric layers in p-PERC, n-TOPCon, and n-HJT cell technologies appear susceptible to permanent and irreversible breakdown under UV exposure. This effect occurs and reaches saturation during the first few years of operation, when predictable investor returns are most critical. Notably, the effect signature is indicative of short-circuit current and open-circuit voltage degradation rather than fill factor degradation.

To help module companies and the technical due diligence community better understand UVID risk in TOPCon PV devices, RETC is conducting a series of experiments designed to answer common questions regarding laboratory-observed test results, such as: Is UVID transient or permanent? To what extent does light soaking reverse UVID effects? Is UVID a linear, non-linear, or sudden-drop degradation mode? What is the best way to test for UVID? RETC encourages module companies to submit multiple BOMs for inclusion in this first-of-its-kind UVID Test Program. Partner organizations will receive an engineering report with BOM-specific test sample results compared to anonymized summary data. Moreover, RETC will feature its partners and test program results at NREL's 2026 PV Reliability Workshop.



For test category high achiever recognition in the *2025 PV Module Index Report,* we required that PV module models withstand the UVID sequence with less than 2.5% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 5% a red-flag result. Reviewing the data aggregated for the 2025 report, RETC is pleased to report a modest year-over-year improvement in the high achiever results and a dramatic reduction in red flag results. Specifically, the percentage of high achievers increased from 40% to nearly 48% while the percentage of red flags decreased from 60% to 4%.

Ultraviolet-induced degradation



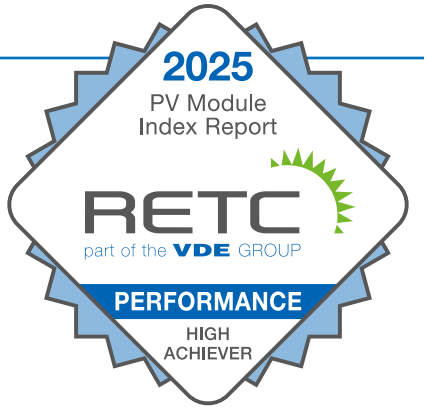
UVID SEQUENCE HIGH ACHIEVERS
JA Solar, JinkoSolar, LONGi Solar, Runergy, SolarSpace, VSUN Solar, Waaree, and Yingli Solar met our UVID test category high achiever criteria.

KEY UVID TAKEAWAYS

- UVID results improved dramatically on a year-over-year basis.
- 48% of models tested met UVID high-achiever criteria.
- 4% of models tested returned a UVID red-flag result.
- 8 different manufacturers were UVID high achievers.


30x UV
WEATHERING

MODULE PERFORMANCE INDICATORS



Third-party performance characterization in an accredited laboratory is foundational to a bankable solar project financial pro forma.

As a highly accredited provider of product certification and bankability testing, RETC plays a critical role in PV performance characterization and optimization. Our laboratory and outdoor testing services help manufacturers identify cell-level degradation mechanisms and module-level failure modes during product development. In parallel, our work assures owners, insurers, financiers, and independent engineers that mass-produced PV products will perform as expected during commercial operations. Our state-of-the-art testing laboratories use calibrated and certified equipment under audited and controlled conditions. Performance characteristics captured under these rigorous test conditions are the true measure of PV module performance.

A bankable solar project financial pro forma relies on independent third-party PV module performance characterization. To meet investor expectations, solar project engineers must be able to accurately and confidently model energy yields for any project location. This is exceedingly difficult given the rapid rate of technological innovation and solar market expansion. From a materials science or mechanical engineering perspective, PV modules today are substantially different from those the industry installed just five or 10 years ago. Meanwhile, solar has eclipsed other energy sources to become the leading source of new power generation capacity globally.

As solar projects increase in scale, frequency, and geographical distribution, project stakeholders must remain vigilant regarding performance risks. How do different technologies perform under low-irradiance conditions or in relation to changing sun angles? Is a specific bill of materials susceptible to irradiance- or temperature-induced degradation under expected conditions of use? Will modules and systems perform as expected under the peak power conditions critical to energy yield optimization? Laboratory data enable a science- and engineering-based understanding of both short- and long-term PV system performance.

For the 2025 edition of the *PV Module Index Report,* RETC identified seven important performance evaluation categories. As summarized in the "Performance Discipline Criteria" table, the categories include specific extended testing sequences as well as important figures of merit. The source data in this discipline derive from either RETC's Thresher Test or our California Energy Commission (CEC) testing. Within individual categories, we recognize manufacturers of products that exceed thoughtfully calibrated performance indicator thresholds as test category high achievers. In the year-in-review section (p. 48), we further highlight manufacturers of products that consistently meet or exceed our high-achiever requirements in the performance discipline.

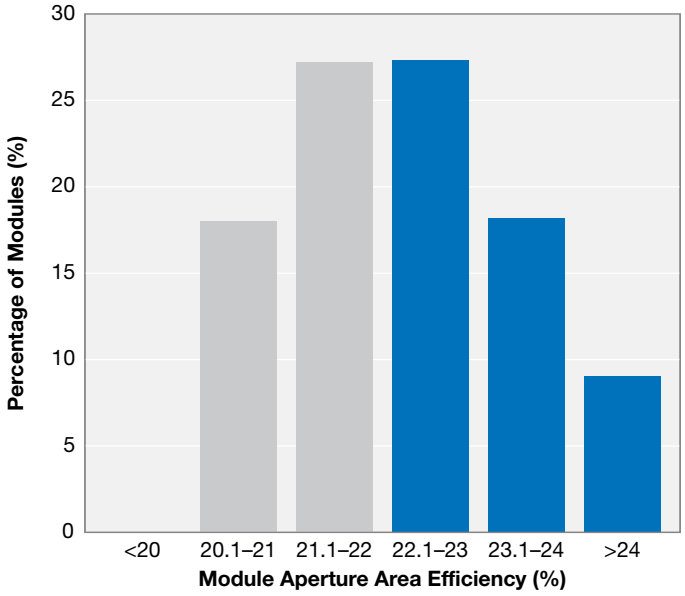
PERFORMANCE DISCIPLINE CRITERIA

Category	Evaluation Method	High Achiever
Module efficiency	CEC testing	≥22%
Incidence angle modifier	CEC testing or Thresher Test	>88% at 70° AOI
Light- and elevated temperature–induced degradation	B-O CID + LETID486	<0.5% degradation
Light-induced degradation	Outdoor light soaking per IEC 61215-2	≤0.5% degradation
PAN file characterization	IEC 61853-1 and performance ratio (PR)	>85% PR
PTC-to-STC ratio	CEC testing	≥94%
Temperature coefficient of power	CEC testing or Thresher Test	<-0.3%/°C

Conversion efficiency

RETC captures PV module conversion efficiency data as part of its CEC testing for manufacturers. To qualify for various solar incentive programs around the United States, PV module models must be included on an eligible equipment list that the CEC maintains. Importantly, the CEC does not accept manufacturer's self-reported data. RETC is one of the accredited third-party laboratories most active in CEC testing. Nominal module conversion efficiency is determined by dividing a product's nameplate maximum power rating under standard test conditions by its total aperture area.

Conversion efficiency



MODULE EFFICIENCY HIGH ACHIEVERS
Astronergy, JA Solar, Mission Solar, and Trina Solar met our module efficiency test category high achiever criteria.

Procuring products with high-efficiency solar cell designs is pointless if device-level maximum power output degrades in the field due to material incompatibilities, poor-quality materials, or poor manufacturing processes related to the laminate stack. In other words, high conversion efficiency in Year 0—or during a factory or laboratory flash test—is a meaningful metric only if it correlates with high efficiency over a 25- to 30-year operating life. Over the life of a PV power system, module conversion efficiency has as much to do with the materials that make up the module's laminate stack as it does with PV cell efficiency.

In the *2025 PV Module Index Report,* RETC has recognized manufacturers of PV module models with conversion efficiencies greater than or equal to 22% as test category high achievers. This level of performance is indicative of sophisticated high-efficiency cell designs. We have not applied red-flag criteria in this category. In this testing category, we note a year-over-year improvement in high achiever results. Specifically, the high achiever percentage increased from 56% to nearly 64%, even though we raised the conversion efficiency high achiever threshold by from 21% to 22%.

While conversion efficiency is a key figure of merit for PV modules, it is also in many cases a function of PV module cell technology. For example, the p-type passivated emitter rear contact (p-PERC) PV cells that are popular today offer improved initial efficiency at time zero as compared to legacy aluminum back surface field (Al-BSF) technologies. Meanwhile, n-type tunnel oxide passivated contact (n-TOPCon) and n-type silicon heterojunction (n-HJT) PV cell technologies provide manufacturers with a roadmap for even higher-efficiency product deigns in the future. While conversion efficiency advancements provide value throughout the industry and contribute to the widespread adoption of solar energy, project stakeholders must remain diligent regarding performance risk.

KEY EFFICIENCY TAKEAWAYS

- 64% of models tested met efficiency high-achiever criteria.
- 27% of models tested achieved >23% efficiency.
- 4 different manufacturers were efficiency high achievers.

