RETC

2022 PV Module Index Report

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CONTENTS

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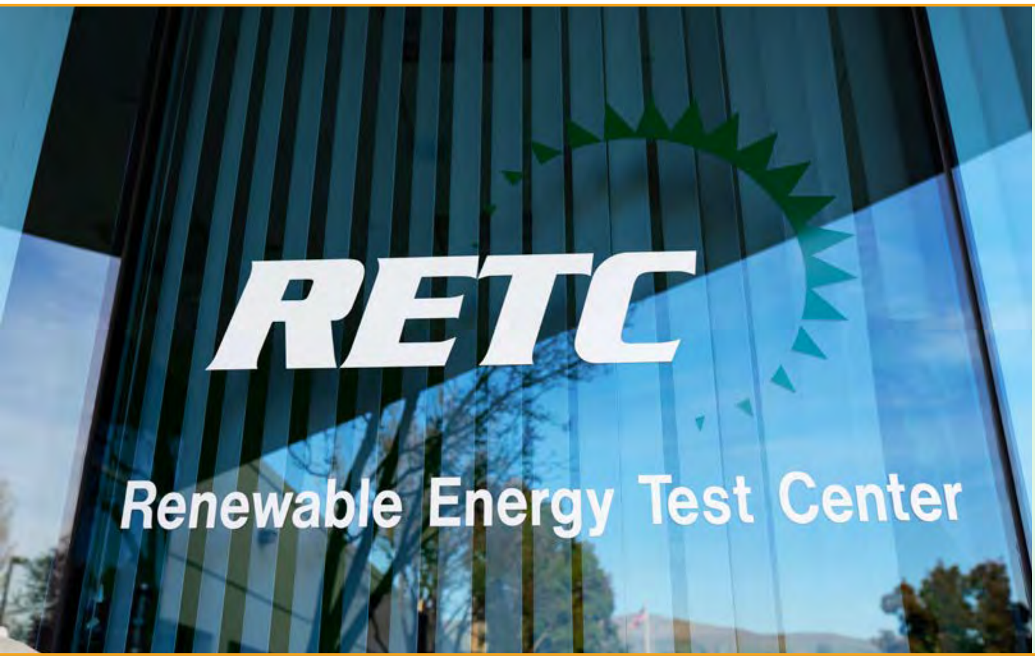
ABOUT RETC

Renewable Energy Test Center (RETC) is a leading engineering services and certification testing provider for renewable energy products with headquarters in Fremont, California. Since its founding in 2009, RETC has partnered with manufacturers, developers and investors to test a wide range of products, including modules, inverters, battery energy storage and racking systems. RETC puts customers at the forefront by bringing value to research and development, market entry and bankability assessments. At its accredited laboratories, RETC evaluates products using only the latest testing standards and industry-accepted methods. At RETC, we are united in the belief that our work enables a safer and more sustainable world.



RETC IS PROUD TO BE:

- ISO 17025 accredited by A2LA (an ILAC affiliated laboratory)
- Awarded IEC CBTL status (the highest accreditation in IEC CB scheme)
- TÜV SÜD America's CARAT Program recipient
- Verified by the UL Data Acceptance Program
- TÜV Rheinland's Partner Laboratory
- A VDE Qualified Test Laboratory
- A California Solar & Storage Association (CALSSA) Member
- An Intertek Recognized Test Laboratory (RTL)

A LETTER FROM OUR CEO

Cherif Kedir is president and CEO of RETC. Building on an extensive background in semiconductors, Cherif is a solar industry veteran with more than 15 years' experience spanning research and development, manufacturing, reliability, field testing, certification and bankability.

As we prepare to publish the fourth annual *PV Module Index (PVMI) Report,* our work at the Renewable Energy Test Center (RETC) has never been more vital to our shared future. On the one hand, recent news headlines highlight the environmental and geopolitical risks of continued global reliance on fossil fuels. On the other hand, current market data demonstrate that the world's biggest economies are increasingly reliant on solar power and battery energy storage.

In March 2022, the US Department of Commerce announced it would investigate the alleged circumvention of antidumping and countervailing duties (AD/CVD). The resulting market uncertainty presents a fierce headwind to solar project development in the world's largest economy. Worse yet, the inevitable supply chain disruptions will increase technical risks for manufacturers, developers, insurers and institutional investors.

Given that increased solar adoption is essential to securing a liveable future, RETC's work on hail durability, bankability, energy storage and beyond-certification testing is mission critical. With that in mind, I am happy to report an expansion of RETC's testing capabilities that will allow us to serve a higher volume of projects and customers.

RETC has strategically partnered with the VDE Group and its wholly owned subsidiary, VDE Americas, for nearly a decade. In June 2021, VDE and RETC formalized this synergistic relationship, with VDE Group acquiring a 70% stake in RETC. This acquisition provides RETC access to VDE's global consortium of laboratories and its world-class subject matter experts, some of whom are featured in this year's *PV Module Index Report*. At the same time, RETC's work and test results will remain independent and unbiased.

By joining the VDE Group, RETC can expand its solar and energy storage testing services to a broader network of manufacturers, investors, insurers and developers. Collectively with VDE, we will continue to advocate for better product reliability, performance and quality. Moreover, we will leverage this partnership to minimize risk and uncertainty in favor of long-term reliability, sustainability and profitability by designing better data-driven risk mitigation programs and service products.

The testing that we do at RETC is foundational to data-driven project development. Our work supports technical due diligence and engineering advisory services—such as those offered by VDE Americas—ensuring that solar projects are bankable, investable and insurable. This work is valuable directly not only to project stakeholders but also indirectly to the well-being of the environment and global community.

Thank you for being our partners and collaborators in this important work,

Cherif Kedir

"By welcoming our long-term business partner RETC as a member of the VDE Group, we can offer our customers worldwide a one-stop shop for testing, inspection, certification and data services that minimizes the risks associated with solar photovoltaics, energy storage systems and other renewable energy technologies. In addition, RETC's industry-leading testing capabilities complement the consulting services provided by our subsidiary VDE Americas." —Ansgar Hinz, CEO, VDE Group

INDUSTRY TRENDS

As an independent testing laboratory with the highest level of accreditation, RETC occupies a unique position in the solar industry.

We test next-generation solar products and technologies to the latest testing standards and sequences to better understand the future. To better understand the past, we conduct forensic investigations into the potential root causes of PV module underperformance in real-world applications.

Informed by these forward- and backward-looking inquiries, RETC helps project stakeholders identify, quantify and mitigate project risks. For this year's *PV Module Index Report,* we explore three interrelated topics—n-type PV modules, field forensics and extreme weather—that demonstrate some of the inevitable technical risks associated with solar project development. These timely topics also elucidate the value of a data-driven approach to risk management.

EVALUATING NEW N-TYPE PV MODULES

The solar industry's continued ability to drive down costs while improving performance is a primary reason solar accounted for the largest share of new US electricity generation capacity in 2021. This trend is best exemplified by continual changes to module designs and cell technologies. Last year, for example, we explored the benefits and challenges of developing and deploying large-format modules, which many analysts expect will dominate the market in the coming years.

This year, RETC is closely monitoring another technology trend that is quickly gaining market traction and acceptance: the rise of next-generation n-type PV cells with passivating contacts. Here, we explore the promise of new n-type PV cell designs and the potential challenges associated with scaling this promising technology.

RISE OF TOPCON

Many industry analysts and material scientists believe emerging n-type PV cell designs are the next logical progression on the PV technology roadmap. In 2013, researchers at Germany's Fraunhofer Institute for Solar Energy Systems presented a method of producing high-

KEY TAKEAWAYS

- New n-type cell technologies are poised for rapid market expansion.
- Emerging cell designs are susceptible to novel degradation pathways.
- Data-driven technical due diligence mitigates emerging technology risks.

efficiency n-type silicon solar cells with a novel tunnel oxide passivated contact (TOPCon) structure. Thanks to excellent surface passivation and effective carrier transport, this novel cell design achieved high marks for open-circuit voltage (Voc), fill factor and efficiency.

Less than a decade later, TOPCon is the buzziest word in solar. The largest module manufacturers in the world are beginning volume production of PV modules with TOPCon cells. While LONGi Solar is betting big on p-type TOPCon, many other leading module companies—such as Jinko Solar, Jollywood Solar Technology, JA Solar and Trina Solar—are making substantial investments in modules with n-type TOPCon cell designs.

This collective pivot in the market is primarily due to flattening efficiency curves for the p-type passivated emitter and rear-contact cell (PERC) modules. Although these have dominated the market in recent years, manufacturers are starting to reach the physical limits of p-type mono PERC cell designs. Transitioning to n-type TOPCon cells will allow module companies to boost cell efficiencies further in the laboratory and in mass production.

"Everybody wants the highest possible module nameplate rating," explains Kenneth Sauer, principal engineer at VDE Americas. "Via higher open-circuit voltage values, you can achieve higher efficiencies and power ratings. In and of itself, that is likely going to move manufacturers to n-type TOPCon cell designs, as soon as they can get there."

BENEFITS OF N-TYPE CELLS

Solar manufacturers have long recognized the potential efficiency benefits of n-type PV cells. For example, Sanyo began developing n-type heterojunction technology (HJT) PV cells in the 1980s. In addition, SunPower has built its interdigitated back contact (IBC) PV cells upon a base of high-purity n-type silicon.

Due to the manufacturing complexities involved, high-efficiency PV modules based on n-type HJT and IBC cell designs are relatively expensive to produce and remain a niche part of the market. By comparison, n-type TOPCon cell manufacturing is very similar to the PERC process. As a result, manufacturers can produce these next-generation high-efficiency TOPCon modules on upgraded PERC production lines.

Though today's n-type TOPCon modules cost slightly more to produce on a per-watt basis than p-type mono PERC modules, the efficiency gains result in a lower levelized cost of energy (LCOE) in large-scale field deployments. Best of all, leading experts expect n-type TOPCon to benefit from an accelerated learning curve.

"I recommend conducting accelerated UVID testing for new n-type modules as part of a technical due diligence survey."

—Kenneth Sauer, VDE Americas

A primary material advantage of n-type TOPCon cells relative to p-type mono PERC cells is a lower degradation rate due to a decreased susceptibility to both light-induced degradation (LID) and light- and elevated temperature–induced degradation (LeTID). Additional advantages may include a higher bifaciality factor, as well as improved performance under both low-light and high-temperature conditions.

RISKS OF EARLY ADOPTION

Most analysts expect modules with n-type TOPCon cells to quickly increase market share based on these performance advantages. However, emerging PV cell technologies—even ones that ultimately prove successful in the field—invariably carry more risk than mature and proven technologies. Until products are deployed at scale, the potential exists for as-yet-undiscovered degradation mechanisms.

Today, for example, independent engineers and financiers consider p-type mono PERC PV modules to be a stable and low-risk technology. This assessment was not always a consensus opinion. Early versions of mono PERC modules had issues with stability, especially LID and, in rare instances, LeTID. These unexpected mono PERC degradation modes demonstrate the performance risks that early adopters face with new technologies.

While n-type TOPCon PV cells have proven resilient to LID and LeTID, some evidence exists of susceptibility to ultraviolet-induced degradation (UVID). For example, researchers at the SLAC National Accelerator Laboratory and the National Renewable Energy Laboratory (NREL) have documented front- and back-side power loss in advanced solar cell technologies after artificially accelerated UV exposure testing. These data do not point to a single degradation mechanism but suggest that different cell designs degrade via different pathways.

CASE-BY-CASE ASSESSMENT

Though it is impossible to eliminate all risk and uncertainty associated with technological innovation, artificially accelerated exposure tests—such as those conducted at RETC's accredited laboratories—are a proven method of identifying novel failure and wearout mechanisms. Beyond-qualification and bankability test sequences and protocols are clearly valuable to manufacturers bringing new products to market. They are also critically important to developers, financiers and independent engineers seeking to de-risk early deployments of next-generation technologies.

"As someone who provides technical advisory services," says Sauer at VDE Americas, "I recommend conducting accelerated UVID testing for new n-type modules as part of a technical due diligence survey. If cell passivation layers are not properly tuned, they can break down with UV exposure. Given all of the new cell designs coming to market, it is important to evaluate each one individually on a case-by-case basis."

