RETC

2021 PV Module Index Report

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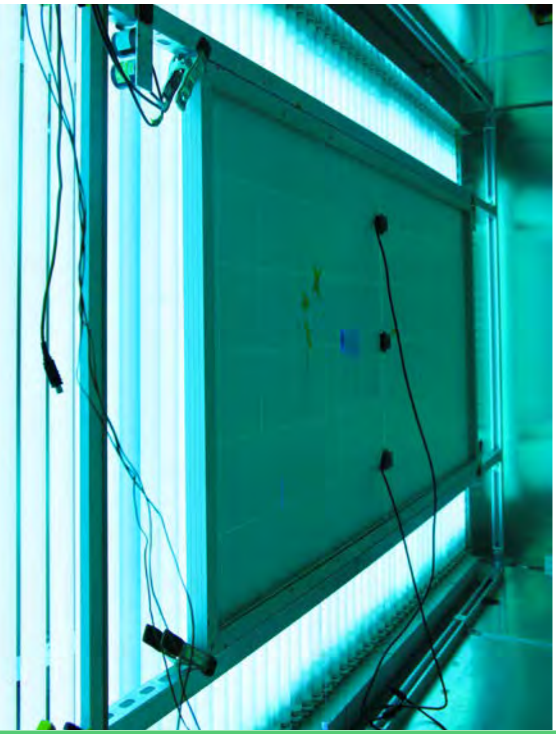
ABOUT RETC

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 these 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 is enabling 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's America CARAT Program recipient
- Verified by the UL Data Acceptance Program
- TÜV Rheinland's Partner Laboratory
- A VDE Qualified Test Laboratory
- A CA Solar & Storage Association (CALSSA) Member
- Intertek Recognized Test Laboratory (RTL)

A LETTER FROM OUR CEO

"The testing that we do at RETC is essential to securing a better future—not only for solar industry stakeholders but also for all of the businesses and communities that require clean energy and a reliable power system."

—Cherif Kedir, RETC

As RETC prepares to publish its third annual *PV Module Index (PVMI) Report*, it occurs to me that my colleagues and I occupy a unique position in the solar industry. As an independent testing laboratory with the highest level of accreditation, RETC tests products that are going to be introduced in the future.

Since these next-generation products have limited in-field exposure, RETC's testing effectively provides us with a sneak preview of what is to come. Collectively, we use these data to build better products and design better systems. Arguably, this work has never been more important or essential.

Insurers are well aware of the growing risks posed by a changing climate driven in large part by an overreliance on fossil fuels. Financiers are well aware of the trend toward ESG investing, which demands that publicly traded companies reduce carbon exposure. In this context, it is no surprise that solar and other renewable energy technologies are in ascendance.

According to the most recent data published by the International Energy Agency (IEA), the world's renewable energy capacity jumped to 280 gigawatts in 2020. This represents a phenomenal 45% increase in renewables, the largest annual increase since 1999. Perhaps most tellingly, demand for renewables increased, in spite of a global pandemic, even as the consumption of all other fuels declined. The IEA concludes that this is not an anomaly but rather represents the new normal.

As solar projects increase in frequency, size, geographic distribution and market share, industry stakeholders—especially project sponsors, owners and underwriters—are counting on the long-term reliable operation of solar assets. Power system operators are increasingly counting on renewables for capacity, grid stability and resilience. Businesses and consumers are entirely reliant on power systems that integrate ever-increasing amounts of renewables and solar. The stakes have never been higher.

Having had a sneak peek of the future via another year of testing, I can tell you that it is an innovative place, populated with large-format bifacial modules and other exciting new technologies. The future also holds risk and uncertainty, as we have learned from lessons on the ground in places such as Texas. A primary benefit of data-driven project development is that it minimizes risk and uncertainty in favor of long-term reliability, sustainability and profitability.

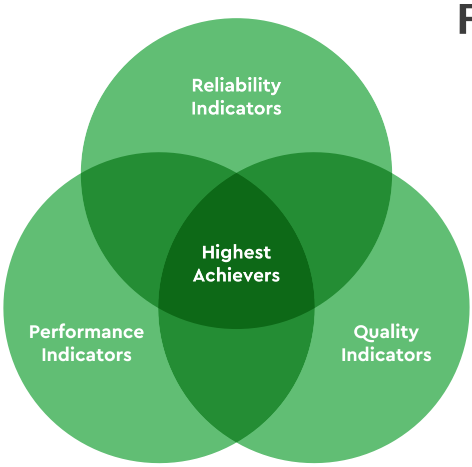
The testing that we do at RETC is essential to securing a better future—not only for solar industry stakeholders but also for all of the businesses and communities that require clean energy and a reliable power system.

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

Cherif Kedir

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

CATEGORIES FOR HIGH ACHIEVEMENT



RETC presents its *PV Module Index Report 2021* not only as a means of showcasing industry-leading technologies and manufacturers but also to empower project stakeholders to make informed, data-driven decisions based on project- and location-specific variables.