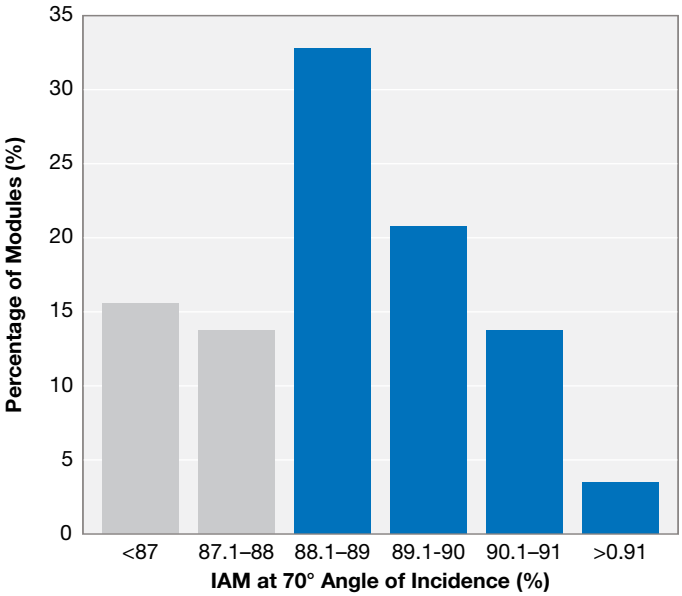


Incidence angle modifier (IAM)

RETC captures IAM data as part of the Thresher Test program or during its CEC testing for manufacturers. IAM is a performance characteristic that accounts for changes in PV module output in relation to changing sun angles relative to the plane of the array. To characterize IAM, RETC conducts electrical characterization tests at different incidence angles, ranging from 0° to 90° as prescribed in IEC 61853-2. These accredited third-party laboratory data mitigate performance risk and facilitate project bankability reviews.

IAM is an important part of a PV module's PAN file, a performance characterization software file that informs energy production and financial performance models. Specifically, IAM accounts for how much light transmits through the surface of the module glass and encapsulants and reaches the PV cell when the solar angle of incidence is not normal to the plane of the array. IAM measurements are essential for understanding module performance at different times and in different seasons, especially early or late in the day or in wintertime, when the sun is more frequently closer to the horizon. It is also relevant for understanding geographical effects, such as module performance at latitudes farther from the equator.

Incidence angle modifier



IAM HIGH ACHIEVERS

Astronergy, DAS Solar, JA Solar, JinkoSolar, LONGi Solar, Meyer Burger, Mission Solar, Qcells, Risen Energy, Runergy, Silfab Solar, SolarSpace, Tata Power Solar, Trina Solar, VSUN Solar, and Waaree met our IAM test category high achiever criteria.



In the *2025 PV Module Index Report,* RETC has recognized manufacturers of PV module models with an IAM greater than 88% at a 70° angle of incidence (AOI) as test category high achievers. This level of performance is indicative of a low-loss optical design under typical operating conditions. We have not applied red-flag criteria in this category. In this testing category, we note that 71% of samples qualified as high achievers. In subsequent editions of this report, we plan to raise the bar for IAM high-achiever status to better differentiate between BOMs.

KEY IAM TAKEAWAYS

- 71% of models tested met IAM high-achiever criteria.
- 16 different manufacturers were IAM high achievers.

Light- and elevated temperature–induced degradation (LETID)

RETC's Thresher Test program requires a LETID testing sequence to investigate a product's susceptibility to light- and elevated temperature–induced degradation. This sequence consists of three 162-hour rounds of 75°C (167°F) temperature exposure in an environmental chamber while connected to a power supply simulating maximum power operation under full sun conditions. The sequence also incorporates a boron-oxygen current-induced degradation (B-O CID) preconditioning step. LETID test results are used to identify hydrogenation state changes in boron-doped p-PERC and similar PV cells. LETID results are also relevant as an input to energy production software models.

LETID is a form of module degradation that affects specific high-efficiency PV cell technologies. For example, boron-doped p-PERC PV cells require advanced hydrogenation processes to mitigate extreme boron-oxygen light-induced degradation (B-O LID), which introduce LETID risks. Gallium-doped p-PERC PV cells, which do not require advanced hydrogenation, are not as susceptible to LETID. LETID risk is low in n-type PV cell technologies. Cadmium telluride thin-film devices are not susceptible to LETID.

For test category high achiever recognition in the *2025 PV Module Index Report,* RETC required that PV module models withstand B-O CID plus LETID486 exposure with less than 0.5% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 2.5% a red-flag result. In this testing category, we note that 82% of the test samples qualified as high achievers whereas 0% returned red-flag results.

LETID HIGH ACHIEVER
Manufacturer (in alphabetical order)
Astronergy
Canadian Solar
DAS Solar
DMEGC Solar
JA Solar
JinkoSolar
LONGi Solar
Meyer Burger
Risen Energy
Runergy
SolarSpace
VSUN Solar
Waaree
Yingli Solar

KEY LETID TAKEAWAYS

- 82% of models tested met LETID high-achiever criteria.
- 0% of models tested returned a LETID red-flag result.
- 14 different manufacturers were LETID high achievers.



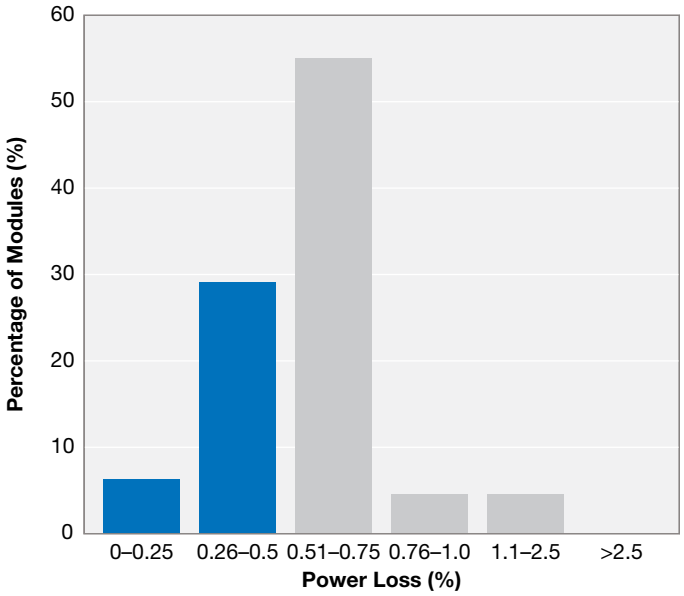
Light-induced degradation (LID)

The Thresher Test program requires a LID sequence to investigate a product's susceptibility to degradation resulting from initial exposure to sunlight. This LID test sequence consists of outdoor light soaking in accordance with IEC 61215-2. PV modules that are prone to LID might experience a relatively rapid rate of performance degradation over a relatively short time in the field—ranging from a few hours to a few weeks, depending on the PV cell technology—before performance stabilizes.

KEY LID TAKEAWAYS

- 35% of models tested met LID high-achiever criteria.
- 0% of models tested returned an LID red-flag result.
- 12 different manufacturers were LID high achievers.

Light-induced degradation



LID HIGH ACHIEVERS

Adani Solar, Canadian Solar, DMEGC Solar, JA Solar, JinkoSolar, LONGi Solar, Qcells, Runergy, Silfab Solar, SolarSpace, VSUN Solar, and Waaree met our LID test category high achiever criteria.

LID impacts some PV cell types but not others. For example, LID risk is low in gallium-doped p-type PV cell technologies but high in boron-doped p-type PV cells. While manufacturers can utilize advanced hydrogenation processes to mitigate B-O LID risk in boron-doped p-PERC cells, this approach introduces LETID risks. Therefore, module designers must balance B-O LID versus LETID risk exposure. Cadmium telluride thin-film devices and n-type PV cell technologies are not susceptible to LID.

For test category high achiever recognition in the *2025 PV Module Index Report,* RETC required that PV module models withstand the LID sequence with less than or equal to 0.5% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 2.5% a red-flag result. Reviewing the data aggregated for the 2025 report, RETC notes mixed results characterized by decreases in both high-achiever and red-flag results. Specifically, the percentage of high achievers decreased from 57% to nearly 35% while the percentage of red flags decreased from 4% to 0%.