Given the high stakes involved, RETC is independently subjecting a variety of next-generation modules with advanced n-type cell designs to highly accelerated UV testing. "We're not trying to sound an alarm for no reason," explains CEO Cherif Kedir. "We just want to test the potential for UV degradation to educate ourselves and the industry. If there's no problem, we can all move forward with our lives. If there is a problem, we will publish a report so that the industry can get out in front of the issue."

FORENSIC ANALYSIS OF FIELD PERFORMANCE

According to kWh Analytics, a leading expert in solar project risk assessment and mitigation, PV system underperformance is a real and growing concern. In the 2021 edition of its *Solar Risk Assessment* report, kWh Analytics warns that "1-in-8 [solar] projects persistently underperform their downside (P99) scenario over multiple years." While most solar projects meet performance expectations, kWh analytics notes that persistently underperforming systems threaten solar loans as an asset class.

Forensic analysis is a detailed investigation that seeks to establish the root cause of PV system underperformance. In many cases, inverter failures or inaccurate production estimates are to blame for real or perceived system underperformance. If PV module health is suspect, RETC's expertise as a testing laboratory is invaluable to forensic investigations conducted in the field.

BASELINE ASSESSMENT

One of the best ways for project stakeholders to reduce project risk is to engage a qualified third party to conduct a baseline module health assessment during project commissioning. By capturing high-quality measurements prior to commercial operations, a baseline forensic assessment provides both short- and long-term benefits over the operating life of a PV power system.

In the short term, a baseline commissioning assessment improves the accuracy of system performance estimates. Project financiers and insurers rely heavily on probabilistic estimates of PV asset performance in the field. Many PV systems are financed using debt under the assumption that the plant's operating cash flow will service the loan. Therefore, improving the accuracy of system performance estimates ultimately reduces the risk of loan default.

Over the long term, baseline commissioning assessments also benefit system owners and operators. It is challenging to process a warranty or insurance claim without high-quality baseline measurements taken at the beginning of the project lifecycle. In addition to determining the initial module health status, a baseline commissioning assessment is also helpful for documenting site-specific risks associated with the environment, design or installation quality.

KEY TAKEAWAYS

- PV system underperformance is a concern, especially in aging systems.
- Quality commissioning data establish a system performance baseline.
- Daytime EL testing can identify the root causes of hidden module damage.
- Digital monitoring plus forensic analysis facilitates predictive maintenance.

DAYTIME EL TESTING

Electroluminescence (EL) testing uses a special camera system to document the light emissions that occur when an electrical current passes through PV cells. EL testing has a long history in the laboratory, where it is used to detect a wide range of hidden module defects. Once relegated to controlled indoor environments, EL testing is increasingly common in field forensic investigations.

RETC conducts daytime EL testing, the most technically advanced type of EL imaging system for field forensic investigations. Daytime EL imaging provides two distinct benefits over earlier approaches. First, our EL testing methodology allows technicians to test modules in situ, which expedites the testing process and eliminates cell damage due to module removal and handling. Second, daytime EL testing eliminates the need to test modules in the dark of night, further improving safety and throughput.

The results of in-field EL testing are valuable for identifying major manufacturing defects, off-site shipping and transportation damages, on-site material handling or installation damages, or damages resulting from severe weather events such as hail, wind or snow. These EL images allow project stakeholders to identify cell damage that can lead to thermal nonconformities, hot spots and future module underperformance.

When adequately documented and reported, third-party EL images can help settle warranty and insurance claims. Unlike aerial infrared (IR) imagery, which identifies only the potential locations of performance issues, daytime EL investigations elucidate the root causes of underperformance. These findings benefit project stakeholders by expediting issue resolution and minimizing production losses.

PREDICTIVE MAINTENANCE

Third-party field performance forensics are especially practical when coupled with a robust monitoring platform and predictive maintenance protocols. As PV modules age, fielded assets are at increased risk of underperformance. Cell microcracking often does not impact module performance when modules are new, but that is not necessarily the case as systems age. After 5 or 10 years in the field, some modules continue to perform as expected, whereas others suffer from accelerated degradation.

"In our PV performance monitoring program, thermal mismatch is something that we monitor closely," says Dr. Ralph Romero, senior managing director of digital infrastructure advisory services at Black & Veatch. "Once individual cells start behaving differently, that thermal mismatch has the potential to create a vicious circle that

"Once individual cells start behaving differently, that thermal mismatch has the potential to create a vicious circle that leads to further mismatch."

—Dr. Ralph Romero, Black & Veatch

leads to further mismatch. Thermal mismatch resulting from cracked cells or other causes needs to be closely monitored as it can lead to substantial PV system underperformance."

Differentiating between "good" modules and "bad" modules is not a simple matter, especially in systems deployed after the US Department of Commerce enacted its AD/CVD policies. Large projects that appear to have a single module supplier may in fact integrate modules manufactured using cells sourced from a dozen different vendors. Given that each bill of materials (BOM) is unique, each has a different risk profile.

"It is important to have a predictive maintenance protocol in place," explains Romero. "We are aware of digital monitoring platforms that are very good at identifying potential root causes of underperformance. It can do so at a granular level in both portfolios of distributed assets and large utility systems.

"If we suspect that PV modules are underperforming and the root causes are not identifiable through performance monitoring," Romero continues, "we can ask the forensic analysis team identify the root causes of underperformance. With this information in hand, we can develop an action plan based on a cost-benefit analysis of potential remediation measures. In the process of engineering a cost-effective solution that immediately improves system performance, we can also take steps to prevent the recurrence of underperformance moving forward."

MITIGATING EXTREME WEATHER RISKS

No one understands the natural perils associated with solar deployments better than renewable energy insurance specialists such as GCube Insurance. According to the company's 2021 market report, *Hail or High Water: The Rising Scale of Extreme Weather and Natural Catastrophe Losses in Renewable Energy*, weather-related insurance claims have grown in frequency and severity as solar projects have increased in frequency, size and geographic distribution.

Given the rapid growth of the solar market globally, a commensurate rise in solar insurance claims is not entirely unexpected. However, the root cause of solar insurance claims has surprised some insurance industry insiders. Specifically, since 2015, insured losses associated with extreme weather events are roughly twice the magnitude of those stemming from natural catastrophes.

This breakdown of weather-related losses is enlightening. As a loss category, natural catastrophes are low-incidence, high-severity events, such as hurricanes and floods, that cause significant damage. Insurance policies often refer to these perils as "acts of God," which speaks to the fact that reasonable care and foresight cannot prevent damages associated with these forces of nature.

While extreme weather events result in more insured losses than natural catastrophes do, insurance claims associated with the severe weather loss category are not unavoidable. Project stakeholders can prevent or mitigate many extreme weather losses by exercising reasonable care and foresight in product selection and system design. Moreover, risk mitigation specialists can help tax equity investors and insurance companies understand the financial risks associated with severe weather.

COMPARATIVE TESTING

Strategic product selection is an essential first step for mitigating the leading causes of extreme weather losses. RETC's bankability and beyond-certification testing results demonstrate how different PV module designs or combinations of modules and racking resist these different types of environmental stresses. These differences are mission critical in the context of extreme weather risk mitigation.

KEY TAKEAWAYS

- Weather-related solar insurance claims and premiums are on the rise.
- Data-driven approaches to product selection mitigate weather risks.
- Active defensive stow and load shed protocols can further reduce risks.
- Probabilistic analyses can quantify the financial value of risk mitigation.

COURTESY NEXTRACKER

Examples of preventable extreme weather perils include wind, hail and snow. Based on claims frequency, high wind events are a leading cause of insured losses in fielded solar assets. Based on the severity of losses, a widely publicized hailstorm in West Texas damaged some 400,000 PV modules, resulting in the largest single solar insurance claim to date. Snow is a relatively lesser hazard overall but presents significant risks at specific elevations or latitudes.

The goal of comparative and accelerated testing is to empower project stakeholders to identify and specify the best products and system designs for specific applications and environments. Modules that perform well under dynamic mechanical load testing are well suited for deployment in high wind environments. Modules that perform well in RETC's Hail Durability Test (HDT) sequence (see p. 15) are well suited for deployment in hail-prone regions. Modules that perform well in mechanical load tests are best suited for resisting the loads associated with ice and snow.

Modules that do not perform well in these two tests are not "bad" products, especially in the proper application. Modules hardened against wind and hail often incur higher manufacturing costs. The conditions for an installation in California's Central Valley, which rarely experiences high winds, hail or snow, may not justify these additional costs.

"Optimizing risk reduction for any one particular threat in a vacuum may not be the best choice."

—Kent Whitfield, Nextracker

To mitigate supply chain risks, developers often evaluate and source a variety of PV module models and vendors. Extreme weather susceptibility will vary across this portfolio of selected PV modules. By paying attention to these differences, developers can direct wind-, hail- or snow-hardened modules respectively to wind-, hail- or snow-prone sites. This type of selective deployment is a relatively simple and cost-effective way to reduce extreme weather risks.

DEFENSIVE STOW STRATEGIES

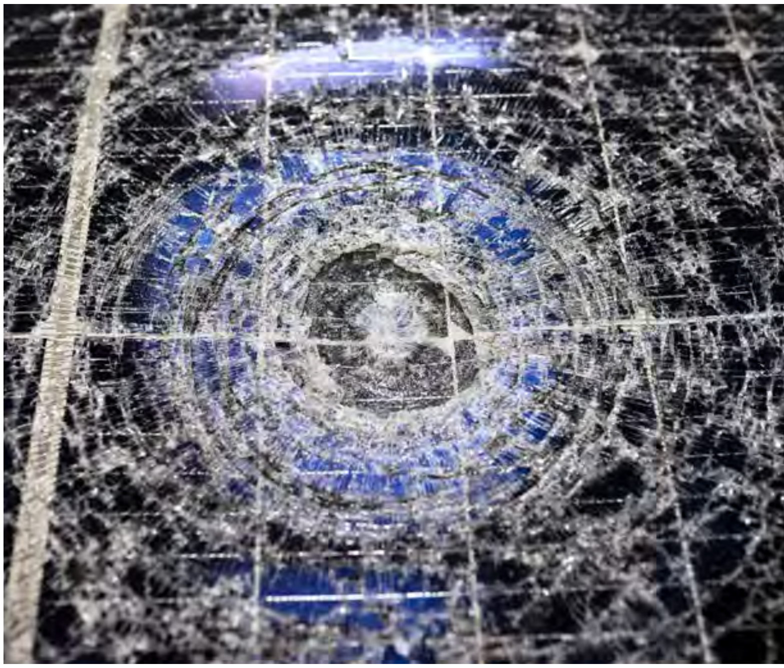
After filtering and selectively deploying modules based on resistance to site-specific conditions, project stakeholders can implement weather-responsive software control strategies to reduce extreme weather risks further in large utility applications. Many large-scale PV systems integrate intelligently controlled single-axis trackers that use software to follow the sun while avoiding self-shading. As weather-related insurance claims have increased, industry-leading tracker manufacturers have implemented novel software-control responses, such as threat-specific defensive stow or load shed modes.

"Leveraging existing and secure software control capabilities, Nextracker was able to implement unique defensive responses to hurricanes, hail, high winds, snow loading and flooding," says Kent Whitfield, the company's vice president for quality. "On- or off-site plant operators can use NX Navigator to securely trigger defensive stow or load shed protocols. Once a user-initiated command is given, all trackers will move to the specified position in roughly one minute. The entire operation is failsafe thanks to our self-powered independent-row architecture."

Due to the highly localized and fast-moving nature of high wind events and hailstorms, severe weather alerts often give plant operators little advance warning. Moreover, the types

Coupling RETC's measuring capabilities with our risk assessment tools, we've been able to quantify the value of mitigation approaches from a financial perspective."

—John Sedgwick, VDE Americas



of storms that produce high winds and large hail often result in downed power lines and loss of ac power. Active software controls can address these challenges and provide effective risk mitigation with product features such as local or remote initiation, rapid response times and failsafe battery backup.

It is also important to consider coincident weather risks. "Optimizing risk reduction for any one particular threat in a vacuum may not be the best choice," warns Whitfield. "To do a proper risk analysis, we can't think only about the probabilities of hail occurring by itself or wind occurring by itself. We also need to account for the probability of hail in conjunction with wind. Otherwise, we can inadvertently increase the risk of wind damage in the process of mitigating risks associated with hail."