The 2021 edition of the *PVMI Report* summarizes results of bankability and beyond-certification testing conducted at RETC's accredited laboratories over a 12-month period, spanning Q2 2020 through Q1 2021. As in previous editions, we have broadly organized test protocols and reported data according to three interrelated and essential disciplines:

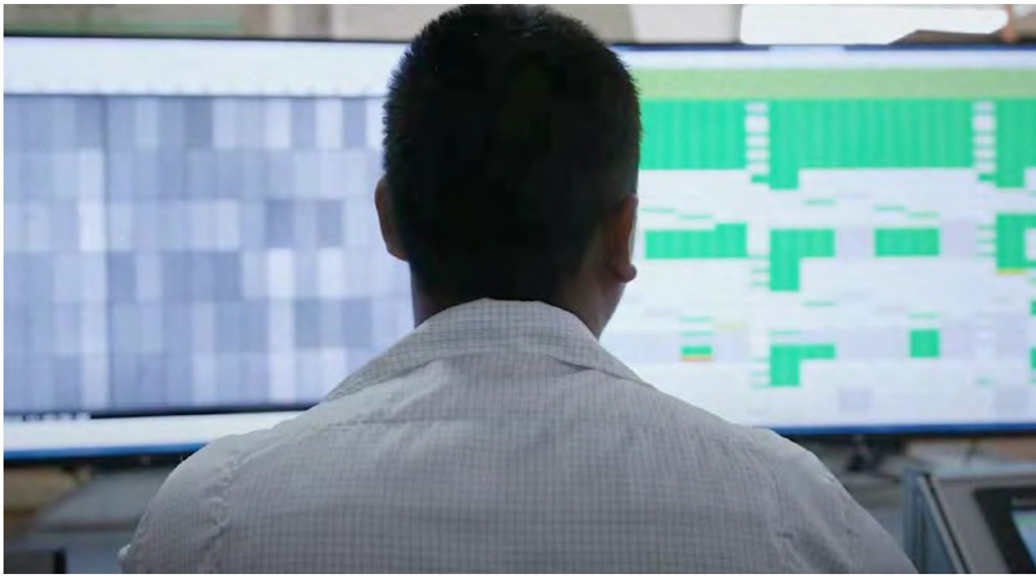
Manufacturers and product lines that achieve high performance according to these three disciplines demonstrate a general commitment to excellence. Within each of these disciplines, we present performance distribution data for specific test sequences. Project stakeholders can strategically identify and specify products or qualify project designs by filtering these comparative data based on individual indicators or test categories most relevant to a specific location, asset or portfolio.

Successful solar project development is incompatible with a one-size-fits-all approach, but rather demands intelligent and strategic differentiation and design adaptation. Products that perform well in a hail durability test may not perform well in a test intended to simulate high wind speeds or extreme snow loads and vice versa. A product that is not ideal for Texas may be perfect for California.

The goal of RETC's reliability and bankability testing is always to provide project stakeholders with independently verified test data that they can use to make informed decisions. Empowered with these data, you can identify and specify the best products and system designs for your specific applications.

"As you review the test data presented in the PVMI Report, please bear in mind that the goal of comparative and accelerated testing is never to vilify a specific product, technology or manufacturer while endorsing another."

—Cherif Kedir, RETC



INDUSTRY TRENDS

Recent industry trends highlight the importance of strategic product selection and differentiated system designs. To better understand the issues and concerns of the day, RETC reached out to colleagues and stakeholders throughout the solar industry value chain, including owners, sponsors, financiers, underwriters, insurers, factory auditors, independent engineers (IEs), developers and EPCs. Interview excerpts and quotes from these conversations with industry colleagues and subject matter experts are included in this year's *PV Module Index Report*.

"At the end of the day, solar has to compete against other energy sources, which means that we have to constantly innovate and evolve as an industry."

—Ryan Simpson, Trina Solar

One of the most widely discussed topics today relates to an industry-wide pivot toward large-format PV modules. Tempering the excitement associated with innovative high-capacity module designs are concerns stemming from large catastrophic project losses, most notably in Texas. While it is impossible to eliminate all of the risk and uncertainty associated with technological innovation and environmental extremes, our featured interviews demonstrate the value of taking a data-driven approach to risk management and bankability analyses.

EVALUATING LARGE-FORMAT PV MODULES

Lowering costs, improving performance and increasing the speed of deployment are essential to the solar industry's ability to compete with fossil fuel power sources. The industry's collective ability to drive costs out of the project value chain over the past decade is one of the primary reasons that solar is expected to account for the largest share of new U.S. electricity generation capacity in 2021.

Today, one of the most promising opportunities for continued cost reductions, both at the module level and the system level, relates to the development and deployment of large-format PV modules. The value proposition is so compelling that some industry analysts expect large-format modules to account for 90% of the market by 2025.

"Every module company wants to build the most efficient and highest-capacity product possible," explains Ryan Simpson, Trina Solar's head of products and marketing for the Americas. "Based on the different ways of creating silicon and advancements in machines and automation, Trina Solar and other manufacturers can now utilize much larger cells and create large-format modules. This natural pivot reflects that research and development activities related to technology, manufacturing and supply chain improvements sometimes resemble a group think tank."

BENEFITS The high-level benefits of large-format PV modules are obvious to see. Larger wafers and cells—typically, 182 mm or 210 mm square—facilitate larger form factor modules. These new modules are generally more than two meters long and have capacity ratings ranging from 500 watts to more than 800 watts. For an industry long accustomed to incremental increases in module capacity, this is a huge jump in power.

The value proposition for large-format PV modules is multi-layered. At the manufacturing level, large-format modules facilitate efficiencies of scale that drive down production costs and reduce the cost per watt downstream. In terms of material handling, fewer numbers of higher-capacity modules provide logistical efficiencies and drive down in-field labor costs. At the system level, large-format modules also facilitate an increase in energy density, higher power source circuits and potential balance of system (BOS) savings.

Hongbin Fang, LONGi Solar's director of product marketing, notes that, "In the last couple of years, large-format modules have been an effective way to improve module power, achieve lower manufacturing cost and help customers to reduce BOS cost. As a result, large-format modules have helped the industry accelerate the process of achieving a lower levelized cost of energy (LCOE)."