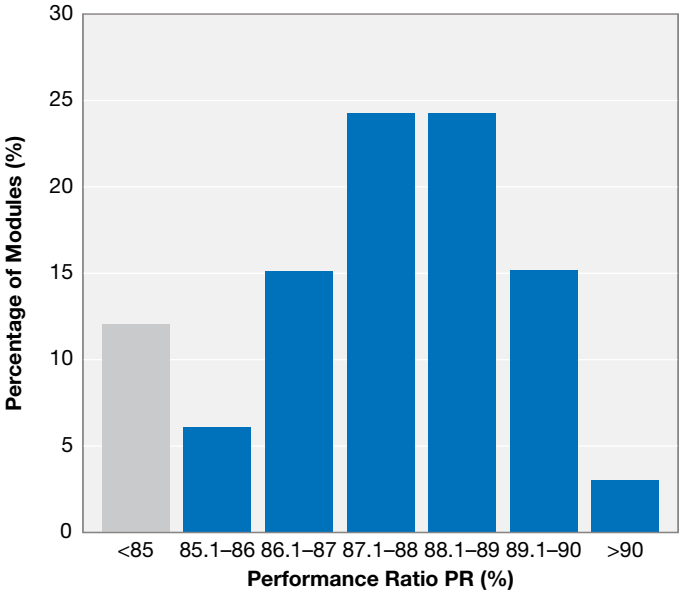
PAN file characterization

PAN files are text-only software files that characterize PV module performance parameters in accordance with IEC 61853. RETC uses state-of-the-art equipment under controlled conditions to generate its third-party PAN files. These small files do a lot of heavy lifting in the context of the PV performance modeling used to inform project bankability assessments. Once imported into industry-standard software, such as PVsyst, these independently verified module-specific performance parameters allow for accurate and bankable energy production estimates.

To identify test category high achievers, RETC conducted PVsyst simulations using its third-party PAN files. These simulations assume a 10 MW utility-scale solar plant in Midland, Texas, deployed using fixed-tilt ground mounts and 500 kVA-rated central inverters. While minor design details may vary per simulation—based on product-specific capacity ratings and so forth—the DC-to-AC inverter loading ratios are functionally equivalent. We then aggregated and compared the results of these simulations on the basis of annual performance ratio.

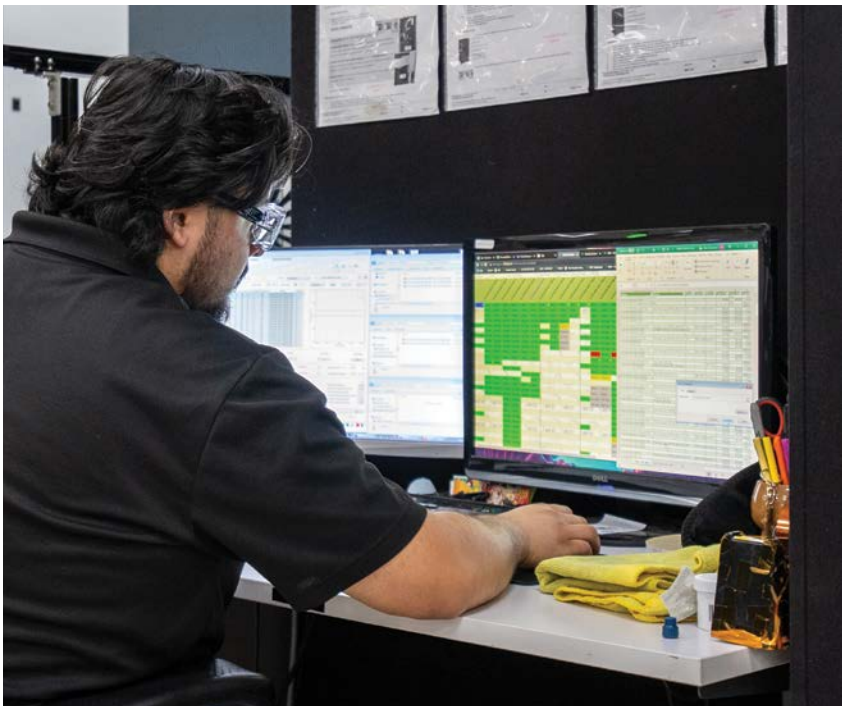
In the *2025 PV Module Index Report,* RETC has recognized manufacturers of PV module models that returned a performance ratio greater than 85% in our PVsyst simulations. We have not applied red-flag criteria in this category. Key drivers of PAN file performance include low-light performance and bifaciality factor. In this testing category, we note that 88% of the test samples qualified as high achievers. In subsequent editions of this report, we plan to raise the bar for PAN file high-achiever status to better differentiate between BOMs.

PAN file characterization



PAN FILE HIGH ACHIEVERS

Astronergy, DA Solar, DMEGC, JA Solar, JinkoSolar, LONGi Solar, Maxeon, Meyer Burger, Mission Solar, Qcells, Risen Energy, Silfab Solar, SolarSpace, VSUN Solar, Waaree, and Yingli met our PAN file test category high achiever criteria.



KEY PAN TAKEAWAYS

- 88% of models tested met PAN file high-achiever criteria.
- 18% of models tested achieved a >89% performance ratio.
- 16 different manufacturers were PAN file high achievers.

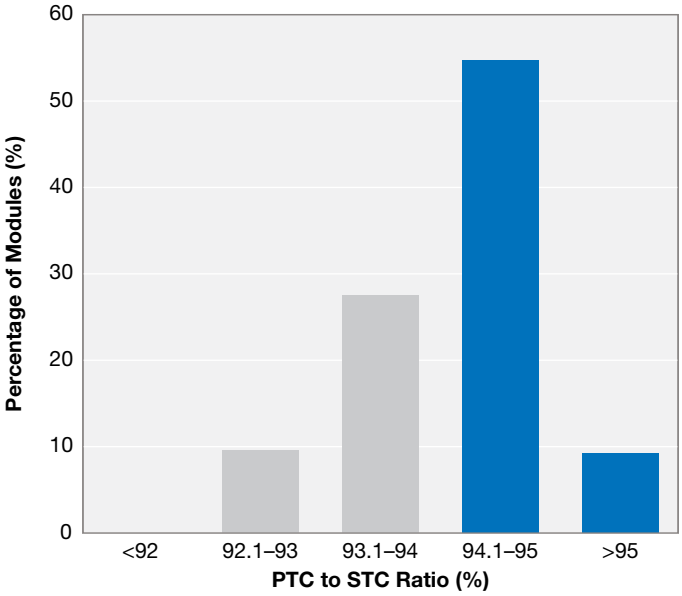
PTC-to-STC ratio

In the 1990s, researchers working on the Photovoltaics for Utility-Scale Applications (PVUSA) project developed a set of performance rating parameters designed to simulate the environmental conditions a module might encounter in the real world. The primary differences between PVUSA test conditions (PTC) and standard test conditions (STC) are cell temperature and wind speed. Specifically, PTC parameters require an elevated cell temperature as compared to standard test conditions, resulting in a lower nominal power rating.

RETC captures PTC and STC performance data as part of its CEC testing for manufacturers. A high PTC-to-STC ratio is of particular interest to project stakeholders as a figure of merit. Products with a high PTC-to-STC metric generally utilize cell technologies that experience less power reduction at elevated temperatures.

In the *2025 PV Module Index Report,* RETC has recognized manufacturers of PV module models that achieved a PTC-to-STC ratio greater than or equal to 94% as test category high achievers. We have not applied red-flag criteria in this category. Reviewing the PTC-to-STC ratio data aggregated for the 2025 report, RETC is please to report an improvement in the year-over-year data. Specifically, the percentage of high achievers increased from 50% to nearly 64%.

PTC-to-STC ratio



PTC-TO-STC HIGH ACHIEVERS

Astronergy, JA Solar, Meyer Burger, Mission Solar, Qcells, and Trina Solar met our PTC-to-STC ratio test category high achiever criteria.



KEY PTC TAKEAWAYS

- 64% of models met PTC-to-STC ratio high-achiever criteria.
- 9% of models achieved a >95% PTC-to-STC ratio.
- 6 manufacturers were PTC-to-STC ratio high achievers.

Temperature coefficient

RETC captures temperature coefficient data as part of the Thresher Test program or during it CEC testing for manufacturers. This performance characteristic accounts for changes in PV module maximum power, current, and voltage due to varying cell temperature conditions. Specifically, the temperature coefficient describes the percentage change in power for each degree Celsius (%/°C) relative to standard test conditions (25°C).

Module output power decreases as cell temperature rises. Therefore, all temperature coefficients of power are negative values (such as -0.3%/°C). For data visualization purposes, however, we are showing these data as absolute values, according to the distance of the number from 0. A lower value in the temperature coefficient chart indicates improved performance under elevated temperature conditions. Results in this category are largely driven by specific properties of the PV cell p-n junction, with n-HJT PV cells providing the best performance, followed by n-TOPCon, p-PERC, and p-type Al-BSF technologies, in that order.