PROBABILISTIC RISK ASSESSMENT

Though the insurance industry has long relied on probabilistic risk assessments to provide coverage sustainably, the challenge posed by solar projects is twofold. First, limited historical data is available to understand extreme weather risks, especially considering the rate of technological change and market expansion. Second, the natural catastrophe data that insurers typically rely on do not capture "uncategorized" extreme weather events.

"Risk mitigation specialists, such as VDE Americas, are overcoming these challenges by working with leading academics and subject matter experts to better quantify the types of local weather risks that bedevil solar project developers and insurers. These detailed probabilistic analyses can assess extreme weather risk on a highly granular locational basis. Moreover, they can account for variances associated with weather phenomena.

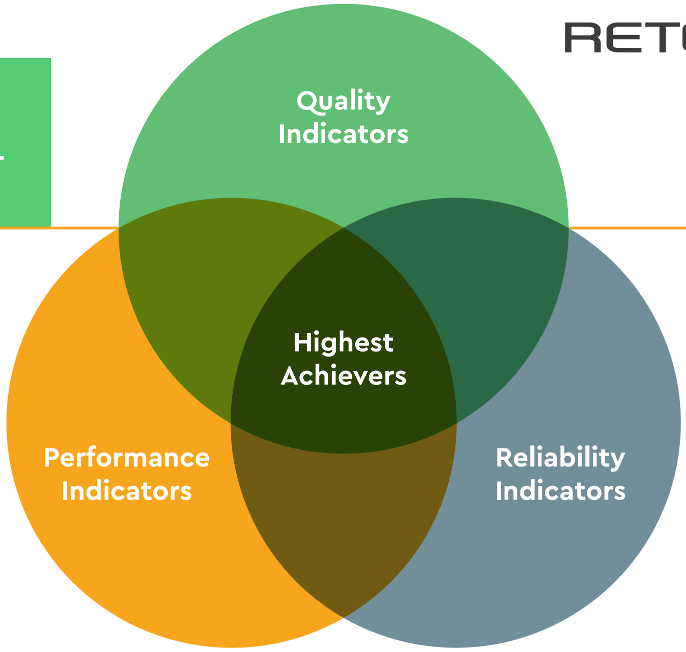
"Traditionally, people have thought about weather across relatively large areas, such as one degree by one degree, which is roughly 10,000 square kilometers," says John Sedgwick, president of VDE Americas. "Because PV power plants are much smaller than that, you need to think about risk at a more local level. That local perspective is fundamental to our risk assessments.

"We also account for the fact that all hail is not the same," Sedgwick continues. "Hail varies from one event to another in terms of its size, density and shape. Some hailstones are similar to solid ice; other hailstones contain more air and are less aerodynamic. Hail also varies within a single event in terms of hailstone size distribution. After accounting for these differences, we can begin to calculate the risks associated with hail strikes for a given utility-scale solar power plant."

RETC's beyond-certification testing data are fundamental to a multilayered probabilistic assessment of extreme weather risk. Testing data not only quantify how well a module design resists dynamic wind loads or ballistic hail strikes but also how effective software-controlled tracker stow strategies are at mitigating these natural perils.

"To analyze the financial impact of risk on the overall investment, we need to understand technical resiliency," concludes Sedgwick. "Coupling RETC's measuring capabilities with our risk assessment tools, we've been able to quantify the value of mitigation approaches from a financial perspective. Selecting the right equipment and correctly operating it provides extreme value on a dollar basis. If the risk is lower, the insurance premiums should be better."

CATEGORIES FOR HIGH ACHIEVEMENT



RETC proudly presents the *PV Module Index Report 2022*. This annual report showcases industry-leading technologies and manufacturers. The collected data empower project stakeholders to make strategic product selection and system design decisions.

The 2022 edition of the *PV Module Index Report* summarizes the results of bankability and beyond-certification tests conducted at RETC's accredited laboratories over 12 months, spanning Q2 2021 through Q1 2022. As was the case with previous editions, we have broadly organized test protocols and reported data according to three interrelated and essential disciplines: module quality, performance and reliability.

We present performance distribution data for specific test sequences within each of these three disciplines. By filtering these comparative data based on individual indicators or test categories, project stakeholders can specify products or qualify project designs best suited to a specific environment, location, asset or portfolio.

As you review the results compiled here, remember that we do not conduct comparative tests to reject or endorse specific products or manufacturers. Solar project development is not a cookie-cutter activity that benefits from a one-size-fits-all approach. Instead, successful development demands differentiated designs that are intentionally and intelligently adapted to project- and location-specific variables.

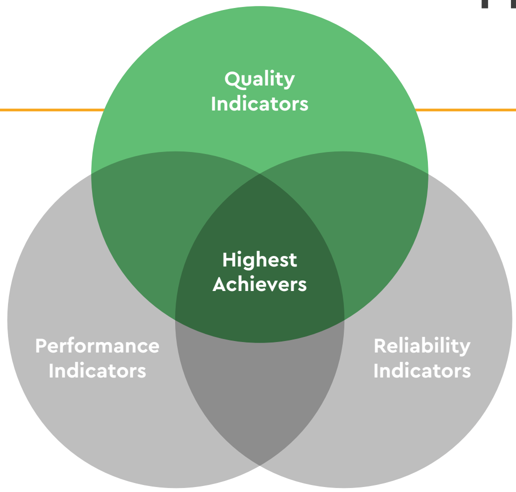
Products that perform well in a test intended to simulate high wind speeds may not perform well in hail durability tests. Modules resistant to ballistic impacts in the laboratory may not perform well in tests simulating extreme snow loads. Modules that are most resilient to severe hail, wind or snow may not be cost effective in large utility-scale applications in California's Central Valley.

This report's reliability and bankability test results provide the foundation for a data-driven approach to project development. Strategic project design eschews oversimplified pass-fail models in favor of sophisticated probabilistic analyses. The goal, after all, is not to eliminate every risk at any cost but rather to balance risk mitigation based on a holistic cost-benefit analysis.

"The goal of the PV Module Index Report *is not to dictate module selection criteria, but rather to empower project stakeholders to identify, quantify and mitigate technical risks associated with specific applications."*

—Cherif Kedir, RETC

MODULE QUALITY



To meet user standards, PV modules must be durable enough to withstand multiple decades of in-field exposure. Not surprisingly, reliable in-field operation over a 25- to 30-year service life is not an accident. Studies have consistently shown a strong positive correlation between quality and return on investment and other profitability indicators.

Products that appear similar on paper may perform very differently in the real world. A manufacturing commitment to quality often accounts for these differences. Though a commitment to quality can take many forms, essential components of a manufacturing quality program include:

- Beyond-qualification testing
- Product conformity analysis
- Random sampling program
- Third-party factory audits

Fielding increasing numbers of higher-capacity solar projects in locations around the globe is not without risk. Mitigating site-specific risk requires the strategic application of products and technologies. A one-size-fits-all approach to product design and project development invariably increases project risk profiles. Strategic product differentiation improves project resilience.

Hail-hardened module and system designs mitigate project risk in hail-prone regions like West Texas. Product and system designs that resist dynamic wind effects reduce project risk in high-wind locations worldwide. Product and system designs that resist high static mechanical loads lessen catastrophic failure risks in extreme-snow locations. Corrosion-resistant products extend operating lifetimes in coastal areas.

See p. 16 for the inaugural published test results for RETC's proprietary HDT program.

QUALITY TESTS & METRICS

To help project stakeholders better assess module quality over a 25- or 30-year time frame in the field, RETC has taken a leadership role in industry efforts to develop and implement beyond qualification-testing standards. Simply meeting minimum certification requirements does not ensure a quality product for all project stakeholders in every application. More-stringent testing protocols are required to identify, compare and contrast modules according to manufacturing and material quality.

HAIL DURABILITY TEST

In response to a recent crisis of confidence, RETC introduced a dedicated beyond-certification test program designed to address the risks associated with large-diameter hailstones. In May 2019, hail damaged some 400,000 modules at the Midway Solar generating facility in West Texas, resulting in a previously unimaginable $80 million in insured losses. Recognizing that basic certification test standards are inadequate to identify and quantify the project risks associated with hail, RETC developed its innovative Hail Durability Test (HDT) program, the results of which are compiled in this year's report for the first time.

THRESHER TEST Introduced more than a decade ago to mitigate long-term performance risks, RETC's Thresher Test is an extended series of beyond-qualification tests designed to separate cream-of-the-crop modules from the chaff. Manufacturers can use the Thresher Test as a tool to identify potential wearout modes and failure mechanisms before volume manufacturing. Developers, financiers, insurers and independent engineers can use Thresher Test results as a comparative product screening tool to mitigate downstream technical risks.

See the results on p. 17 for detailed product performance across the multiple accelerated test sequences in RETC's Thresher Test.

UNDERSTANDING THE HDT PROGRAM

Here, we provide answers to some frequently asked questions about RETC's proprietary HDT sequence and classifications system. By expanding upon existing UL and IEC standards, the HDT program helps project stakeholders better understand hail effects on PV modules in real-world applications.

WHAT ARE THE BENEFITS OF RETC'S HDT PROGRAM?

The vast majority of modules are unscathed by the basic ballistic impact tests found in Underwriters Laboratories (UL) and International Electrotechnical Commission (IEC) standards. UL 1703 subjects modules to the impact of a 50-millimeter (2-inch) steel sphere dropped from a height of roughly 130 centimeters (51 inches); in rare cases, the resulting 6.78-joule impact will result in cell damage. Virtually all module designs pass the hail test in IEC 61215-2, which subjects modules to 11 impacts of a 25-millimeter (1-inch) ice ball traveling at its terminal velocity; this basic product certification test results in a modest impact force of 1.99 joules.

To differentiate product designs, RETC's HDT program expands and improves upon UL and IEC requirements in meaningful ways. First, the HDT program subjects modules to higher kinetic impact energies, ensuring that the test standard better reflects the risk posed by hail over a 25- or 30-year operating life. Second, RETC designed the program to thoroughly investigate a range of possible outcomes, which provides valuable data for probabilistic analyses. Third, the test sequence is not limited to ballistic impact testing; it also includes thermal cycle and hot-spot tests to reveal potential long-term module degradation modes.

WHAT IS THE BASIC SCOPE AND STRUCTURE OF THE HDT?

The HDT Test Procedure flow chart (p. 15) graphically represents RETC's extended test sequence. To start, RETC characterizes the initial condition of eight randomly selected test samples based on EL testing, visual inspection and maximum power measurement. Next, RETC subjects each test sample to ten hail impacts at five locations. To understand how impact severity affects outcomes, we divide the eight modules into four test cases that vary based on hailstone diameter, mass, impact velocity and kinetic energy.

After exposing each two-module test case to 10 strikes from an iceball of a specific diameter—45 millimeters (1.8 inches), 50.8 millimeters (2 inches), 55 millimeters (2.2 inches) or 60-millimeters (2.6 inches)—RETC characterizes the post-hail condition of each test sample. We then put all eight modules into an environmental chamber and cycle the temperature 50 times from 85°C on the high end to -40°C on the low end, as detailed in IEC 61215. After this TC50 exposure, we characterize the post–thermal cycle condition of the modules.

The final step in RETC's HDT sequence is to subject the test samples to the hot-spot endurance test found in IEC 61215.

"The module's hail-resiliency characteristic makes a huge difference to the probable maximum loss—and this risk profile drives insurance premiums."

—John Sedgwick, VDE Americas

This test evaluates how the modules withstand hot-spot heating effects under worst-case shading and operating conditions. After hot-spot testing, RETC characterizes the final condition of the test samples based on EL testing, visual inspection and maximum power measurement.

WHO CAN USE THE INFORMATION CONTAINED IN AN HDT REPORT?

The detailed information contained in a completed HDT report is helpful to module manufacturers, insurance companies, investors, developers and independent engineering firms. By exposing modules to severe, very severe and extreme hail strikes, the HDT sequence effectively investigates ballistic-impact resistance at the threshold of damage, just over this threshold and at material failure. The program ensures consistent ice ball quality, repeatable impact velocities and precise kinetic impact energies to maximize stakeholder confidence in the test results.