TRADEOFFS When evaluating large-format modules for specific projects and applications, it is important to keep in mind that upfront savings may come at a cost. Some risk and uncertainty is inherent to any new product or technology with limited field exposure. However, large-format modules also present some unique challenges.

From a structural point of view, large-format PV modules expose a larger area to the same amount of wind for a given location. This larger module may have the same thickness of glass and the same frame as its smaller-format predecessors, effectively increasing per-module wind loads. Especially in high wind areas or high elevation locations with extreme snow loads, large-format modules may increase project risk or long-term operating costs.

Hail durability test data also indicates that large modules with thinner front glass are less resilient to large-diameter hail than previous module designs. This is in part a function of the fact that thinner glass has less area to absorb a shock without shattering. More critically, thinner front glass materials—common in bifacial modules with a glass-on-glass package—cannot be tempered via traditional means and must be strengthened via alternative methods, such as chemical treatments.

"By validating module performance through third-party accelerated testing, we are able to make technology advances in the industry while maintaining quality and reliability."

—Vikash Venkataramana, Jinko Solar

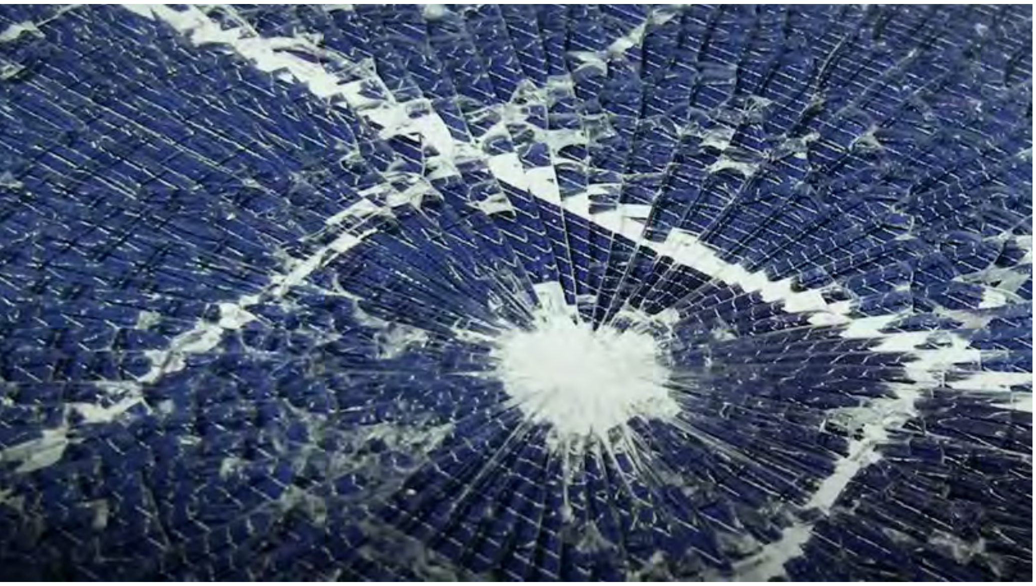
"Working in partnership with RETC, we have seen a massive improvement in hail-impact survivability at high-tilt angles."

—Greg Beardsworth, Nextracker

MEETING THE CHALLENGE Until large-format modules are a proven commodity in geographically diverse field applications, project stakeholders need to assess these products carefully based on the specific installation environment and highly accelerated life testing data. Moreover, the industry needs to ensure that its testing protocols and sequences are adequate to capture potential failure modes and wearout mechanisms in modules that may be subject to higher mechanical stresses, including heavy snow loads and dynamic wind effects.

"Innovation and improvements need to withstand a 25- to 30-year project life," notes Vikash Venkataramana, technical director for Jinko Solar. "Performance in extreme environments needs to be guaranteed. This is where extended reliability testing helps the industry move forward. By validating module performance through third-party accelerated testing, we are able to make technology advances in the industry while maintaining quality and reliability."

At the end of the day, the risks and rewards associated with large-format modules are not equitably distributed. For module manufacturers, the trend toward large-format modules is an opportunity to increase profit margins and differentiate themselves in the market. For developers and EPCs, this cost-saving opportunity may increase close rates and market share. In the event that in-field reliability and performance suffer, insurance companies and financiers are likely the ones footing the bill. It is important, therefore, that sponsors, underwriters and IEs ask the right questions and review relevant testing data when qualifying large-format modules, especially for locations subject to severe or extreme weather.



"Large-format modules have helped the industry accelerate the process of achieving a lower LCOE."

—Hongbin Fang, LONGi Solar

RELIABILITY LESSONS FROM TEXAS

According to the latest data from the Energy Information Administration (EIA), one-third of the utility-scale solar capacity set to come online in the U.S. through 2022 will be located in Texas. Best known as the country's leading wind power producer, Texas is also blessed with the nation's best solar resource, based on its sheer size and average sun hours. Once a sleeping giant in the solar market, Texas is now narrowing the gap with California, the long-standing U.S. state solar market leader.

The solar boom underway in Texas illustrates the extreme highs and lows of life on the solarcoaster. On the one hand, Texas is home to Invenergy's 1,310 MW Samson Solar Energy Center, the largest solar project in development in the U.S. today. On the other hand, Texas is also home to the 182 MW Midway Solar generating facility in West Texas, which infamously experienced large-scale losses due to hail damage.

Depending upon the source, the insured losses associated with the Midway Solar farm were somewhere on the order of $70M to $85M, likely the largest solar claim to date. While the impacts of this single event in May 2019 are still rippling throughout the industry, collectively we have learned some valuable lessons.