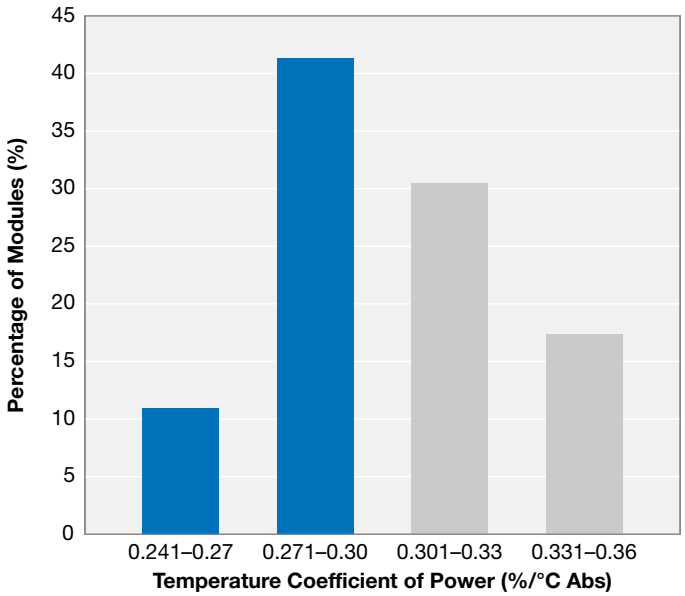
In the *2025 PV Module Index Report,* RETC has recognized manufacturers of PV module models with temperature coefficient values less than -0.3%/°C as test category high achievers. We have not applied red-flag criteria to temperature coefficient results. Reviewing the temperature coefficient data aggregated for the 2025 report, RETC is pleased to report an improvement in the year-over-year data. Specifically, the high achiever percentage increased from 29% to slightly more than 52%

KEY TC TAKEAWAYS

- 52% of models met temperature coefficient high-achiever criteria.
- 11% of models achieved a temperature coefficient ≤-0.27%/°C.
- 14 manufacturers were temperature coefficient high achievers.



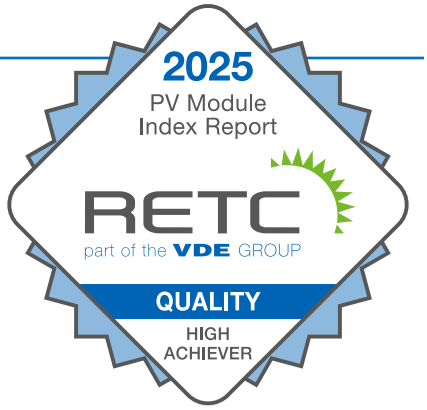
Temperature coefficient



TEMPERATURE COEFFICIENT HIGH ACHIEVERS

Astronergy, JinkoSolar, LONGi Solar, Meyer Burger, Qcells, REC Solar, Risen Energy, Runergy, Silfab Solar, SolarSpace, Trina Solar, VSUN Solar, Waaree, and Yingli Solar met our temperature coefficient test category high achiever criteria.

MODULE QUALITY INDICATORS



Beyond-qualification bankability testing allows stakeholders to differentiate seemingly similar PV modules based on build quality.

Products and materials that appear very similar on paper may perform, wear out, or break down very differently under actual conditions of use. A commitment to quality often accounts for these differences in real-world applications. When combined with third-party factory witness BOM verification, RETC's comparative Thresher Test program data helps ensure that fielded projects meet stakeholder expectations by empowering them to distinguish between high- and low-quality products.

Imagine two nominally equivalent solar power systems installed in identical operating environments with the expectation of a 25-year service life. In a downside scenario, the PV modules at Project A fail prematurely and need to be replaced in Year 12. In an upside scenario, the PV modules at Project B exceed expectations and remain in service until Year 50. In practice, the only difference between these wildly different outcomes might be a seemingly insignificant bill of materials change.

To meet the expectations of solar project stakeholders, PV modules and systems must withstand harsh operating conditions while meeting or exceeding performance predictions over a 25- to 30-year service life. Sourcing high-quality PV modules optimizes energy yields, investor confidence, decarbonization benefits, and energy security. It is, however, a complex and interconnected undertaking, especially in the context of a terawatt-scale market.

To facilitate exponential market growth, module companies must manufacture products in high volumes without compromising durability and performance. Inspectors and auditors must verify that factories are controlling quality in their supply chain management, material handling, and manufacturing processes. Accredited laboratories must analyze and test random product samples leaving the factory and arriving at the project site. Perhaps most importantly, beyond-qualification testing ensures that products are engineered and manufactured to meet user expectations, which is the ultimate measure of quality.

QUALITY DISCIPLINE CRITERIA	
Category	**Evaluation Method**
Bill of materials	Third-party factory bill of materials verification
High achievement in reliability	Product recognized as high achiever in three or more reliability categories*
High achievement in performance	Product recognized as high achiever in three or more performance categories

*Glass-on-backsheet products must meet high achiever requirements for BUDT plus at least three additional reliability test sequences.

As summarized in the "Quality Discipline Criteria" table, RETC applied three evaluation criteria for the quality discipline for the *2025 PV Module Index Report.* These categories include third-party factory BOM verification and cross-disciplinary reliability and performance evaluations. These categories reflect the fact that commercial PV modules must excel in both reliability and performance to meet stakeholder expectations. In the year-in-review section (p. 48), we celebrate manufacturers of products that check all quality discipline boxes as "Overall Highest Achievers."

Thresher Test overview

Holding PV modules to a higher standard by probing manufacturing and material quality is the fundamental concept behind our Thresher Test program. Basic IEC and UL certification tests focus primarily on ensuring performance and safety over the wear-in phase of the product's lifetime, meaning the first few years of outdoor operation. More rigorous testing is required to ensure PV modules can withstand the expected 25- to 30-year service life implied by modern PV module warranties.

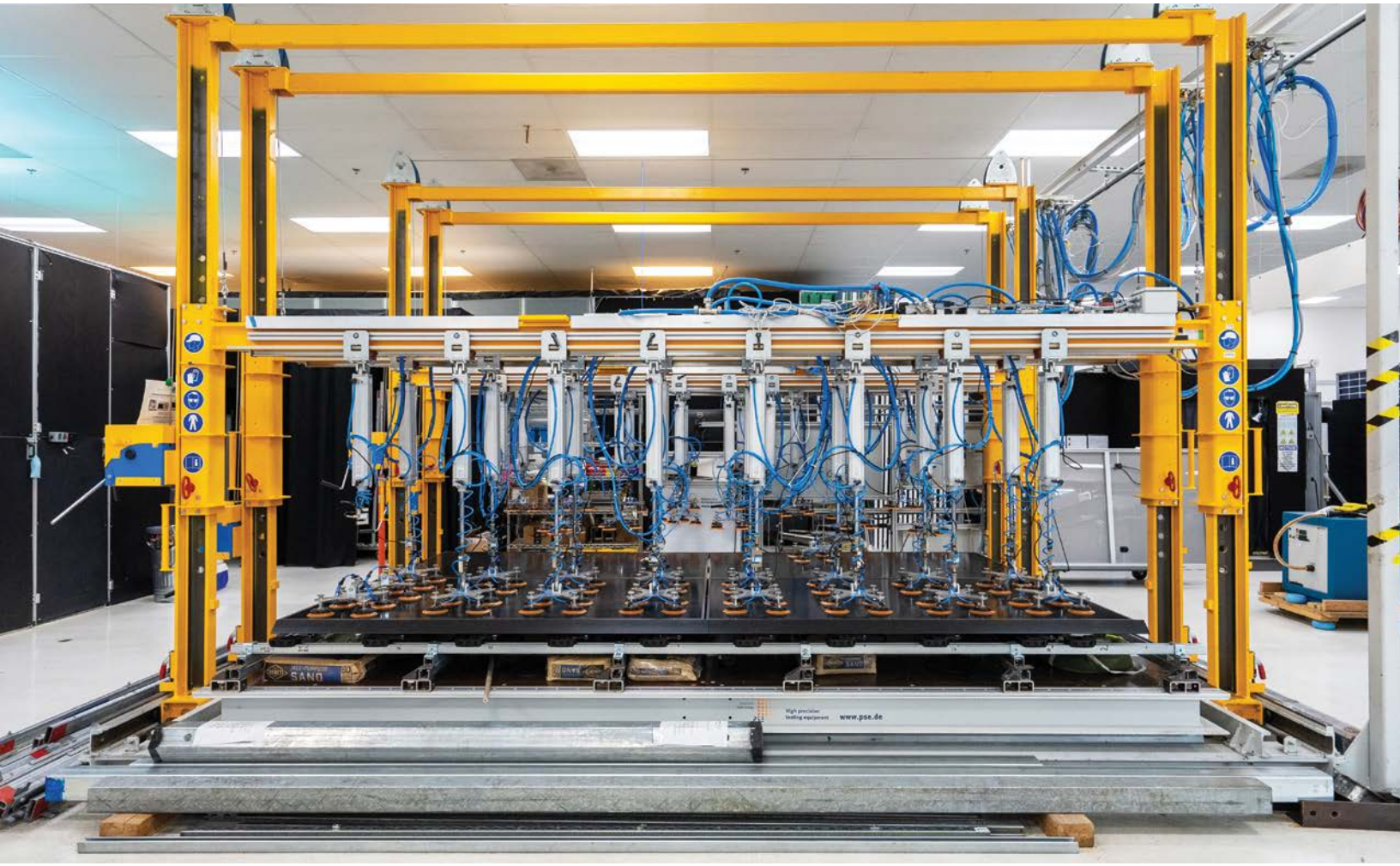
The development of the Thresher Test was a joint industry effort, one that began in earnest approximately 16 years ago. The stakeholder working group included leading module manufacturers and notable subject matter experts from NREL and Sandia National Laboratories. Since the program goal was to develop a protocol that any independent testing laboratories could implement, the working group also included RETC, TÜV Rheinland, TÜV SÜD, and others. Collectively, the group selected Hugh Kuhn to serve as project leader. As a technical advisor for an early solar independent power producer, Kuhn had an interest in engineering due diligence to support bankability assessments.