The resulting final report analyzes the collected module characterization data, identifying and quantifying uncritical, critical and very critical abnormalities. After processing these results, RETC characterizes product designs according to a hail-impact classification system from Class A (best) to Class D (worst). Conceptually, RETC's PV module hail-rating system is similar to PV system fire-rating classifications, which are essential to product selection and qualification.

HAIL IMPACT CHARACTERIZATIONS

Module HDT Classification	Impact Characterization
Class A	No abnormalities that can lead to premature drop in power. Low to no power loss.
Class B	A few abnormalities that do not lead to premature drop in power.
Class C	Increased abnormalities that may lead to premature drop in power and risk of hot spot.
Class D	Negative properties that can directly lead to a drop in power with an elevated risk of hot spot.

HAIL DURABILITY TEST (HDT) PROCEDURE

INITIAL CHARACTERIZATION

Electroluminescence testing; maximum power determination; visual inspection

HAIL IMPACT TESTING

Two test samples per case; ten shots total (5 impact locations per module with 2 impacts per location)

Case	Diameter	Mass	Velocity	Kinetic Energy
1	45 mm	43.9 g	30.7 m/s	20.69 J
2	50.8 mm	63.3 g	32.0 m/s	32.14 J
3	55 mm	80.2 g	33.9 m/s	46.08 J
4	65 mm	132.0 g	36.6 m/s	88.89 J

POST-HAIL CHARACTERIZATION

Electroluminescence testing; maximum power determination; visual inspection

THERMAL CYCLING

TC 50 testing per IEC 61215:2021 for all test samples

POST-THERMAL CYCLE CHARACTERIZATION

Electroluminescence testing; maximum power determination; visual inspection

HOT-SPOT ENDURANCE TESTING

Hot-spot testing per IEC 61215:2021 for all test samples

FINAL CHARACTERIZATION

Electroluminescence testing; maximum power determination; visual inspection

HAIL CLASSIFICATION

Module HDT Classification	Impact Characterization		
	Uncritical	Critical	Very Critical
Class A	<10%	0%	0%
Class B	<20%	<10%	0%
Class C	≥20%	≥10%	<10%
Class D	>10%	>10%	≥10%

HAIL DURABILITY TEST RESULTS

New to the 2022 edition of the *PV Module Index Report*, RETC presents a table ranking module performance in our pioneering HDT program. To celebrate high performance in ballistic-impact resistance, we recognize those products that achieved a Class A hail rating while effectively withstanding kinetic energy of at least 20 joules.

Products that receive a Class A rating in RETC's HDT program experience less than 1% power degradation and do not display any meaningful abnormalities upon completion of the test sequence. Resistance to kinetic impact energy is the ultimate measure of a hail-hardened PV module. Products that withstand kinetic energy of at least 20 joules have effectively demonstrated resistance to a 45-millimeter (1.8-inch) ice ball traveling at a terminal velocity of 30.7 meters per second.

Note that front glass thickness is strongly correlated to ballistic-impact resistance. Many manufacturers have reduced front glass thickness to control weight as module aperture areas have increased. Glass-on-glass bifacial module designs also use relatively thin module glass.

A side effect of thinner module glass is a decrease in hail-impact resistance. Glass manufacturers need a minimum thickness of roughly 3 millimeters to temper glass for maximum strength. The thinner 2-millimeter glass used for many of today's large-format or bifacial modules is not tempered during manufacturing; it is heat-strengthened glass only, which increases the likelihood of breakage due to hail.

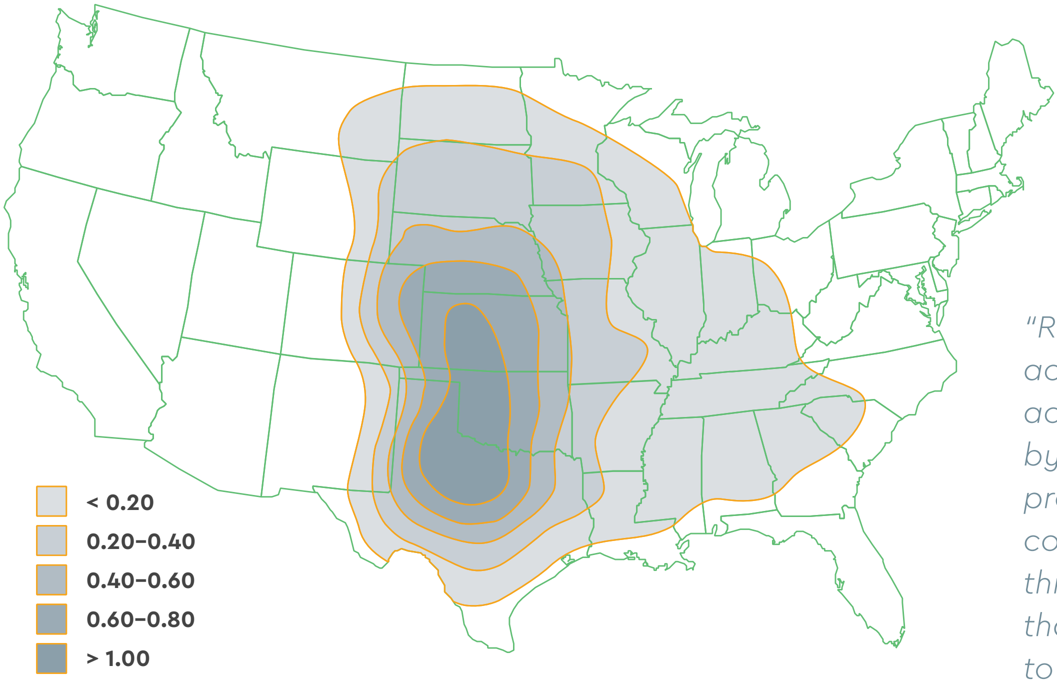
HAIL DURABILITY TEST

Rank	Model	Effective Kinetic Energy (J)	HDT Class
1	P1	26.47	A
2	P2	22.06	A
3	P3	21.98	A
4	P4	20.22	A
5	P5	19.95	A
6	P6	12.17	A
7	P7	12.12	A
8	P8	31.92	B
9	P9	46.46	C
10	P10	43.51	C
11	P11	21.74	C
12	P12	21.47	C
13	P13	53.01	D
14	P14	52.44	D
15	P15	43.09	D
16	P16	42.81	D
17	P17	32.48	D
18	P18	26.23	D

HIGH QUALITY IN HAIL DURABILITY TEST

RETC proudly recognizes the manufacturers whose modules effectively resisted kinetic impact energy greater than 20 joules, experienced less than 1% power degradation and achieved a Class A hail-resistance rating: Jinko Solar, LONGi Solar.

PROBABILITY OF GREATER THAN 2-INCH HAIL



Mean Number of Hail >2.00 in. Days per Year
Within 25 Miles of a Point, 1986–2015

"RETC can mount the actual modules to the actual racking purchased by an owner for a specific project and run this combination of equipment through a variety of tests that evaluate its resiliency to hail."

—Danny Seagraves, Brown & Brown

THRESHER TEST RESULTS

For its 2022 edition of the *PV Module Index Report*, RETC presents a Thresher Test performance matrix. To showcase high performance in manufacturing, we recognize those manufacturers that achieve high performance across a diverse set of accelerated test sequences. To demonstrate quality, products must achieve less than 2% power degradation per accelerated aging test across the greatest number of tests.

Fielded PV modules experience a wide variety of environmental stresses. To perform well over a long period of time, these products must resist the instantaneous impacts of these stressors as well as the cumulative effects of prolonged exposure. To account for these conditions holistically, the Thresher Test protocol includes humidity-freeze cycling (HF30), thermal cycling (TC600), damp heat exposure (DH2000), dynamic mechanical loading and UV soaking.

Note that manufacturers may elect to subject some products to only one or two accelerated reliability tests, which provides limited insight into long-term performance. Those that characterize modules based on an exhaustive set of accelerated stress tests demonstrate a commitment to quality. For best results, beyond-qualification testing will cover multiple products and assess changes to individual module families.

HIGH QUALITY IN THRESHER TEST

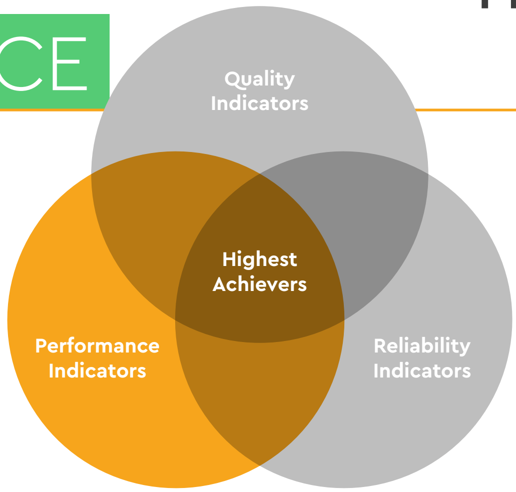
RETC proudly recognizes, in alphabetical order, manufacturers that tested products to a wide range of beyond-qualification test sequences for demonstrating a commitment to quality: Hanwha Q CELLS, JA Solar, LONGi Solar, Tesla, Trina Solar, Yingli Solar.

THRESHER TEST

Model	HF30	TC600	DH2000	DML	UV Soak
P1	✓	✓	✓	✓	-
P2	✓	✓	✓	✓	-
P3	✓	✓	✓	✓	-
P4	✓	✓	✓	✓	-
P5	✓	-	✓	✓	-
P6	✓	-	-	✓	-
P7	✓	-	-	✓	-
P8	✓	-	-	✓	-
P9	-	✓	✓	-	-
P10	✓	-	-	✓	-
P11	-	-	✓	-	-
P12	-	-	✓	-	-
P13	-	-	✓	-	-
P14	-	-	✓	-	-
P15	-	-	✓	-	-
P16	-	-	✓	-	-
P17	-	✓	-	-	-
P18	-	✓	-	-	-
P19	-	✓	-	-	-
P20	-	-	-	✓	-
P21	-	-	-	✓	-
P22	-	-	-	✓	-
P23	-	-	-	✓	-
P24	-	-	-	✓	-
P25	-	-	-	✓	-
P26	-	-	-	✓	-
P27	-	-	-	✓	-
P28	-	-	-	✓	-
P29	-	-	-	✓	-
P30	-	-	-	✓	-
P31	-	-	-	✓	-
P32	-	-	-	✓	-
P33	-	-	-	✓	-
P34	-	-	-	✓	-
P35	-	-	-	✓	-
P36	-	-	-	✓	-
P37	-	-	-	✓	-
P38	-	-	-	✓	-
P39	-	-	-	✓	-
P40	-	-	-	✓	-
P41	-	-	-	✓	-
P42	-	-	-	✓	-
P43	-	-	-	✓	-
P44	-	-	-	✓	-
P45	-	-	-	✓	-
P46	-	OK	✓	✓	-
P47	-	-	OK	-	-
P48	✓	✓	OK	✓	✓
P49	✓	-	OK	✓	-
P50	-	✓	OK	✓	-
P51	✓	✓	OK	✓	-
P52	OK	✓	OK	✓	OK
P53	OK	✓	OK	✓	-
P54	OK	OK	OK	✓	✓
P55	OK	OK	OK	✓	OK
P56	OK	-	-	✓	-
P57	OK	✓	X	✓	-
P58	OK	✓	X	✓	-
P59	OK	OK	X	✓	-
P60	OK	OK	X	✓	-
P61	OK	OK	X	✓	-
P62	✓	X	-	-	-

Key	✓	OK	X	-
	<2% Excellent	2–5% Average	>5% Fail	No Data

MODULE PERFORMANCE



As an independent testing laboratory with the highest level of accreditation, RETC plays an essential role in ensuring that module performance characterization is as accurate and reliable as possible.

Testing laboratories use calibrated and certified equipment under audited and controlled test conditions. Characteristics captured under these rigorous conditions represent the proper measure of PV module performance and provide value to multiple project stakeholders.

While factory testing according to standard test conditions (STC) parameters is ideal for establishing module nameplate ratings, factory test results do not characterize typical module operating conditions. To accurately model system performance in the real world, it is essential to understand how modules perform under low-irradiance conditions or in relation to changing sun angles. Moreover, it is crucial to characterize module performance under test conditions that reflect the operating conditions under which PV systems typically produce optimal energy yields. It is also critical to understand how short-term sun exposure and the resulting degradation impacts in-field PV performance.