HAIL TESTING The basic hail assessment test for product certification is based on 11 impacts of a 1-inch hailstone traveling at terminal velocity. This minimum testing standard is insufficient to assess the risk of hail damage in hail-prone regions, which include Texas, the central region of the U.S. and other locations around the world. As module form factor increases and front-side glass thickness decreases, hail is potentially more impactful both in terms of glass breakage and cell cracking.

To address this gap, RETC developed the Hail Durability Test (HDT), a beyond-qualification test program designed to better characterize project risk. The HDT uses enhanced stress test criteria to simulate larger-diameter hailstones. It is also able to characterize the effectiveness of trackers with defensive stow modes that rotate modules to a high tilt angle, effectively minimizing opportunities for direct strikes.

Greg Beardsworth, Nextracker's director of product management, says, "Working in partnership with RETC, we have seen a massive improvement in hail-impact survivability at high-tilt angles. The test data indicates that stowing modules facing into the wind at 60° during a hailstorm can increase the survivability of PV panels from 81.6% to 99.4% based on severe weather data."

While RETC's preliminary HDT results are promising, additional research is needed and ongoing. Henry Hieslmair, PhD, principal engineer for solar at DNV, notes, "The question we need to answer is not whether or not glass breaks with 25mm hail. The hail damage of greatest concern is whether cells begin to break at 35mm or 45mm hail sizes. The type of hail testing that RETC is pioneering is needed by the industry."

HIGH WIND From Gulf Coast hurricanes to West Texas wind farms, Texas is also one of the regions of the country where solar farms experience high wind speeds. In these high-wind regions—such as Florida, Hawaii, New Jersey and North Carolina—the mechanical integrity on the negative side of the module with the uplift is extremely important. The mechanical strength ratings for many modules are very low relative to the wind loads associated with a hurricane.

DNV's Hieslmair would also like to see more reliance on enhanced stress testing for high-wind areas. "The dominant test standard for module mounting on trackers, UL 3703, does not test for cell cracking and module power degradation," he explains. "DNV is scrutinizing the gap between typical IEC-type static/dynamic mechanical loading tests and the UL 3703 test standards for tracker mounting. Of great concern to clients is that the UL test also lacks the subsequent thermal cycling and humidity-freeze cycling required to open the cell cracks to observe them at maximum power in an electroluminescence tester."

INSURANCE One of the biggest lessons coming out of Texas is that the days of relatively inexpensive insurance with broad coverage are over. Prior to the large insured losses at the Midway Solar farm—as well as other large catastrophic losses—it was possible to buy affordable solar project insurance coverage that effectively transferred risk from the owner to the underwriter. This is no longer the case, as insurers have increased pricing and premiums and introduced sublimits and exclusions.

Navigating these waters requires more sophisticated insurance products and approaches. In today's market, project stakeholders need to focus on eliminating losses before they happen, in which case insurance operates more as a credit support tool based around net capital expenditure. This approach to insurance requires extensive technical due diligence and beyond-certification testing data.

DATA-DRIVEN BANKABILITY ANALYSES FOR SOLAR ASSETS

DANNY SEAGRAVES is a risk management and risk finance specialist working for Willis Towers Watson (WTW), which specializes in developing insurance-backed solutions that provide purchasers with a positive return on investment. To learn more about this innovative method of utilizing insurance capacity as a project finance tool, RETC interviewed Seagraves from his home in Charlotte, North Carolina.

"This is the perfect storm for a long-duration hard market—the likes of which has not been seen since the mid-1980s."

—Danny Seagraves, WTW

RETC: In what ways has the insurance market for renewables changed in recent years?

DS: *To understand where we are today, you have to consider a confluence of factors. Since the end of the Great Recession, government-backed bonds, such as the U.S. 10-year treasury, have been near or at historical lows. This is relevant because insurance companies have to invest their balance sheet very conservatively, typically in low-risk bonds like treasuries. Since insurance companies have realized minimal yield out of these investments since the Great Recession, they have been forced to succeed or fail based on the profitability of their underwriting efforts.*

Going into 2015 and 2016, carriers had a tremendous amount of surplus that they could offer the solar industry in the form of insurance capacity. This was especially true for many of the London-based managing general underwriters (MGUs), which dominated the solar insurance marketplace during this time period. In order to grow top-line premiums, MGUs and traditional insurers were offering unsustainable cheap rates and unsustainably broad coverages—a combination that has proven to be shortsighted. Starting in 2017, we started seeing wildfires pick up in the U.S., Europe and Australia, and a dramatic increase in Atlantic hurricane activity. Simultaneously, damages from hail storms were becoming much more prevalent around the globe.

"While there are certainly renewable energy modeling lessons to be learned by studying the past, the insurance industry must avoid tripping over the future while looking backward."

—Danny Seagraves, WTW

This combination of events resulted in dramatic underwriting losses, which the carriers had no ability to offset via investment income. This is the perfect storm for a long-duration hard market—the likes of which has not been seen since the mid-1980s. As a matter of context, the hard market of the 1980s reshaped the liability insurance marketplace and those changes are still in place today.

RETC: Has this changed the way that you are qualifying products and assets?