RETC played a critical role as the program coordinator. Due to manufacturer concerns about intellectual property, module companies were understandably reluctant to share their internal testing protocols with industry competitors. As a workaround, manufacturers agreed to share testing program details with RETC under a non-disclosure agreement. By guaranteeing data anonymity, RETC could review manufacturer testing protocols against an NREL database of failure modes observed in fielded PV power plants or during product certification testing.

On July 15, 2011, Hugh Kuhn and RETC's Alelie Funcell introduced the cooperatively developed Thresher Test to the world as part of the International PV Module Quality Assurance Forum in San Francisco. Having grown up in a farming community, Kuhn named the extended test protocol after a type of farm equipment used to separate seed and grain (the good stuff) from straw and chaff (the bad stuff). Much as a threshing machine beats up a plant to separate useful materials from waste, the Thresher Test uses stress sequences to separate good products from bad ones.

As the program coordinator, RETC was the first independent testing laboratory to offer the Thresher Test. Other laboratories followed suit, making the Thresher Test the solar industry's original commercial test standard for characterizing PV module designs based on long-term performance, reliability, and durability. In the years since its introduction and adoption as the de facto standard for comparative PV module testing, RETC has adapted or added Thresher Test sequences to better align test outcomes with the latest field-failure data. This commitment to continuous improvement ensures that the industry's first commercial bankability test for PV modules remains the final word on product design and manufacturing quality.

> "To separate the wheat from the chaff, the Thresher Test development team expanded standard accelerated testing sequences to much longer cycles and times."
>
> **HUGH KUHN**
> Thresher Test Program Lead



Red flags

RETC has highlighted red-flag results for specific testing sequences throughout the *2025 PV Module Index Report.* A red-flag result is a measured value that raises questions about a product's ability to perform reliably in the field and meet stakeholder expectations over a 25- or 30-year lifetime. Red-flag results could be indicative of an immature cell technology, an incompatible BOM, a departure from quality during a manufacturing or assembly process, or an expected statistical variance in high-volume manufacturing. Test samples that return red-flag results do not qualify for "Overall Highest Achiever" recognition.

To set red-flag thresholds, RETC relied on best engineering judgment. We polled internal and external subject matter experts who participate in IEC project team meetings and industry working groups. We compared Thresher Test data across multiple years. We considered both experimental and anecdotal evidence linking trends in laboratory test data to observed field failure or degradation modes. We looked for outliers in our annual test results. Based on this holistic analysis, we set red-flag thresholds for specific test categories to highlight test results that are likely to correlate with elevated technical risk in field deployments.

Reviewing the metadata for the 2025 report, RETC is pleased to report a significant year-over-year improvement in the red-flag results. Specifically, the total percentage of BOMs returning red-flag results decreased from 14% in 2024 to less than 3% in 2025. This dramatic improvement speaks to the industry's ability to solve material science, supply chain, and manufacturing challenges. Beyond-qualification testing ensures that stakeholders have the ability to identify and remedy these types of problems during early-stage product development and commercialization, before design deficiencies propagate across high-volume field deployments.

SUMMARY DATA AND RED FLAGS BY MODEL

PV Module Index Report Test Category	High Achievement		Red Flag	
	Threshold	Percentage	Threshold	Percentage
Backsheet ultraviolet durability	No cracking	100%	Backsheet cracking	0%
Potential-induced degradation	<2% degradation	94%	≥5% power degradation	0%
PAN file characterization	>85% PR	88%	—	—
Thermal cycling	<2% degradation	85%	≥5% power degradation	0%
Light- and elevated temperature–induced degradation	<0.5% degradation	80%	≥2.5% power degradation	0%
Damp heat	<2% degradation	73%	≥5% power degradation	6%
Incidence angle modifier	>88% at 70° AOI	71%	—	—
Hail durability test	>20-joule impact	70%	—	—
Module efficiency	>22%	64%	—	—
PTC-to-STC ratio	≥94%	64%	—	—
Static and dynamic mechanical load	<2.5% degradation	53%	≥5% power degradation	0%
Temperature coefficient of power	<-0.3%/°C	52%	—	—
Ultraviolet-induced degradation	<2.5% degradation	48%	≥5% power degradation	4%
Light-induced degradation	≤0.5% degradation	35%	≥5% power degradation	0%
OVERALL	See p. 10	13%	—	3%

Bill of materials (BOM) verification

The Thresher Test—and the heuristic thresholds applied to its various testing sequences—are intended to identify high-quality module types and models. Though beyond-certification testing is essential for identifying high-quality PV modules, it is only the first of many technical due diligence steps required to construct a long-lifetime solar project. After entering into a high-volume supply agreement, stakeholders must remain vigilant to deviations from quality product designs. This is the role of third-party factory BOM verification, which ensures that products delivered to the project site will consistently meet the high standards established by rigorous Thresher Testing.

As a placeholder for on-site sample witness and BOM verification, RETC has elected to recognize in the *2025 PV Module Index Report* those manufacturers who used an independent third party to randomly select PV modules from inventory for Thresher Testing. Random sampling ensures that manufacturers do not cherry-pick only the highest-quality PV modules for Thresher Testing. This practice demonstrates that a module company is committed to transparency and has full confidence in its manufacturing quality programs.

BOM VERIFICATION HIGH ACHIEVER
Manufacturer (in alphabetical order)
Adani Solar
Astronergy
Canadian Solar
DAS Solar
DMEGC Solar
JA Solar
JinkoSolar
LONGi Solar
Qcells
Risen Energy
Runergy
Silfab Solar
SolarSpace
Trina Solar
VSUN Solar
Waaree
Yingli Solar




RETC PV
CER
答谢
RECIPRO
铂驷


ETC
YMI AWARDS
REMONY
谢晚宴
OCAL BANQUET
多功能厅

OVERALL HIGHEST ACHIEVERS

Analyzing our annual PV module test results, 13% of models tested met RETC's rigorous standard for our top accolade—recognition as an "Overall Highest Achiever."

In this preliminary June 2025 release of the *PV Module Index Report,* RETC has recognized 21 module manufacturers for some form of high achievement across the 14 different testing sequences included within the reliability and performance disciplines. As was the case last year, we will publish a final report release in September 2025, which will capture the results of any remaining long-duration testing sequences.

2025 PV Module Index Report
RETC part of the VDE GROUP
OVERALL HIGHEST ACHIEVER

To achieve RETC's top honor, module companies had to meet high achievement criteria in three disciplines: module reliability, performance, and quality. In other words, "Overall Highest Achiever" status effectively indicates that RETC recognizes these companies for "High Achievement in Reliability," "High Achievement in Performance," and "High Achievement in Quality." This is an exceptionally high bar to pass.

To identify top PV module models and manufacturers in our annual data set, we first evaluated data distributions within specific sequences. We then identified thresholds for high achievement and red-flag results based on engineering best judgment and a review of scientific literature. Subsequently, we analyzed these summary data and established holistic criteria for recognition, which are included in this report for transparency.

Based on a thorough review of beyond-qualification test results collected at RETC's highly accredited independent testing laboratories between Q2 2024 and Q1 2025, we have identified 12 manufacturers that met or exceeded our rigorous criteria for our "Overall Highest Achiever" recognition. RETC commends these module companies for consistently achieving excellence in PV module manufacturing.

ASTRONERGY
DASOLAR
DMEGC SOLAR
JA SOLAR
JinKO Solar
LONGi Solar
RUNERGY 润阳股份
SolarSpace 中润光能
Trinasolar
VSUN Innovative & Smart
WAAREE One with the Sun
YINGLI SOLAR

Caveat emptor

While laboratory-observed module reliability and performance indicators trended in a positive direction on a year-over-year basis, we remind downstream stakeholders that due diligence for project procurement is considerably more complex than simply entering into a supply agreement with a manufacturer we have recognized for high achievement in PV module manufacturing. Even the best module manufacturers sometimes make PV modules that underperform in Thresher Test sequences. Buyers who want to source high-quality BOMs and avoid low-quality ones should request a copy of RETC's Thresher Test report from the manufacturer.