PERFORMANCE TESTS & METRICS

Here, we provide a high-level overview of some of the relevant PV module performance parameters that RETC characterizes in its state-of-the-art facilities. Following these descriptions, we provide a sampling of performance test results that RETC compiled in 2021 and showcase manufacturers according to high achievement in manufacturing.

CEC CERTIFICATION In the 1990s, researchers working on the Photovoltaics for Utility-Scale Applications (PVUSA) project developed a set of performance rating parameters intended to simulate environmental conditions a module might experience in the real world. The primary differences between PVUSA test conditions (PTC) and STC are cell temperature and wind speed. Specifically, PTC parameters call for an elevated cell temperature of 45°C, an ambient temperature of 22°C and a wind speed of 1 meter per second (2.2 mph). PTC ratings are foundational module performance characteristics required by the California Energy Commission (CEC).

Solar modules must be included on an eligible equipment list maintained and regularly updated by the CEC to qualify for solar incentive programs around the US. This CEC listing requires additional testing and characterization beyond the basic UL product certification tests. Note that the CEC does not accept self-reported data from manufacturers. The CEC accepts listing data from accredited third-party laboratories only. RETC is one of the laboratories most active in CEC testing.

See the table on p. 22 for a sampling of high-performing PV modules based on PTC-to-STC ratio.

CONVERSION EFFICIENCY The percentage of incident solar energy converted to electrical energy is an essential figure of merit for PV modules and cell technologies. Nominal module conversion efficiency is determined by dividing a product's nameplate STC-rated power by its total aperture area. Cell technology and module design play a significant role in module efficiency.

See the table on p. 20 for the maximum module efficiency ratings calculated and ranked per manufacturer based on a year's worth of RETC's module characterization test data.

INCIDENCE ANGLE MODIFIER (IAM) IAM is a performance characteristic that accounts for changes in PV module output based on changing sun angles. To characterize IAM, RETC conducts electrical characterization tests at 13 different incidence angles, ranging from 0° to 90°. IAM testing is essential for understanding module performance at different times or seasons, especially early or late in the day or in winter when the sun is low on the horizon.

LIGHT- AND ELEVATED TEMPERATURE–INDUCED DEGRADATION (LeTID) Newer cell technologies may experience a type of long-term in-field degradation associated with exposure to light and elevated temperatures. To characterize LeTID susceptibility, the IEC has developed a protocol of light soaking, followed by 75°C temperature exposure for two or three (optional) 162-hour cycles to identify significant degradation (>3%). Subsequently, test samples are subject to 500 hours of 85°C temperature exposure followed by two or three additional 162-hour cycles.

See the table on this page (bottom right) for module performance distribution data based on LeTID test results.

LIGHT-INDUCED DEGRADATION (LID) As a service to manufacturers, RETC offers LID testing to IEC standards to ensure manufacturing quality control and in-field reliability. LID is a type of degradation resulting from exposure to sunlight that impacts some PV cell types but not others. PV modules that are prone to LID might experience a relatively rapid rate of performance degradation over a relatively short time in the field—typically a few hours or days—before performance stabilization.

See the table on p. 20 for module performance distribution data based on LID test results.

PAN FILES The de facto standard module characterization file format is a PAN file, which defines 22 parameters that PVsyst software uses for its production modeling calculations. Project developers use PVsyst to evaluate potential sites based on energy production and financial performance. Independent engineers use its simulations to validate the project developer's assumptions. Financial institutions rely on these independent engineering analyses to ensure a return on investment. EPCs and asset managers use PVsyst simulations for capacity testing, commissioning and plant performance benchmarking.

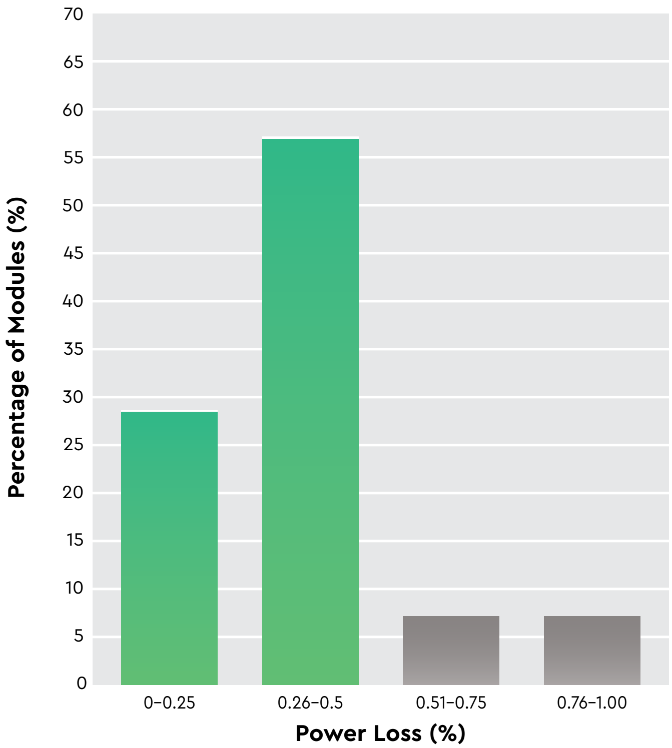
See the table on p. 21 for module-specific PVsyst performance estimates for a 10 MW ground-mounted application in Texas simulated based on RETC's third-party validated and optimized PAN files.

LeTID TEST RESULTS

For the 2022 edition of its *PV Module Index Report*, RETC has ranked the top-performing PV modules based on the results of LeTID testing and characterization. To showcase high performance in manufacturing, we recognize manufacturers whose products experience the least power loss after 486 hours of exposure.

Note that most of the products RETC tested performed well on the basis of LeTID. More than 25% of modules tested experienced less than 0.25% power loss. Moreover, 85% of the modules tested experienced less than 0.5% power loss.

486-HOUR LeTID EXPOSURE



HIGH PERFORMANCE IN LeTID RESISTANCE

RETC proudly recognizes, in alphabetical order, those manufacturers that achieve a Top 10 ranking, among all modules tested, based on LID performance ratio: Hanwha Q CELLS, JA Solar, Jinko Solar, LONGi Solar, Trina Solar, Yingli Solar.

LID TEST RESULTS

For the 2022 edition of its *PV Module Index Report*, RETC has ranked the top-performing PV modules based on the results of LID testing and characterization. To showcase high performance in manufacturing, we are recognizing the manufacturers of the Top 10 modules in this list.

LID TESTING DATA

Rank	Model	Cell Technology	Performance Ratio
1	P1	Mono	0.45%
2	P2	Mono	0.44%
3	P3	Mono	0.28%
4	P4	Mono	0.25%
5	P5	Mono	0.23%
6	P6	Mono	0.20%
7	P7	Mono	0.19%
8	P8	Mono	0.17%
8	P9	Mono	0.17%
9	P10	Mono	0.06%
10	P11	Mono	0.05%
10	P12	Poly	0.05%
11	P13	Mono	0.02%
12	P14	Mono	0.01%
12	P15	Mono	0.01%
12	P16	Mono	0.01%
12	P17	Mono	0.01%
13	P18	Mono	0.00%
14	P19	Mono	-0.02%
15	P20	Mono	-0.03%
16	P21	Mono	-0.04%
17	P22	Mono	-0.10%
18	P23	Mono	-0.12%
19	P24	Mono	-0.14%
19	P25	Mono	-0.14%
20	P26	Mono	-0.20%
21	P27	Mono	-0.21%
21	P28	Mono	-0.21%
22	P29	Mono	-0.22%
23	P30	Mono	-0.24%
23	P31	Mono	-0.24%
23	P32	Mono	-0.24%
24	P33	Mono	-0.25%
24	P34	Mono	-0.25%
25	P35	Mono	-0.27%
26	P36	Mono	-0.28%
26	P37	Mono	-0.28%
27	P38	Mono	-0.30%
28	P39	Mono	-0.31%
29	P40	Mono	-0.32%
30	P41	Mono	-0.34%
31	P42	Mono	-0.35%
32	P43	Mono	-0.38%
33	P44	Mono	-0.40%
33	P45	Mono	-0.40%
34	P46	Mono	-0.41%
35	P47	Mono	-0.46%
36	P48	Mono	-0.50%
37	P49	Mono	-0.53%
37	P50	Mono	-0.53%
38	P51	Poly	-0.59%
39	P52	Poly	-0.61%
39	P53	Mono	-0.61%
40	P54	Mono	-0.64%
41	P55	Poly	-0.66%
42	P56	Mono	-0.69%
43	P57	Mono	-0.81%
44	P58	Mono	-0.83%
45	P59	Mono	-0.93%
46	P60	Mono	-0.96%
47	P61	HJT	-1.18%

Note that there is some correlation between cell technology and average LID values in these results. Moreover, some products experience an increase—rather than a decrease—in measured power after LID test exposure. The top-performing products based on LID performance ratio experience an increase in power or very modest power loss after test exposure as a result of the specific cell or module technology.

MODULE EFFICIENCY RESULTS

For the 2022 edition of its *PV Module Index Report*, RETC has ranked the recorded maximum module efficiency values—as well as other relevant product attributes—per manufacturer based on third-party I-V characterization measurements conducted at our accredited testing laboratories over 12 months. To showcase high performance in manufacturing, we recognize those manufacturers with products that achieved conversion efficiencies of 20% or greater based on total module area.

MODULE I-V CHARACTERIZATION DATA

Rank	Model	Technology	Pmax (W)	Aperture (m^2)	Aperture Efficiency
1	P1	Mono Perc	547.513	2.517	21.8%
2	P2	Mono Perc	493.592	2.285	21.6%
3	P3	Mono Perc	536.147	2.489	21.5%
4	P4	Mono-c-Si	382.409	1.794	21.3%
5	P5	Mono Perc	364.362	1.722	21.2%
5	P6	Mono Perc	447.45	2.115	21.2%
6	P7	Mono Perc	400.938	1.896	21.1%
7	P8	Mono Perc	441.672	2.115	20.9%
8	P9	Mono-c-Si	366.35	1.770	20.7%
8	P10	Mono Perc	435.813	2.108	20.7%
9	P11	Mono Perc	391.047	1.896	20.6%
9	P12	Mono Perc	441.38	2.145	20.6%
10	P13	Mono-c-Si	358.876	1.770	20.3%
10	P14	Mono-c-Si	326.838	1.610	20.3%
11	P15	Mono Perc	358.749	1.772	20.2%
11	P16	Mono Perc	427.314	2.111	20.2%
12	P17	Mono-c-Si	351.138	1.776	19.8%
13	P18	Mono Perc	418.637	1.120	19.7%
14	P19	Mono Perc	344.517	1.766	19.5%
15	P20	Mono Perc	382.009	1.990	19.2%
16	P21	Mono-c-Si	330.205	1.734	19.0%
17	P22	Mono-c-Si	175.944	1.092	16.1%
17	P23	Thin Film	189.559	1.180	16.1%
18	P24	Mono-c-Si	342.781	2.137	16.0%
19	P25	Mono-c-Si	335.259	2.137	15.7%
20	P26	Mono-c-Si	118.125	0.763	15.5%
21	P27	Mono-c-Si	117.05	0.763	15.3%
22	P28	Mono-c-Si	166.432	1.092	15.2%

HIGH PERFORMANCE IN MODULE EFFICIENCY

RETC proudly recognizes, in alphabetical order, those manufacturers whose modules achieved greater than 20% total area module efficiency: JA Solar, LONGi Solar, REC Solar, Silfab Solar, Tesla, Yingli Solar.

HIGH PERFORMANCE IN LID RESISTANCE

RETC proudly recognizes, in alphabetical order, those manufacturers that achieve a Top 10 ranking, among all modules tested, based on LID performance ratio: Hanwha Q CELLS, Jinko Solar, LONGi Solar, Trina Solar.

PAN FILE RESULTS

For the 2022 edition of its *PV Module Index Report*, RETC has ranked the top-performing PV modules based on the results of plant-level PVsyst production estimates that use our third-party–validated PAN files. To showcase high performance in manufacturing, we recognize those manufacturers with products that achieved a PVsyst-modeled performance ratio of 85% or greater.