DS: *The soft market spoiled everybody. The current hard insurance marketplace demands the development and execution of sound risk management and risk finance strategies for each project. During their underwriting due diligence, insurers and financiers are taking the time to thoroughly evaluate a project's engineering, installed equipment and operating protocols, as well as its collective ability to mitigate natural catastrophe and non-natural catastrophe damages. Moreover, risk-mitigating operating protocols must be embraced by a project's EPC and O&M providers and should be reflected in their respective contracts.*

As risk management and risk finance consultants, our team spends an inordinate amount of time modeling natural catastrophe exposures, making various assumptions in order to quantify a client's expected losses at the asset or portfolio level. Many facets of this modeling are somewhat subjective, as there is a shortage of experiential data available due to the relative short history of renewables. Accordingly, the loss-forecasting models that do exist—such as those from AIR Worldwide and Risk Management Solutions (RMS)—are understandably basic. As a result, our more sophisticated clients are engaging us, or other reputable third-party consultants, to conduct project-level deterministic modeling whereby we develop the secondary risk characteristics needed to apply to the probabilistic modeling that is already available. This extra effort brings us a very significant step closer to accurately understanding the potential losses faced by the asset and the portfolio.

RETC: How does this protect against large losses associated with increasingly severe weather?

DS: *This is where laboratory testing is so important. For example, 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 to evaluate its resiliency to the natural catastrophe peril being tested, such as hail. The results of this resiliency testing are compared to the original equipment manufacturer's (OEM's) original product specification to determine the percentage increase in equipment resiliency. Some of RETC's published work indicates up to a 300% increase in resiliency when equipment is tested* *in accordance with the OEM's prescribed defensive stow protocols. We can then compare these data to the historical hail records available from sources such as NOAA and CoreLogic to refine the original loss-forecast modeling results.*

Collectively, this process allows our clients to purchase higher natural catastrophe limits with lower deductibles at a lower cost, which is a competitive advantage. One of our immediate goals is to work with firms such as RETC to subject varying combinations of equipment to testing with the goal of developing a resiliency database to aid project procurement teams, financiers and insurers in their respective tasks. This type of resource will allow each stakeholder to make educated decisions, improve operating efficiencies and deliver long-term cost savings.

It all begins with testing. We must have reliable and statistically credible test data and testing protocols. Data based on manufacturer-provided samples is not adequate. We strongly believe in testing modules that are randomly selected from procured lots paired with randomly selected racking from the procured lot for the same project. In doing so, we hope to maintain as high a degree of objectivity as possible during the testing phase. The need for such testing will continue and the tests themselves will continue evolving as long as there continues to be advancement in the technologies. Legacy insurance coverages relied heavily upon historical data to forecast future results. While there are certainly renewable energy modeling lessons to be learned by studying the past, the insurance industry must avoid tripping over the future while looking backward.

TESTING & INSPECTION MITIGATE PROJECT RISK

FRÉDÉRIC DROSS is the vice president of strategic development for Senergy Technical Services (STS), an ISO 17020-accredited inspection body. To understand how PV module pre-shipment inspection complements accelerated testing, RETC interviewed Doss from his home in South Lake Tahoe, California.

"The modules' actual performance has a direct effect on the plant's actual performance and therefore on the investor's actual return on investment and debt coverage ratio."

—Frédéric Dross, STS

RETC: How can project stakeholders qualify new product designs or module architectures and mitigate project risk?

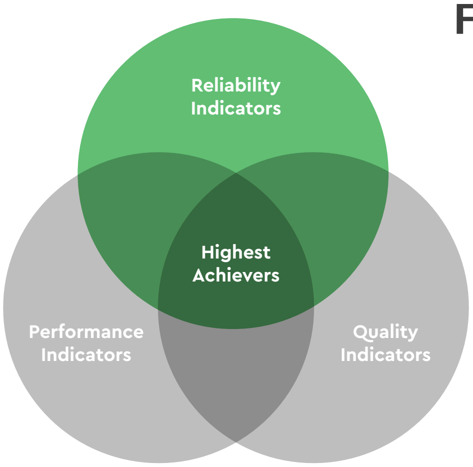
FD: *Accelerated lifetime tests, such as the ones offered in RETC's Thresher Test, are today the best known indicator of module durability. Independent engineers use the results of such tests to evaluate the useful life of the modules purchased, the required warranty reserves, or the expected operations 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 bill of materials (BOM) is controlled by an ISO 17020-accredited inspection body, both during test sample manufacturing and project manufacturing. Historically, 80% of STS' customers already require 24/7 BOM control, even in some very cost-aware markets such as India. With the new requirements for traceability and control of the provenance of the components, we expect that all new projects will require 24/7 BOM control in the very near future.

RETC: How do lot testing and BOM control affect a project's bottom line?

FD: *The modules' actual performance has a direct effect on the plant's actual performance and therefore on the investor's actual return on investment and debt coverage ratio. In our practice, we recommend having an ISO 17025-accredited lab, such as RETC, measure the low-irradiance performance and temperature coefficient for every manufacturing lot, at a minimum, to better quantify actual module performance in the field. Low-irradiance performance, for instance, has an impact on plant performance during the times of the day when there is no inverter clipping, making it a critical item to verify on a lot-per-lot basis.*

MODULE RELIABILITY



Product reliability describes the probability that a device will perform its design function for a specific period of time based on certain conditions of use. Reliable PV modules must output power at or above warrantied levels for 25 or 30 years based on harsh conditions of use. Since PV modules are deployed outdoors in full sun, they are exposed to ultraviolet light, thermal cycling, damp heat, dry heat, humidity-freeze cycles, wind loads, snow loads and so forth. These conditions of use require durable products and proven product designs.

Product certification and qualification are essential first steps on the road to reliability. Accredited laboratories, such as RETC, play an important role in this process by offering certification testing to relevant Underwriters Laboratories (UL) and International Electrotechnical Commission (IEC) standards. These certification and qualification tests represent the legal minimum requirements for product safety.