> "To procure high-performing modules within a specific test sequence or discipline, contact manufacturers directly to request a model- and BOM-specific Thresher Test report."
>
> **CHERIF KEDIR**
> RETC

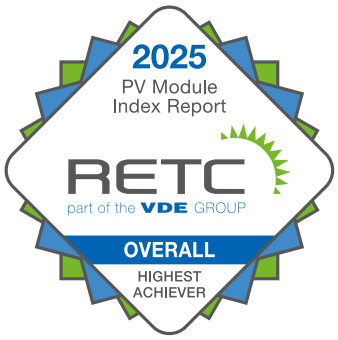
Representing an extreme downside scenario, a PV module model submitted by a developer to RETC for Thresher Testing in 2023 returned red-flag results in both reliability and performance test sequences. Upon further investigation, we discovered that these test samples had not been directly sourced from a factory but had been stored for an unknown period in a warehouse and subsequently resold. This double red-flag result serves as a reminder that the bitterness of poor quality persists long after the sweetness of a low price is forgotten. If a deal seems too good to be true, it usually is.

Outlier cases aside, a more pervasive procurement threat is currently hiding in plain sight. Today, established solar manufacturing landscapes and supply chains are shifting in unprecedented ways, in some cases driven by tax credits and other incentives, but more often by duties, tariffs, and other regulatory pressures. It is difficult to build a foundation for success on these shifting sands. In recent rounds of bankability testing, RETC has observed an increase in PV cell-related issues, many of which have not been seen in our bankability testing for the better part of a decade, underscoring the importance of having a plan in place to mitigate supply chain risks.

Recent testing has also shown how novel technologies tend to degrade in novel ways, revealing evidence of structural deficiencies, such as PV module frame and glass failures during mechanical loading, cyclical loading, and ballistic-impact testing. These red-flag results serve as a reminder that industry stakeholders must remain vigilant regarding the technical risks inherent in an accelerated pace of change and the short time frames between innovation and mass production. It is incumbent on the technical due diligence community to anticipate teething issues associated with new technologies and product designs and to test, validate, and verify accordingly. Although we may trust in a higher power, all others must provide evidence.



2025 AWARD SUMMARY



ASTRONERGY

DASOLAR

DMEGC SOLAR

JA SOLAR

JinKO Solar

LONGi Solar

RUNERGY 润阳股份

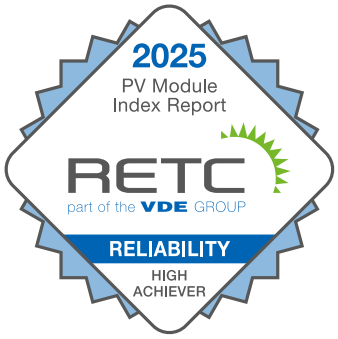
SolarSpace 中润光能

Trinasolar

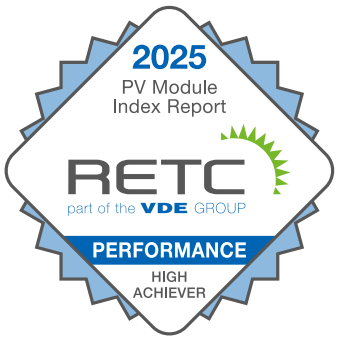
VSUN Innovative & Smart

WAAREE One with the Sun

YINGLI SOLAR



CanadianSolar

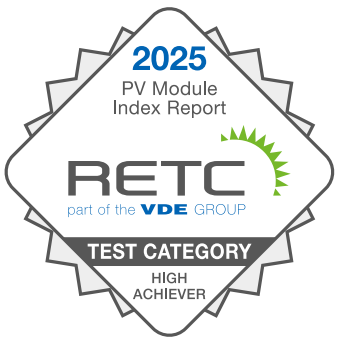


MEYER BURGER

MISSION SOLAR ENERGY

Q CELLS a Hanwha company

SILFAB SOLAR



adani Solar

risen

TATA

TATA POWER SOLAR

REC

2025 TEST CATEGORY RESULTS

HIGH ACHIEVEMENT IN RELIABILITY

Astronergy • Canadian Solar
DAS Solar • DMEGC Solar • JA Solar
JinkoSolar • LONGi Solar • Runergy
SolarSpace • Trina Solar • VSUN Solar
Waaree • Yingli Solar

RELIABILITY DISCIPLINE HIGH ACHIEVERS

BUDT

JinkoSolar • Qcells • VSUN Solar

Damp Heat

Astronergy • Canadian Solar • DAS Solar
DMEGC Solar • JA Solar • JinkoSolar • LONGi Solar
Runergy • SolarSpace • Trina Solar • VSUN Solar
Waaree • Yingli Solar

HDT

JA Solar • JinkoSolar • LONGi Solar • Runergy

PID

Astronergy • Canadian Solar • DAS Solar
DMEGC Solar • JA Solar • JinkoSolar • LONGi Solar
Qcells • Risen Energy • Runergy • SolarSpace
Trina Solar • VSUN Solar • Waaree • Yingli Solar

SDML

Astronergy • Canadian Solar • DAS Solar
DMEGC Solar • JA Solar • JinkoSolar • LONGi Solar
Qcells • Runergy • SolarSpace • Trina Solar
VSUN Solar • Yingli Solar

TC

Astronergy • Canadian Solar • DAS Solar
DMEGC Solar • JA Solar • JinkoSolar • LONGi Solar
Runergy • SolarSpace • Trina Solar • VSUN Solar
Waaree • Yingli Solar

UVID

JA Solar • JinkoSolar • LONGi Solar • Runergy
SolarSpace • VSUN Solar • Waaree • Yingli Solar

HIGH ACHIEVEMENT IN PERFORMANCE

Astronergy • DAS Solar • DMEGC Solar
JA Solar • JinkoSolar • LONGi Solar
Meyer Burger • Mission Solar • Qcells • Runergy
Silfab Solar • SolarSpace • Trina Solar
VSUN Solar • Waaree • Yingli Solar

PERFORMANCE DISCIPLINE HIGH ACHIEVERS

EFFICIENCY

Astronergy • JA Solar • Mission Solar • Trina Solar

IAM

Astronergy • DAS Solar • JA Solar • JinkoSolar
LONGi Solar • Meyer Burger • Mission Solar
Qcells • Risen Energy • Runergy • Silfab Solar
SolarSpace • Tata Power Solar • Trina Solar
VSUN Solar • Waaree

LETID

Astronergy • Canadian Solar • DAS Solar
DMEGC Solar • JA Solar • JinkoSolar • LONGi
Solar • Meyer Burger • Risen Energy • Runergy
SolarSpace • VSUN Solar • Waaree • Yingli Solar

LID

Adani Solar • Canadian Solar • DMEGC Solar
JA Solar • JinkoSolar • LONGi Solar • Qcells • Runergy
Silfab Solar • SolarSpace • VSUN Solar • Waaree

PAN FILE

Astronergy • DAS Solar • DMEGC Solar • JA Solar
JinkoSolar • LONGi Solar • Maxeon • Meyer Burger
Mission Solar • Qcells • Risen Energy • Silfab Solar
SolarSpace • VSUN Solar • Waaree • Yingli Solar

PTC-TO-STC

Astronergy • JA Solar • Meyer Burger
Mission Solar • Qcells • Trina Solar

TEMP COEFFICIENT

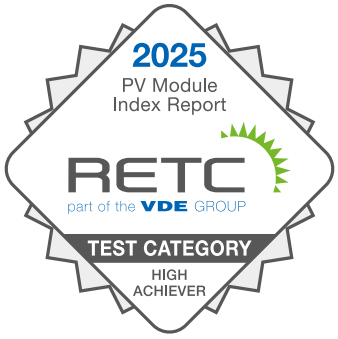
Astronergy • JinkoSolar • LONGi Solar • Meyer
Burger • Qcells • REC Solar • Risen Energy
Runergy • Silfab Solar • SolarSpace • Trina Solar
VSUN Solar • Waaree • Yingli Solar

QUALITY DISCIPLINE HIGH ACHIEVERS

BOM VERIFICATION

Adani Solar • Astronergy • Canadian Solar • DAS Solar • DMEGC Solar • JA Solar • JinkoSolar • LONGi Solar
Qcells • Risen Energy • Runergy • Silfab Solar • SolarSpace • Trina Solar • VSUN Solar • Waaree • Yingli Solar

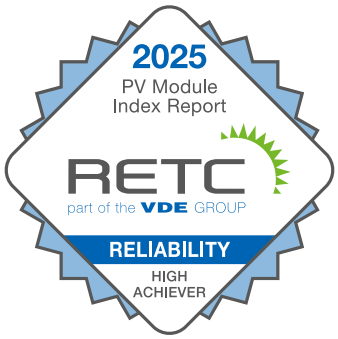
2025 CRITERIA FOR RECOGNITION



AWARDED IF ANY TEST CATEGORY SCORE IS "YES"