As a service to project developers, independent engineers, operators, asset managers, insurers and financiers, RETC generates third-party–validated PAN files that enable site-specific, plant-level performance evaluation. Conducted to IEC standards, PAN file-characterization tests precisely evaluate module performance under specific operating conditions. Once imported into industry-standard software, such as PVsyst, these independently verified module-specific performance parameters allow for accurate and bankable real-world production estimates.

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.

PAN FILE TESTING DATA

PVSyst Simulation for 10MW Ground Mount in Texas

Rank	Model	Specific Prod kWh/kWp/yr	Performance Ratio [%]
1	P1	1918	89.09%
2	P2	1896	88.06%
3	P3	1894	88.01%
4	P4	1892	87.91%
5	P5	1891	87.86%
6	P6	1890	87.80%
7	P7	1886	87.61%
8	P8	1883	87.50%
9	P9	1873	87.02%
10	P10	1867	86.74%
11	P11	1845	85.71%
12	P12	1815	84.30%
13	P13	1814	84.27%
14	P14	1812	84.17%
15	P15	1810	84.10%
16	P16	1805	83.86%
17	P17	1802	83.70%
18	P18	1801	83.66%
19	P19	1789	83.12%
20	P20	1789	83.11%
21	P21	1786	82.95%
22	P22	1774	82.42%
23	P23	1749	81.24%
24	P24	1741	80.87%

HIGH PERFORMANCE IN PAN FILE CHARACTERIZATION

RETC proudly recognizes, in alphabetical order, those manufacturers with PV modules that produced a performance ratio greater than 85%, as calculated in PVsyst using RETC's independently validated third-party PAN files: JA Solar, Jinko Solar, LONGi Solar, Trina Solar.

PTC-TO-STC RATIO RESULTS

For the 2022 edition of its *PV Module Index Report*, RETC has ranked the top-performing PV modules according to the PTC-to-STC ratio. To showcase high performance in manufacturing, we recognize the manufacturers of the Top 10 modules in this summary table.

The data used to calculate PTC ratings are of particular interest to manufacturers. As compared to the STC ratings used to characterize module performance in factory settings, PTC ratings provide a better indication of in-field performance. Generally speaking, manufacturers with the highest-performing products according to this PTC-to-STC metric utilize cell technologies that experience less power degradation at elevated temperature, which is a function of lower module temperature coefficients.

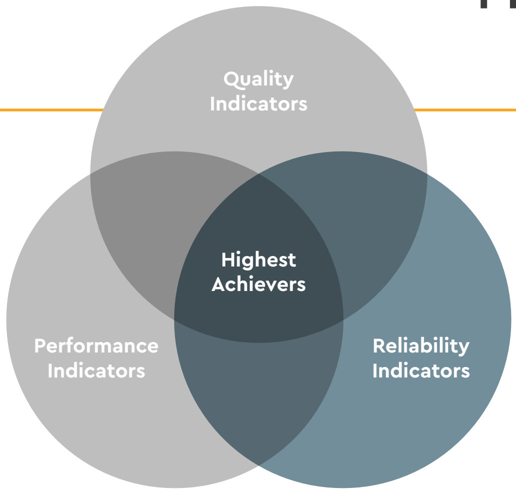
CEC TESTING DATA

Rank	Model	Technology	Efficiency	STC	PTC	PTC Ratio
1	P1	Mono-c-Si	21.3%	390	371.317	95.2%
2	P2	Mono-c-Si	20.7%	370	348.528	94.2%
3	P3	Mono Perc	21.8%	540	508.36	94.1%
4	P4	Mono Perc	21.2%	445	418.462	94.0%
4	P5	Mono Perc	20.7%	440	413.463	94.0%
5	P6	Mono Perc	20.9%	445	417.545	93.8%
6	P7	Mono Perc	21.1%	405	379.572	93.7%
7	P8	Mono Perc	20.6%	440	411.805	93.6%
8	P9	Mono-c-Si	19.0%	335	313.265	93.5%
8	P10	Mono Perc	20.2%	365	341.158	93.5%
9	P11	Mono Perc	20.2%	420	392.228	93.4%
10	P12	Mono-c-Si	20.3%	360	335.979	93.3%
10	P13	Mono-c-Si	19.8%	365	340.637	93.3%
10	P14	Mono Perc	20.6%	390	363.946	93.3%
11	P15	Mono Perc	19.5%	360	335.622	93.2%
11	P16	Mono Perc	21.5%	535	498.685	93.2%
12	P17	Mono Perc	21.6%	490	456.421	93.1%
12	P18	Mono Perc	21.2%	365	339.947	93.1%
13	P19	Mono Perc	16.0%	360	326.64	90.7%
14	P20	Mono Perc	16.1%	180	163.223	90.7%
15	P21	Mono Perc	15.5%	120	108.681	90.6%
16	P22	Mono Perc	15.7%	350	313.748	89.6%
17	P23	Mono Perc	15.2%	175	156.773	89.6%
18	P24	Mono Perc	15.3%	117	104.682	89.5%

HIGH PERFORMANCE IN PTC-TO-STC RATIO

RETC proudly recognizes, in alphabetical order, those manufacturers of the Top 10 PV modules based on PTC-to-STC ratio, which have lower module temperature coefficients and therefore see less performance degradation at elevated temperatures: Hanwha Q Cells, JA Solar, REC Solar, Silfab Solar, Tesla, Yingli Solar.

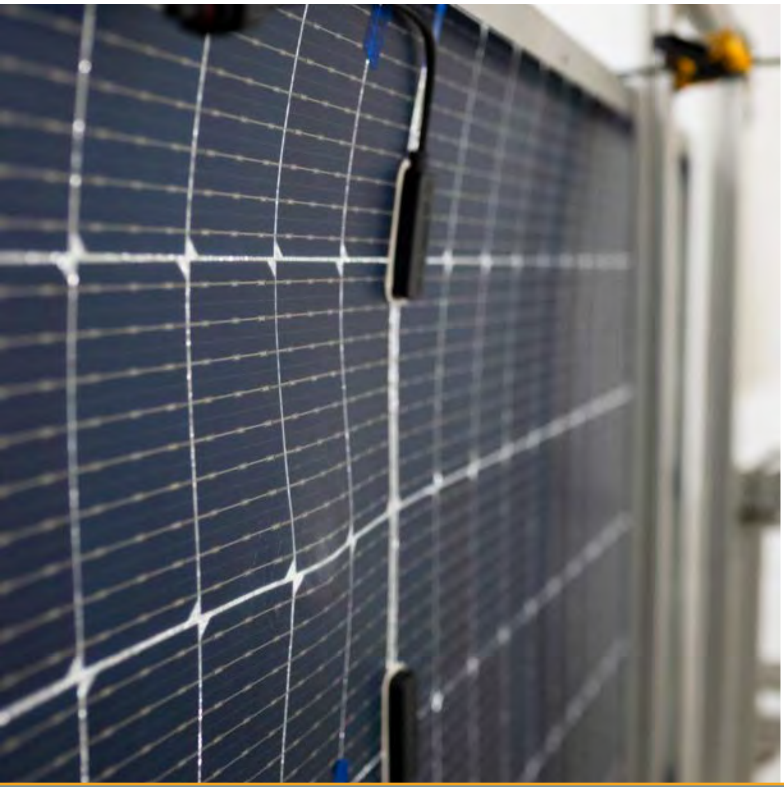
MODULE RELIABILITY



Product reliability describes the probability that a device will perform its design function for a specific period based on certain conditions of use.

PV modules in outdoor, full-sun locations are routinely exposed to ultraviolet light, thermal cycling, damp heat, dry heat, humidity-freeze cycles, wind loads, snow loads and so forth. Under these harsh conditions of use, PV products must output power at or above warrantied levels for at least 25 years.

As an accredited laboratory, RETC plays an important role in maintaining product reliability. In addition to offering basic certification tests to relevant UL and International IEC standards, RETC also tests products and systems to beyond-qualification test protocols. Whereas certification and qualification tests represent the legal minimum requirements for product safety, enhanced or extended tests put additional stress on modules to identify areas of weakness and better predict long-term in-field reliability.



RELIABILITY TESTS & METRICS

The following test descriptions provide a high-level overview of the flat-plate PV module tests that RETC offers within its accelerated reliability testing program. In the test data that follow, we celebrate high performance based on indicators of module reliability.

DAMP HEAT (DH) RETC's Thresher Test includes a DH2000 test, indicating a duration of exposure of 2,000 hours—twice the duration typically required for product certification. DH testing aims to characterize a PV module's ability to withstand prolonged exposure to humid, high-temperature environments. Taking place inside an environmental chamber, the test exposes modules to a controlled temperature of 85° Celsius and a relative humidity of 85% for a set amount of time.

See the bar chart on p. 24 for module performance distribution data based on DH test results.

DYNAMIC MECHANICAL LOAD (DML) The DML test sequence subjects modules to 1,000 cycles of +1,000 Pascal (Pa) and -1,000 Pa loads at a frequency of three to seven cycles per minute. Subsequently, test samples in an environmental chamber undergo TC50 testing followed by HF10 or HF30 testing. Measurements taken upon completion characterize electrical performance. DML testing evaluates a module's ability to withstand wind loading. Whereas standard mechanical load (ML) tests simulate static snow and ice loads, DML testing simulates the dynamic push-pull loads associated with hurricanes, typhoons and other high-wind events.

See the bar chart p. 25 for module performance distribution data based on DML, TC and HF test results.

HUMIDITY FREEZE (HF) HF testing characterizes a PV module's ability to withstand the alternating effects of high heat and humidity followed by extreme cold. For this accelerated aging test, modules in an environmental chamber are exposed to a relative humidity of 85% and subjected to temperature cycling from 85°C to -40°C with no relative humidity control. Certification standards call for a 10-cycle test and allow for no more than 5% degradation. RETC's Thresher Test subjects modules to 30 or more humidity-freeze cycles.

POTENTIAL INDUCED DEGRADATION (PID) The PID test protocol places rack-mounted modules in an environmental chamber, which controls temperature and humidity, and exposes them to a voltage bias of several hundred volts with respect to the mounting structure. Typically, exposure times range from 96 hours to as much as 500 hours. PID testing characterizes a module's ability to withstand degradation due to voltage and current leakage resulting from ion mobility between the semiconductor material and other elements of the module packaging.

See p. 25 for module performance distribution data based on PID test results.

THERMAL CYCLING (TC) RETC's Thresher Test calls for extended 600-cycle TC600 testing as a means of detecting weaknesses in module designs. TC testing assesses product reliability and identifies thermal fatigue failure modes. The TC test protocol calls for cycling modules in an environmental chamber between two temperature extremes—85°C on the high end and -40°C on the low end. Typical certification standards call for a TC200 test, consisting of 200 cycles only.

See the bar chart on p. 26 for module performance distribution data based on TC test results

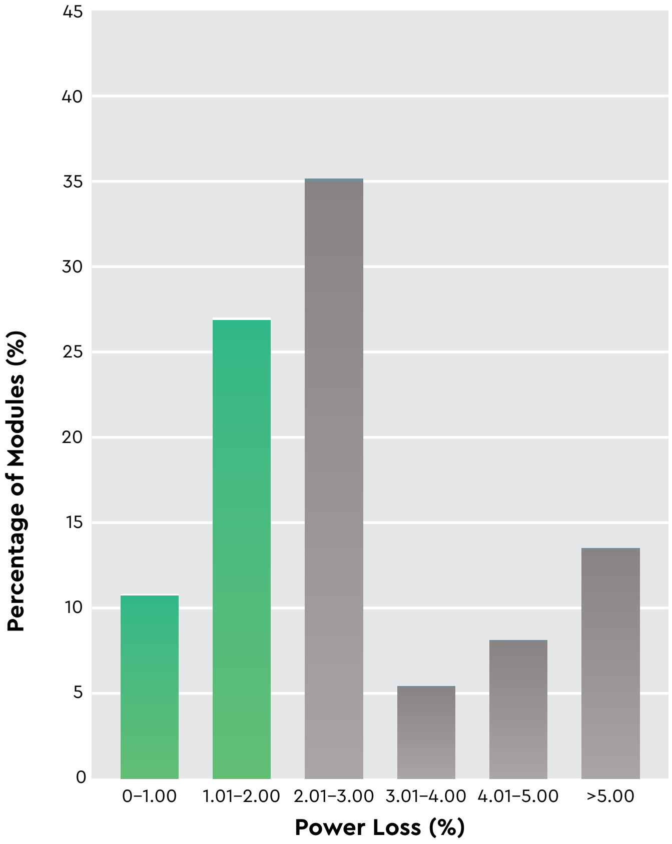
ULTRAVIOLET (UV) EXPOSURE The enhanced UV preconditioning test conducted for accelerated reliability assessment exposes modules to two cycles of UV irradiation at 45 kWh/m^2, which is six times greater than the IEC 61215 requirements for product qualification. This test maintains modules at an elevated temperature of 60°C while a UV light is tuned to the ultraviolet A and ultraviolet B regions. UV soaking or preconditioning characterizes a module's susceptibility to degradation and performance loss resulting from exposure to ultraviolet light.