To better characterize long-term in-field reliability, laboratories can also test PV modules to enhanced or extended stress tests, such as RETC's Thresher Test, which is designed to separate the wheat from the chaff. A decade ago, RETC led industry efforts to develop expanded standardized accelerated test protocols and procedures. These long-term reliability test sequences involve much longer cycle times.

Beyond-qualification test sequences put additional stress on modules in order to identify areas of weakness and better predict long-term in-field reliability. Unlike simple pass/fail certification and qualification tests, reliability tests gather and report degradation through the course of the test sequences. Given that project stakeholders cannot wait 20 or 30 years to find out whether or not a module is durable and performs as expected, beyond-certification testing followed by comparative test data analysis is a good way to mitigate product reliability risk.

RELIABILITY TESTS & METRICS

Here, we provide a high-level overview of some flat-plate PV module tests that RETC offers within its accelerated reliability testing program. Following the test descriptions, we provide a sampling of reliability test data that RETC compiled in 2020 and showcase OEMs according to high achievement in manufacturing.

"Accelerated reliability testing has become industry standard to assess reliability of any new technology, new design, materials and processes."

—Hongbin Fang, LONGi Solar

DAMP HEAT (DH) DH testing characterizes a PV module's ability to withstand prolonged exposure to humid, high-temperature environments. Inside an environmental chamber, modules are exposed to a controlled temperature of 85° Celsius and a relative humidity of 85% for a set amount of time. 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. The DH2000 test is an effective means of characterizing aging effects and potential failure modes associated with electrochemical corrosion; delamination; encapsulation adhesion and elasticity; junction box adhesion; and general deficiencies in edge deletion.

See bar chart on p. 15 for module performance distribution data based on DH test results.

HUMIDITY FREEZE (HF) HF testing takes place in an environmental chamber and characterizes a PV module's ability to withstand the alternating effects of high heat and humidity followed by extremely cold environmental conditions. For this accelerated aging test, modules 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 calls for modules to be subjected to 30 or more humidity-freeze cycles. The HF30 test is an effective means of characterizing junction box adhesion rates, proper edge deletion and delamination.

THERMAL CYCLING (TC) TC testing is an environmental stress test used to assess product reliability and identify 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. RETC's Thresher Test calls for extended 600- or even 1,000-cycle TC600 or TC1000 tests as a means of detecting weaknesses in module designs. Typical issues and failures modes identified via extended TC testing include broken interconnects, cracked cells, electrical bond failures, junction box adhesion deficiencies, and the potential for electrical arcs or open circuits.

DYNAMIC MECHANICAL LOAD (DML) DML testing characterizes a module's ability to withstand continuous wind loading. Unlike standard mechanical load (ML) tests, designed to simulate static snow and ice loads, DML testing simulates dynamic push-pull loads associated with hurricanes, typhoons and other high-wind events, which are a leading cause of in-field insurance claims. As part of the DML test, modules are subjected to 1,000 cycles of +1,000 Pascal (Pa) and -1,000 Pa loads at a frequency of three to seven cycles per minute. Afterward, modules are placed in an environmental chamber and subjected to TC50 testing followed by HF10 or HF30 testing. Upon completion, measurements are taken to characterize electrical performance. DML testing is effective for detecting structural failures, broken glass, interconnect ribbons, cells and electrical bond failures.

See bar chart p. 15 for module performance distribution data based on DML, TC, and HF test results.

ULTRAVIOLET (UV) EXPOSURE UV soaking or preconditioning is a test that characterizes a module's susceptibility to degradation and performance loss resulting from exposure to ultraviolet light. 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. For this test, modules are maintained at an elevated temperature of 60°C and UV light is tuned to the ultraviolet A and ultraviolet B regions. UV exposure is an effective means of detecting failure associated with EVA yellowing; backsheet discoloration; delamination; loss of encapsulation adhesion or elasticity; ground faults due to backsheet degradation; or a general impairment of optics.

POTENTIAL INDUCED DEGRADATION (PID) 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. In addition to being accelerated with higher heat and humidity, PID is potentially triggered by system grounding polarity. To conduct PID tests, rack-mounted modules are placed in an environmental chamber, to control temperature and humidity, and exposed 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. As the name suggests, this test is an effective means of characterizing a module's susceptibility to potential-induced degradation.

See p. 16 for module performance distribution data based on PID test results.

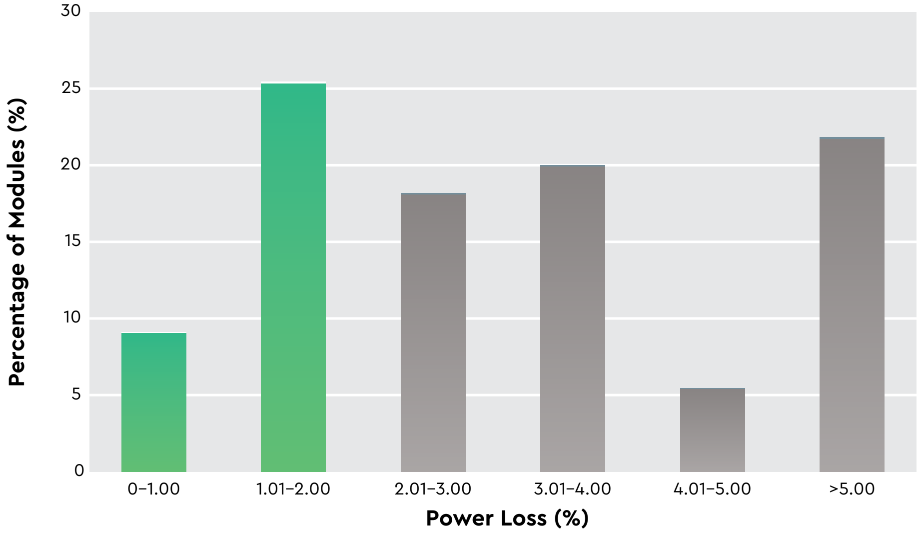
DH TEST RESULTS

For its 2021 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). The benefit of DH2000 testing, as compared to minimum certification requirements, is that the extended test duration better characterizes module durability and robustness. To showcase high performance in manufacturing, we have highlighted data for modules that experienced less than 2% power loss. By comparison, IEC and UL certification standards require only a 1,000-hour damp heat test (DH1000) and allow for a maximum performance degradation of 5%.