RELIABILITY DISCIPLINE TEST CRITERIA

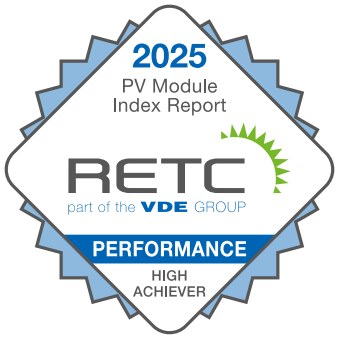
CATEGORY	SEQUENCE	SOURCE	HIGH ACHIEVER	RED FLAG	SCORE
BUDT[1]	DH1000+, 3 x (UV65+TC50+HF10) + UV6.5	Thresher	No backsheet cracking	Not eligible for OHA if product fails BUDT	Y / N
DH	DH2000 + BO-LID		<2.0% degradation	Not eligible for OHA if product experiences ≥5% degradation	Y / N
HDT	HDT Hail+ TC50 + Hot-spot[2]	HDT	>20 joule impact	N/A	Y / N
PID	192 hours + UV2 (2 bias)	Thresher	<2.0% degradation	Not eligible for OHA if product experiences ≥5% degradation	Y / N
SDML[3]	SML + DML + TC50 + HF30		<2.5% degradation		Y / N
TC	TC600		<2.0% degradation		Y / N
UVID[4]	UV220 frontside / UV66 backside + lightsoak recovery		<2.5% degradation		Y / N



AWARDED IF RELIABILITY DISCIPLINE TOTAL IS ≥3 OF 7[5]

PERFORMANCE DISCIPLINE TEST CRITERIA

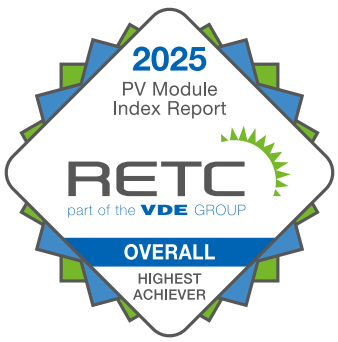
CATEGORY	SEQUENCE	SOURCE	HIGH ACHIEVER	RED FLAG	SCORE
Efficiency	Pmax ÷ aperture area	CEC listing	>21%	N/A	Y / N
IAM	Based on 70° angle of incidence	Thresher	>88% at 70° AOI		Y / N
LETID	BO-CID + 486-hour LETID		<0.5% degradation	Not eligible for OHA if product experiences ≥2.5% degradation	Y / N
LID					Y / N
PAN File	Per IEC61853-1		>85% PR	N/A	Y / N
PTC-to-STC		CEC listing	≥94%		Y / N
Temp Coefficient		Thresher or CEC listing	<-0.3%/°C		Y / N



AWARDED IF PERFORMANCE DISCIPLINE TOTAL IS ≥3 OF 7

OVERALL HIGHEST ACHIEVER CRITERIA

DISCIPLINE	MINIMUM REQUIREMENT FOR RECOGNITION	SCORE
RELIABILITY	Reliability discipline total is 3 out of 6 for dual glass module or 4 out of 7 if BUDT is required	Y / N
PERFORMANCE	Performance disciple total (from below) is 3 out of 7	Y / N
QUALITY[6]	3rd party sample witness & bill of material (BOM) verification via independent third party (STS, CAC, or similar)	Y / N



AWARDED IF DISCIPLINE-LEVEL RECOGNITION IS 3 FOR 3

1. Required if polymeric backsheet; not required for glass backsheet.
2. Test samples must achieve Class A HDT rating (<1% degradation, no significant visual defects).
3. At least ±2,400 Pa for 4-point clamp or ±1,800 Pa for 400-mm tracker mounting.
4. Two test modules w/ both front and backside testing and a lightsoak recovery stage.
5. Module models with a polymeric backsheet must meet requirements for BUDT plus at least three additional reliability test categories.
6. Not eligible for OHA if audit or inspection reveals major nonconformance.


RETC's Global Presence
RETC is proudly represented by employees in the U.S., Philippines, and China.
RETC's community of experts are not only passionate about testing new solar technology and power electronics, they also come from a diverse set of backgrounds including semiconductor and PV manufacturing experience.
RETC is united by the belief in

ZEN ON THE ART OF MODULE QUALIFICATION



Zen Villanueva, RETC's vice president of quality, represents the VDE Group and its customers and partner organizations on many working groups that contribute to international PV standards and specifications and model test programs. Here, we share Villanueva's insights into the ways in which standards are evolving to support next-generation PV module technologies and shape the commercial solar technologies of the future.

As photovoltaic technology continues to evolve rapidly, the groups responsible for industry standards are working hard to keep pace. With the transition to higher-efficiency cell architectures, lighter and thinner modules, and new material configurations, the reliability expectations and qualification requirements for PV components are expanding. New areas of concern range from n-TOPCon reliability to glass breakage to perovskite testing protocols. Mitigating these concerns is leading to a suite of upcoming changes across IEC and UL standards that reflect the industry's focus on robust long-term performance.

As PV technology enters a new phase of complexity and capability, standards bodies are adapting accordingly. Whether it is redefining fire safety for polymeric modules, improving stress tests for bifacial designs, or laying the groundwork for perovskite commercialization, the coming wave of standards is setting the stage for the next generation of solar. For manufacturers and developers alike, staying current with these updates is not just about compliance—it is about ensuring that today's innovative designs become tomorrow's long-lasting, high-performing assets in the field. These are some state-of-the-art trends Villanueva recommends watching.

TOPCon takes the spotlight—and the heat

Since 2024, n-TOPCon has emerged as a leading PV technology, surpassing p-PERC with its superior efficiency and bifacial gains—particularly in utility-scale projects. However, its rise has raised concerns about durability, particularly in damp heat conditions. Studies show TOPCon modules, particularly those with glass-on-backsheet designs, are prone to degradation due to acidic byproducts from ethylene vinyl acetate (EVA) encapsulants during damp heat exposure. These byproducts corrode key interfaces such as electrodes and interconnects. To combat this, new encapsulant combinations—using polyolefin elastomer (POE) on the front and acid-neutralizing EVA on the back—have significantly reduced damp heat–related power loss, even after 2,000 hours. These materials may prove crucial in ensuring the long-term reliability of TOPCon modules.



anghinet / stock.adobe.com

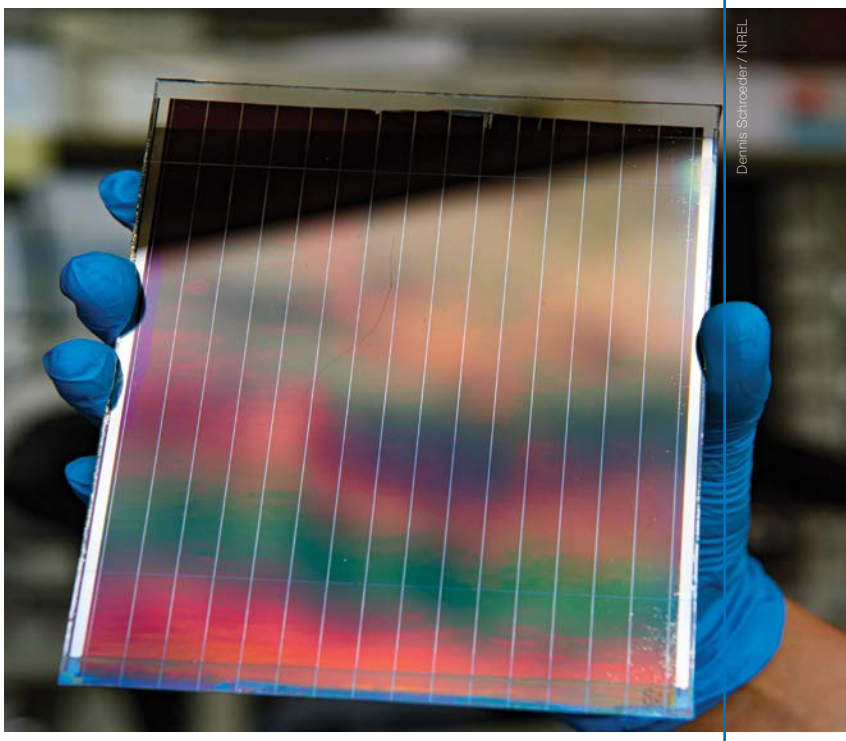


Thin is in—but can it take the pressure?

In the push for lighter, more cost-effective module designs, manufacturers are embracing larger formats, thinner glass, and slimmer frames—often in bifacial glass-on-glass configurations. While these trends offer clear logistical and economic benefits, they come with a downside: a noticeable uptick in spontaneous glass breakage in the field. To address this, standardization efforts are focusing on the mechanical robustness of PV glass. A new framework is under consideration to guide glass manufacturers in publishing datasheets that detail essential performance characteristics such as edge finish, surface roughness, impact resistance, surface stress, bending strength, and thermal shock tolerance. However, before such datasheets can be mandated, the industry is first working to develop consistent and reliable test methods for evaluating these properties.

Metastability: stabilizing the unstable

Metastability is becoming an increasingly important focus in the qualification of advanced PV technologies, including perovskites, tandem cells, heterojunction (HJT) devices, and TOPCon modules. These technologies can exhibit transient performance shifts due to light soaking, temperature fluctuations, or environmental exposure, making accurate measurement and reliability testing more complex. For HJT and TOPCon devices, effects such as charge trapping and interface degradation can lead to temporary changes in key electrical parameters. In contrast, perovskite and tandem devices are prone to light- and bias-induced instability. To ensure consistent and representative results, evolving test protocols now incorporate preconditioning measures, such as controlled light soaking, thermal stabilization, and biasing, before performance evaluation. Industry experts are actively testing and updating IEC and UL standards to formalize these stabilization procedures, aiming to deliver more reliable and efficient methods for characterizing next-generation PV technologies.