DH TEST RESULTS

For its 2022 edition of its *PV Module Index Report*, RETC has compiled performance distribution data for modules exposed to a 2,000-hour damp heat test (DH2000). As compared to minimum certification requirements, the extended DH2000 test duration better characterizes module durability and robustness. IEC and UL certification standards require only a 1,000-hour damp heat test (DH1000) and allow for a maximum performance degradation of 5%.

To showcase high performance in manufacturing, RETC has highlighted data for modules that experienced less than 2% power loss after DH2000 exposure. As shown in these data, roughly 38% of modules that RETC subjected to DH2000 testing in 2021 experienced less than 2% power loss. Since RETC began publishing its *PV Module Index Report*, we have observed a steady year-over-year improvement in DH tests results.

2000-HOUR DAMP HEAT (DH2000)



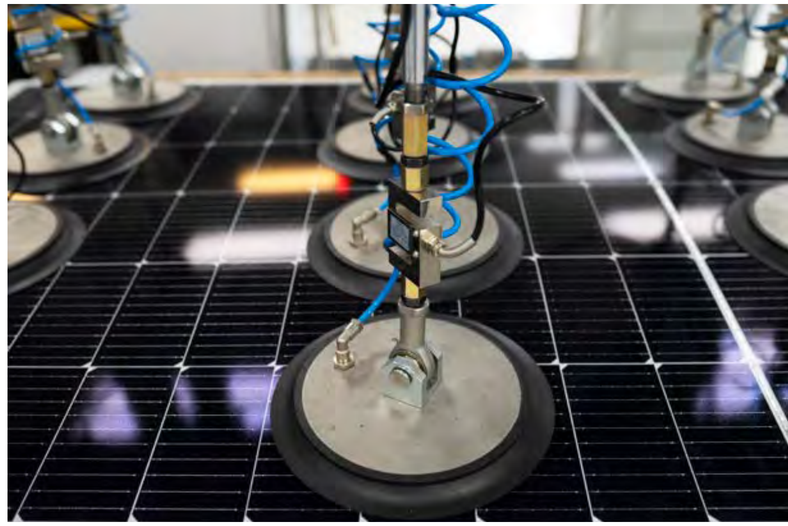
HIGH RELIABILITY IN DAMP HEAT TEST

RETC proudly recognizes, in alphabetical order, those manufacturers whose modules degraded less than 2% after being subjected to 2,000-hour damp exposure: JA Solar, LONGi Solar, Hanwha Q Cells, Tesla, Trina Solar, Yingli Solar.

DML TEST RESULTS

For its 2022 edition of the *PV Module Index Report*, RETC has compiled performance distribution data for modules exposed to DML testing followed by TC50 and HF10 environmental exposure. To showcase high performance in manufacturing, we recognize module companies that achieved less than 2% degradation in power.

As shown in these test results, more than 45% of the modules that RETC subjected to simulated wind and environmental stresses achieved less than 2% degradation in power. Roughly one-third of these high-performing modules, or 15% of the total test samples, experienced less than 1% degradation in power after the DML sequence.

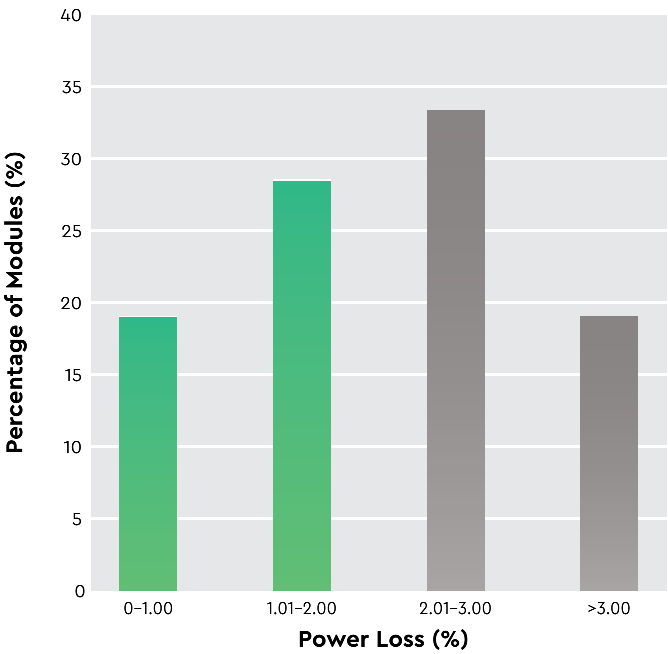


PID TEST RESULTS

For its 2022 edition of the *PV Module Index Report*, RETC has compiled performance distribution data for modules exposed to PID testing. To showcase high performance in manufacturing, we have highlighted data for modules that achieved less than 2% of performance degradation through 192 hours of exposure.

These tests results show that roughly 55% of modules achieved top-performing status, experiencing less than 2% degradation through 192 or more hours of PID test exposure. Roughly one in five of these high-performing modules, or 11% of the test samples, achieved less than 1% degradation over the test period. By comparison, more than 20% of modules experienced greater than 5% power loss.

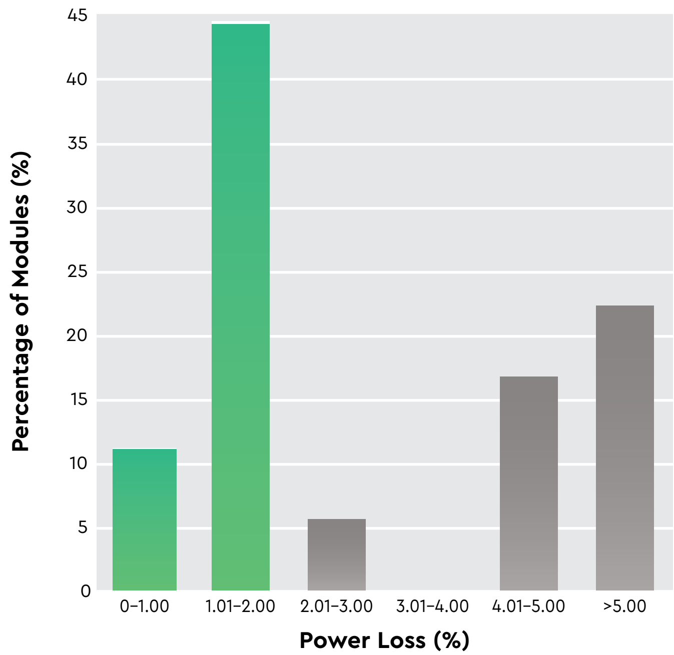
DYNAMIC MECHANICAL LOAD (DML | TC50 | HF30)



HIGH RELIABILITY IN DML TEST

RETC proudly recognizes, in alphabetical order, those manufacturers whose modules degraded less than 2% after being subjected to dynamic mechanical loading followed by 50 thermal cycles and 50 humidity-freeze cycles: JA Solar, Jinko Solar, LONGi Solar, Trina Solar, Yingli Solar.

192-HOUR POTENTIAL INDUCED DEGRADATION (PID)



HIGH RELIABILITY IN PID RESISTANCE

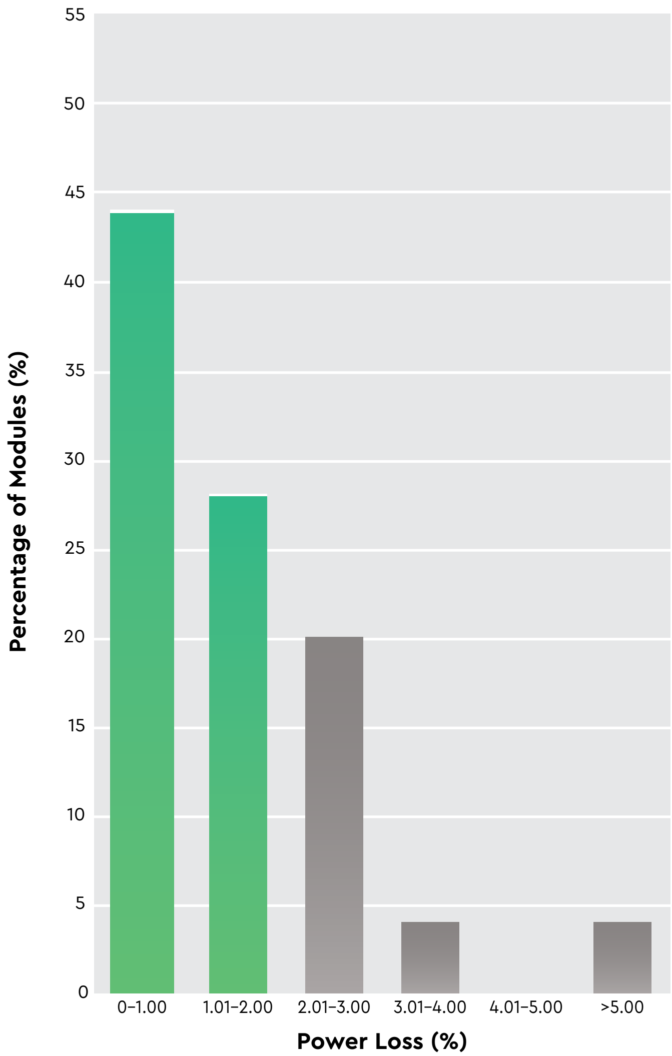
RETC proudly recognizes those manufacturers whose modules degraded less than 2% after 192-hour PID test exposure: JA Solar, Jinko Solar, LONGi Solar.

TC TEST RESULTS

For its 2022 edition of its *PV Module Index Report*, RETC has compiled performance distribution data for modules exposed to a 600-cycle thermal cycle test (TC600). Compared to minimum certification requirements, the extended TC600 test duration better characterizes module durability and robustness. IEC and UL certification standards require only a 200-cycle thermal cycle test (TC200).

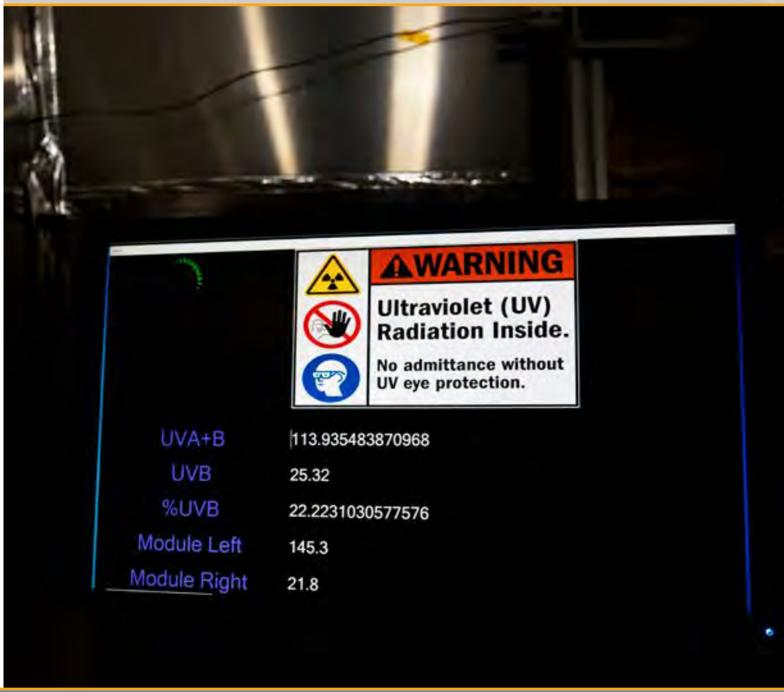
To showcase high performance in manufacturing, RETC has highlighted data for modules that experienced less than 2% power loss after TC600 exposure. As shown in these data, more than 70% of modules that RETC subjected to TC600 testing in 2021 experienced less than 2% power loss.