"I am starting to see more activity on the debt side, which means longer investment horizons compared to tax equity terms and more sensitivity to underperformance in out years."

—Jonathan Previtali

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 heat exposure: **JA Solar, LONGi Solar, Trina Solar.**

As shown in these data, roughly 35% of modules that RETC subjected to DH2000 testing in 2020 experienced less than 2% power loss. Additionally, more than 40% of products tested experienced power loss between 2% and 5%, meaning these modules meet the 5% performance degradation allowance in the certification standard in spite of the doubled test duration. Note that more than 20% of the modules subjected to the DH 2000 test experienced greater than 5% loss of power.

DML TEST RESULTS

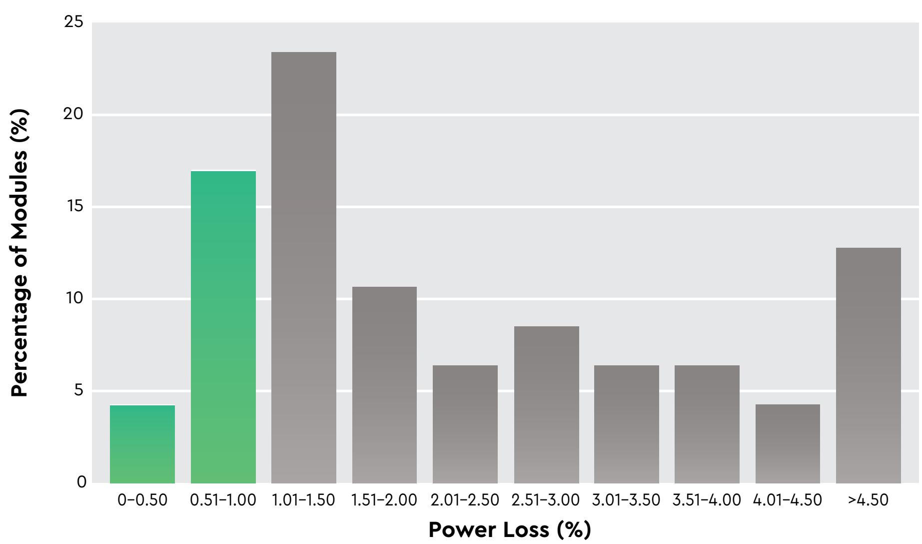
For its 2021 edition of the *PV Module Index Report*, RETC has compiled performance distribution data for modules exposed to DML testing followed by TC50 and HF30 environmental exposure. To showcase high performance in manufacturing, we have highlighted data for modules that achieved less than 1% degradation in power.

As shown in these test results, more than 17% of the modules that RETC subjected to simulated wind and environmental stresses achieved less than 1% degradation in power. At the same time, more than 10% of modules tested experienced power loss greater than 4.5%. Interestingly, the percentages of both the high-performing and underperforming modules increased relative to last year's PVMI report.

HIGH RELIABILITY IN DML SEQUENCE

RETC proudly recognizes, in alphabetical order, those manufacturers whose modules degraded less than 1% after being subjected to dynamic mechanical loading followed by 50 thermal cycles and 30 humidity-freeze cycles: **JA Solar, LONGi Solar, Trina Solar.**

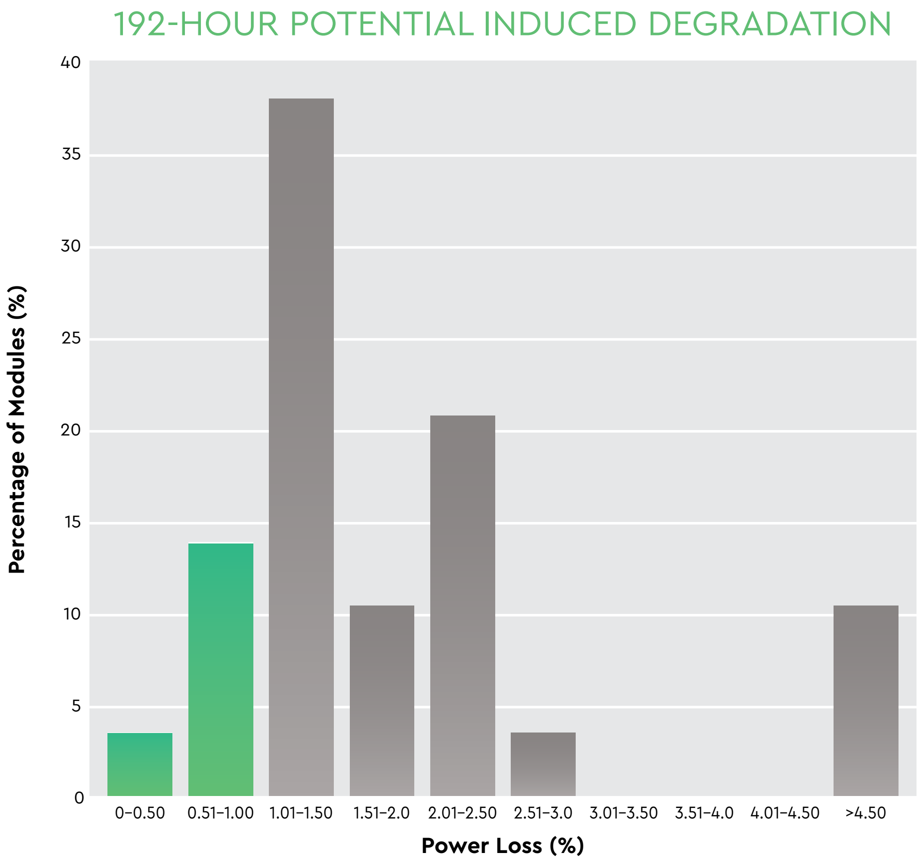
DYNAMIC MECHANICAL LOAD (DML | TC50 | HF30)