Kurhan / Fotolia

Perovskites under the microscope

Perovskite-based PV cells continue to generate buzz for their high efficiency potential and low-cost manufacturing. However, their stability remains a key concern. In response, work is underway on a new annex to IEC 60904-1-4 to define clear protocols for I-V testing and stabilization of perovskite devices. Establishing repeatable procedures will be essential to moving these promising technologies from lab to large-scale deployment.

Fire safety: making room for modern modules

UL is also modernizing its standards to accommodate the growing diversity of module designs. A proposal under UL 61730-2 seeks to expand the number of fire-tested module types from 49 to 66, specifically to account for modules with reduced back glass thickness and polymeric front and rear surfaces. This update complements a proposed change to UL 2703, which would waive fire testing for mounting systems used with Class A-rated PV modules, provided they are installed over non-combustible materials like clay tiles, concrete, 28-gauge steel panels, or shingles. Together, these adjustments aim to streamline certification for emerging module formats without compromising fire safety.



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Higher voltage, higher stakes

As system designs push for greater power density, higher operating voltages are becoming a key consideration. Under IEC TS 63543, a proposal is being drafted to increase the allowable system voltage from the current 1,500 V to 3,000 V. This shift has implications for multiple tests, including insulation resistance, wet leakage, and impulse voltage performance, all of which depend on adequate module clearance and creepage distances, and the voltage ratings of individual components. As this proposal evolves, alignment between component-level design and system-level standards will be crucial to ensuring a safe implementation. In the United States, a Certification Requirement Decision (CRD) under UL 61730 already allows certification bodies to approve modules rated up to 2,000 V, provided the associated risks are adequately evaluated, even in the absence of a full consensus standard.

IEC 61215 Edition 3: closing the gap between design and reality

The upcoming third edition of IEC 61215 will introduce a range of updates that reflect both technological progress and lessons learned from field performance. These revisions aim to make the standard more representative of real-world stressors and to enhance consistency across related IEC documents. Some notable changes include:

- Bifacial Stress Irradiance (BSI) replaced with applied Bifacial Stress Irradiance (aBSI) for improved alignment with IEC 61730.
- Hot-spot testing procedures refined to include the use of shadowing covers extending 1 cm beyond cell edges.
- The application of weights to junction boxes during damp heat testing to better simulate mechanical stresses.
- Visual defect criteria updated to match those in IEC 61730.
- Wet leakage testing of cemented joints now includes a 1.35x safety factor, aligning with insulation test methodologies.
- Post-PID recovery now calls for UV exposure of 100 Wh/m^2 ±10 Wh/m^2, ensuring a more realistic stabilization process.



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tongpatong / stock.adobe.com

Walking the line: drafting a new load test

Field conditions can be unpredictable, and real-world mechanical loads often do not conform to lab protocols. To simulate such events, a new walking load test is being drafted under IEC 63632. This test applies a 1-kN concentrated load over a 100 mm-diameter area, targeting the module's weakest points as installed, for 30 minutes. The goal is to evaluate the structural integrity of modules under foot traffic or unintentional pressure during maintenance, factors that have grown more relevant with the adoption of thinner glass and framing.

IN MEMORIAM: FRÉDÉRIC DROSS

On February 17, 2025, the solar industry—and its tight-knit technical due diligence community—lost one its heroes when a back-country avalanche in El Dorado County, California, claimed the life of Frédéric Dross. After completing a PhD program at Telecom Paris in semiconductor device physics, Frédéric worked as a principal researcher at Imec, a renowned research institute in Belgium, leading the PV group's efforts to increase PV cell efficiency while lowering production costs. In 2014, the Dross family relocated to Silicon Valley, where Frédéric held various roles with leading technical advisory firms and PV module companies, including Qcells and, most recently, Swift Solar, a perovskite PV startup.

A champion for PV module quality, reliability, and sustainability, Frédéric spent nearly five years at STS (Senergy Technical Services), a company dedicated to helping PV module buyers identify, assess, and mitigate technical risks. While he was working as the vice president of strategic development for STS, RETC had the honor of interviewing Frédéric for the *PV Module Index Report.* In that 2021 interview, Frédéric shared best practices for PV module lot testing and BOM control as part of a rigorous pre-shipment factory inspection.

"Accelerated lifetime tests are today the best known indicator of module durability," Frédéric noted. "Independent engineers use the results of such tests to evaluate the useful life of the modules purchased, the required warranty reserves, or the expected operations and maintenance costs. Accelerated testing is therefore a key component of bankability and levelized cost of energy calculations. These testing efforts are only worthwhile, however, if the BOM is controlled by an ISO 17020-accredited inspection body, both during test sample manufacturing and project manufacturing."

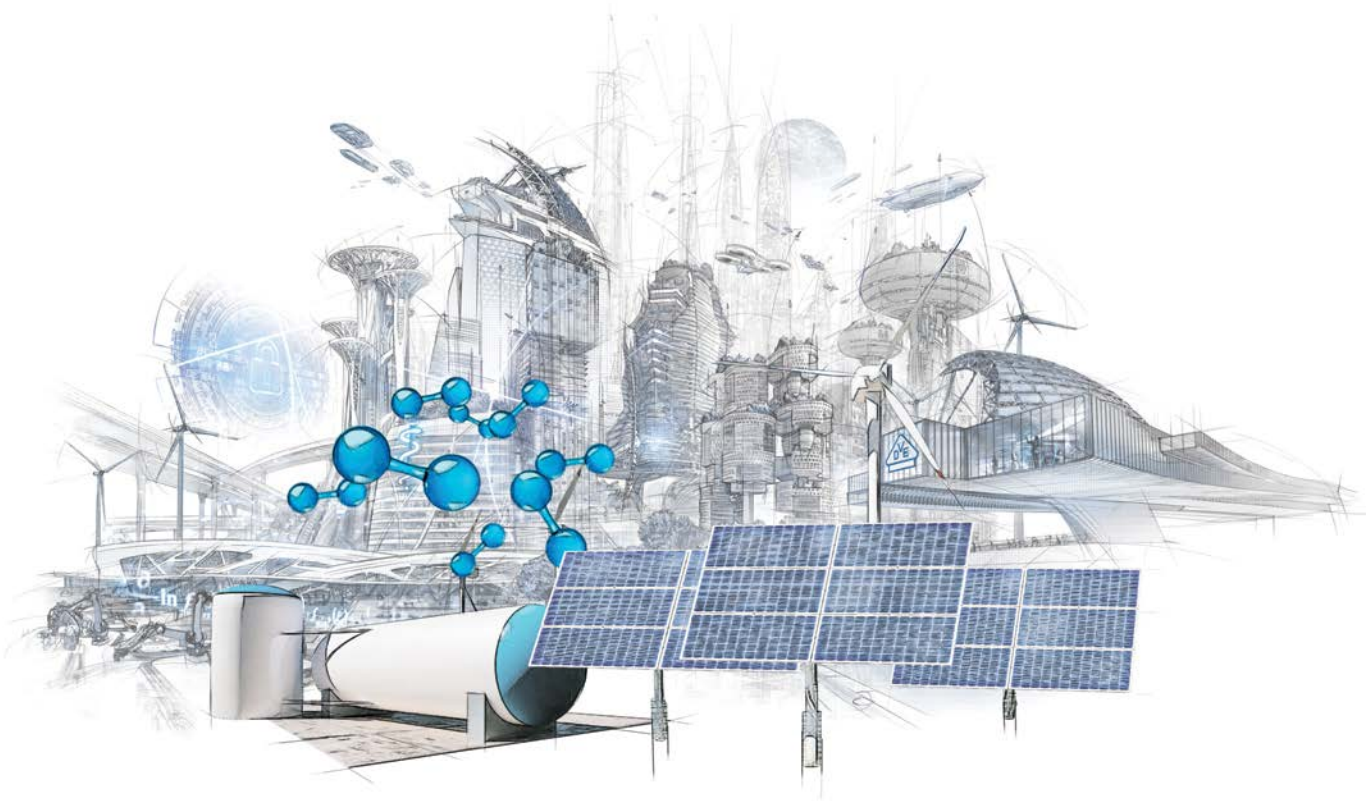
In addition to dedicating his career to the advancement of renewable energy technologies, Frédéric was a dear friend who will be missed by many, including those of us at RETC who had the pleasure and privilege to work with him. Most importantly, he was a devoted family man who left behind a wife, Liesbeth, and two young daughters. If you feel moved to honor Frédéric's legacy, please consider donating to help his family in this time of need.

Please join us in supporting Frédéric's wife and 2 daughters by contributing to this fund. They need our support right now to keep moving through this tough time.

https://gofund.me/8c016c5a




FREDERIC
DROSS
Frederic Dross
STS
Beyond inspection



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