600-CYCLE THERMAL CYCLE (TC600)



HIGH RELIABILITY IN THERMAL CYCLE TEST

RETC proudly recognizes, in alphabetical order, those manufacturers whose modules degraded less than 2% after being subjected to 600-cycle thermal cycle exposure: Hanwha Q CELLS, JA Solar, Jinko Solar, LONGi Solar, Tesla, Trina Solar, Yingli Solar.



OVERALL HIGH ACHIEVEMENT IN MANUFACTURING

Throughout the 2022 edition of the *PV Module Index Report*, RETC has recognized 9 different manufacturers and showcased 61 instances of high achievement in manufacturing.

To identify the best of the best, we reviewed and ranked the overall data distributions across all three disciplines: quality, performance and reliability. The Overall Results Matrix on the right summarizes the results of this analysis, which highlights six top performers based on overall high achievement in manufacturing.

Note that this summary analysis of high achievement in manufacturing is based on available data. Products and manufacturers that are not recognized as overall high achievers may still be robust, reliable and high quality. However, RETC cannot make an overall determination regarding high achievement in manufacturing without module tests data across all three categories.

RETC compiled the data and results presented herein at its accredited testing facilities during a 12-month period, starting in Q2 2021 and extending to Q1 2022. We share these results in the *PV Module Index Report 2022* to showcase and recognize industry-leading PV module companies and technologies.

OVERALL RESULTS MATRIX

Model	Quality	Reliability	Performance
P1	✓	✓	✓
P2	✓	✓	✓
P3	✓	✓	✓
P4	✓	✓	✓
P5	✓	✓	✓
P6	✓	✓	✓
P7	✓	✓	✓
P8	✓	✓	✓
P9	✓	✓	✓
P10	-	✓	-
P11	-	-	✓
P12	-	-	✓
P13	-	-	✓
P14	-	-	✓
P15	-	-	✓
P16	-	-	✓
P17	-	-	✓
P18	-	-	✓
P19	-	-	✓
P20	-	-	✓
P21	-	✓	-
P22	-	✓	OK
P23	-	✓	OK
P24	-	✓	OK
P25	-	✓	OK
P26	-	OK	✓
P27	-	OK	✓
P28	-	-	OK
P29	-	-	OK
P30	-	-	OK
P31	-	-	OK
P32	-	-	OK
P33	-	-	OK
P34	-	-	OK
P35	-	-	OK
P36	-	-	OK
P37	-	-	OK
P38	-	OK	OK
P39	-	OK	OK
P40	-	OK	OK
P41	-	OK	OK
P42	-	OK	OK
P43	-	OK	OK
P44	-	OK	OK
P45	-	OK	-
P46	-	OK	-
P47	-	X	-

Key	✓ <2% Good	OK 2–5% Average	X >5% Fail	- No Data

2022 TOP PERFORMERS OF THE YEAR

RETC congratulates and recognizes, in alphabetical order, manufacturers with products recognized for high achievement in manufacturing across three essential disciplines—quality, performance and reliability—in the 2022 edition of the *PVMI Report*: Hanwha Q CELLS, JA Solar, Jinko Solar, LONGi Solar, Trina Solar, Yingli Solar.

A YEAR IN REVIEW

PV MODULE INDEX REPORT 2022 AWARDEES

OVERALL HIGH ACHIEVEMENT IN MANUFACTURING

Congratulations to our top six performers of the year!

Hanwha Q CELLS • JA Solar • Jinko Solar • LONGi Solar • Trina Solar • Yingli Solar

HIGH ACHIEVEMENT IN QUALITY

HAIL DURABILITY TEST

Jinko Solar • LONGi Solar

THRESHER TEST

Hanwha Q CELLS • JA Solar • LONGi Solar • Tesla • Trina Solar • Yingli Solar

HIGH ACHIEVEMENT IN PERFORMANCE

LeTID RESISTANCE

Hanwha Q CELLS • JA Solar • Jinko Solar • LONGi Solar • Trina Solar • Yingli Solar

LID RESISTANCE

Hanwha Q CELLS • Jinko Solar • LONGi Solar • Trina Solar

MODULE EFFICIENCY

JA Solar • LONGi Solar • REC Solar • Silfab Solar • Tesla • Yingli Solar

PAN FILE PERFORMANCE

JA Solar • Jinko Solar • LONGi Solar • Trina Solar

PTC-TO-STC RATIO

Hanwha Q CELLS • JA Solar • REC Solar • Silfab Solar • Tesla • Yingli Solar

HIGH ACHIEVEMENT IN RELIABILITY

DAMP HEAT TEST

JA Solar • LONGi Solar • Hanwha Q CELLS • Tesla • Trina Solar • Yingli Solar

DYNAMIC MECHANICAL LOAD TEST

JA Solar • Jinko Solar • LONGi Solar • Trina Solar • Yingli Solar

PID RESISTANCE

JA Solar • Jinko Solar • LONGi Solar

THERMAL CYCLE TEST

Hanwha Q CELLS • JA Solar • Jinko Solar • LONGi Solar • Tesla
Trina Solar • Yingli Solar

In Alphabetical Order:

LOOKING AHEAD

As we look ahead to future editions of the *PV Module Index Report*, RETC is keeping its eye on the upcoming versions of the design qualification, type approval and safety standards for terrestrial PV modules.

Here, we unpack some notable changes and revisions anticipated in the upcoming edition of IEC 61730, a two-part standard pertaining to PV module safety qualification. We also review key updates to IEC TS 62915, a technical specification (TS) pertaining to PV module approval, design and safety qualification.

PV MODULE SAFETY QUALIFICATION

The redline version of the soon-to-be-published third edition of IEC 61730 is close to completion. Once published, this third edition will cancel and replace the second edition of the standard, which the IEC published in 2016. The forecast publication date for the third edition is November 3, 2022.

Part 2 of IEC 61730 covers module safety test (MST) requirements, which are of particular interest to RETC and its manufacturing partners. Some of the changes to this standard complement revisions to the module quality test (MQT) requirements in IEC 61215:2021 that address the requirements for bifacial modules and very-large modules. Other revisions improve existing testing protocols. A few of the new revisions eliminate unnecessary testing requirements.

MST 06: Whereas previous versions of the standard indicate that the sharp-edge test is an alternative to visual inspection, the new edition clarifies that it is required. Note that the apparatus used for testing requires three layers of vinyl and TFE tapes per UL 1439 rather than the single layer of PTFE tape previously called for in ISO 8124.

MST 14: The revised impulse voltage testing requirements contain changes to the rise time and waveform pulse duration (T1 and T2). Note that an altitude correction factor is required if a product has insufficient spacings.

MST 21: The third edition eliminates the temperature test previously found in Part 2 of the standard. Modules tested individually in unrestricted mounting systems in open-air climates with an ambient temperature below 40°C were found to operate at or below a 98th-percentile temperature of 70°C. As a result, the committee determined that the minimum thermal index requirement of 90°C from Part 1 of the standard is generally adequate. Note that testing to elevated temperatures, as outlined in IEC 63126, is still recommended for modules installed using mounting systems that restrict airflow or in warm-weather environments that may result in operating temperatures beyond 70°C.

MST 24: The latest version of the standard expands and improves upon the ignitability test description, adding images depicting burner application to target combustible layers in multilayer products.

MST 26: The third edition revises the reverse current overload test requirements. Note that the hottest point is now determined using an infrared camera rather than a thermocouple.

MST 32: The module breakage test is no longer required for Class 0 modules, which are intended only for use in non-conducting applications or protected by electrical separation.

MST 54: The revised standard updates the UV test requirements. Rather than sequentially testing the front and back sides of a single module, exposure testing based on 60 kWh/m^2 of UV irradiation is now conducted on two samples. Note that the effective number of humidity-freeze cycles is ten rather than 20 cumulatively.

MST 57: The third edition introduces a new term *distance through functional insulation* (DTFI). DTFI is used to evaluate clearance and creepage.

MQT references: All references to IEC 61215 are updated to reflect the most recently adopted version of the standard, which is Edition 2 published in 2021.

Bifacial modules: Specific requirements related to bifacial module testing are now found in MST 02 (performance at STC), MST 07 (bypass diode functionality), MST 22 (hot-spot endurance test), MST 25 (bypass diode thermal test), MST 51 (thermal cycling test). Applied bifacial stress irradiance is also introduced.

Very-large modules: The latest edition of the standard addresses large-format modules by adding a definition for *very-large modules* based on module length and width (greater than 2.2 meters-by-1.5 meters). Annex C of the standard clarifies when reduced-size representative samples are allowed in lieu of full-sized test samples. Note that the list of tests that require full-sized samples includes: mechanical load, module breakage, impulse voltage and reverse current overload. Full-sized samples are also required for tests conducted in an environmental chamber—such as thermal cycling, humidity-freeze cycling, cold conditioning and dry heat conditioning—unless there are parallel strings in the circuit.

Part 1: In addition to the aforementioned changes to Part 2 of IEC 61730, the committee also updated the companion part of the standard. Part 1 of the standard now includes bifacial technology design requirements. Another major change is the introduction of new or updated definitions and requirements related to insulation, such as, *functional insulation, insulation coordination* and *relied upon insulation*. Lastly, Part 1 of the standard now includes component qualification standards for encapsulant (IEC 62788-1), frontsheets and backsheets (IEC 62788-2), junction boxes (IEC 62790), connectors (IEC 62852) and cables (IEC 62930).

TYPE APPROVAL AND DESIGN QUALIFICATION

First published in 2018, IEC TS 62915 is a technical specification relating to PV module type approval, design and safety qualification. Changes in material selection, components and manufacturing processes can impact the electrical performance, reliability, and safety of the modified product. As such, this standard lists the typical product modifications that could trigger retesting requirements. The IEC forecasts that the second edition of this TS could be published in May 2023.

Harmonizing requirements: Because IEC TS 62915 is closely related to other PV module standards, the technical committee has revised the second edition of this TS as necessary to harmonize its requirements with those in the IEC 61215 and IEC 61730 series of standards. These changes include incorporating the references to the new bending test for flexible PV products, which was introduced in IEC 61215:2021. The revised TS will also reflect updates to tests related to dynamic mechanical loading, potential-induced degradation, insulation thickness, ingnitability, creep, sequence B, sequence B1, screw connection, peel test, lap shear test and bypass diode functionality.

Technology considerations: To the extent possible, the second edition of the TS standardizes the retest guidelines for crystalline silicon cell technologies with those for thin films. It also adds language addressing emerging technologies, such as bifacial cells, as well as increasing PV cell sizes and cut PV cells.

Retest guidelines: Retest guidelines vary depending on the nature of the testing program. The previous version of the test defined the two groups of test, depending on whether the intent was to satisfy a combined IEC 61215 and IEC 61730 qualification program or one based only on IEC 61215. The new version adds a third group of tests, which applies when the qualification program only requires IEC 61730.

Note that new information in the Annex section in IEC TS 62915 helps to clarify the retest guidelines found in the text. For example, Annex 1 provides a tabular matrix that describes the test requirements associated with specific component changes. Annex 2 presents the combined test flows based on the latest versions of IEC 61215 and IEC 61730. Lastly, Annex 3 clarifies which tests are required for combined bill of materials (BOM) changes.

Renewable Energy Test Center (RETC) is a leading engineering services and certification testing provider for renewable energy products with headquarters in Fremont, California. Since its founding in 2009, RETC has partnered with manufacturers, developers and investors to test a wide range of products including modules, inverters, battery energy storage and racking systems. As a member of the VDE Group, RETC is helping provide customers worldwide with a one-stop shop for testing, inspection, certification and data services that de-risk renewable energy projects. At RETC, we are united in the belief that our work enables a safer and more sustainable world.

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