PID TEST RESULTS

For its 2021 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 1% of performance degradation through 192 hours of exposure.

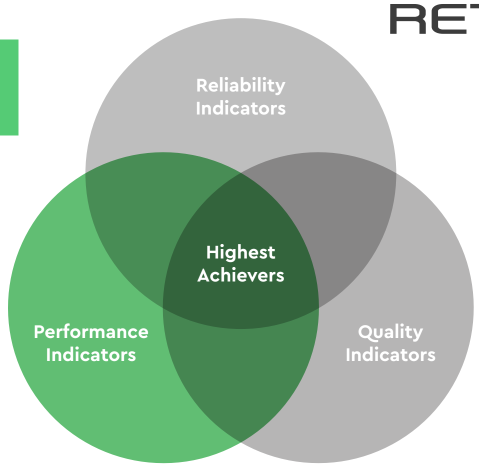
As shown in these data, 17% of modules achieved top-performing status with less than 1.0% degradation through 192 or more hours of PID test exposure. At the same time, more than 10% of modules experienced greater than 4.5% power loss over this same test period. Compared to last year's data distributions, the percentage of top-performing modules decreased by roughly 20% while the percentage of modules with greater than 4.5% power loss increased by nearly 4%.



HIGH RELIABILITY IN POTENTIAL-INDUCED DEGRADATION

RETC proudly recognizes the manufacturer whose modules degraded less than 1% after 192-hour PID test exposure: **LONGi Solar.**

MODULE PERFORMANCE



RETC and other accredited testing laboratories play an important 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. Performance characteristics captured under these rigorous conditions represent the true measure of PV module performance and provide value to multiple project stakeholders.

As a service to module companies, RETC benchmarks the performance of reference modules that plant operators can use to calibrate factory testing equipment. These so-called "golden modules" are also useful as part of a statistical quality-control program, providing a calibrated baseline that manufacturers can use to demonstrate they are meeting or exceeding acceptable limits for output variation.

Manufacturers use sun simulators in concert with other test equipment to characterize PV module performance in the factory under standard test conditions (STC), such as a cell temperature of 25°C, irradiance of 1,000 W/m^2, and an air mass of 1.5. This flash test typically takes place at the end of a production line and allows manufacturers to properly warranty, label and bin modules before they leave the factory. The resulting power, current and voltage characteristics are only as accurate as the test equipment and factory controls.

While factory testing according to STC parameters is ideal for establishing module nameplate ratings, factory test results are not intended to characterize typical module operating conditions. In order 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 important to characterize module performance under test conditions that reflect the real-world 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.

"We recommend having an ISO 17025-accredited lab, such as RETC, measure the low-irradiance performance and temperature coefficient for every manufacturing lot, at a minimum, to better quantify actual module performance in the field."

—Frédéric Dross, STS

"Module quality, reliability and performance are critical to the sustainability of the solar project finance market. Substantial underperformance will sour the market for investors who are looking for consistent returns within a predictable range."

—Jonathan Previtali

PERFORMANCE TESTS & METRICS

Here, we provide a 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 2020 and showcase manufacturers according to high achievement in manufacturing.

CONVERSION EFFICIENCY Conversion efficiency—the percentage of incident solar energy converted to electrical energy—is a key figure of merit for PV modules and cell technologies. Nominal module efficiency is determined by dividing a products nameplate STC-rated power capacity by its total aperture area. Cell technology and module design play a large factor in module efficiency.

See table on p. 19 for a ranking of maximum module efficiency ratings calculated and ranked per manufacturer based on a year's worth of RETC's module characterization test data.

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).

See table on p. 20 for a sampling of high-performing PV modules based on PTC-to-STC ratio.

INCIDENCE ANGLE MODIFIER (IAM) IAM is a performance characteristic that accounts for changes in PV module output based on changing sun angles. Optimal transmission of incident sunlight occurs when the solar incidence angle is directly normal (perpendicular) to the surface of the module. As the incidence angle changes, power density decreases due to transmission losses. These transmission losses occur due to reflection at each material interface—air-to-glass, glass-to-EVA, EVA-to-glass—and absorption within the glass itself. 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.

PAN FILES In order to model plant-level performance based on typical meteorological year (TMY) weather data, industry-standard software tools require component characterization files. The de facto standard module characterization file format is a PAN file, which defines 22 parameters that PVsyst software uses as the basis of its production modeling calculations. Project developers use the PVsyst simulations to evaluate potential sites based on energy production and financial performance. IEs use PVsyst 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 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.

LIGHT-INDUCED DEGRADATION (LID) As the name suggests, LID is a type of degradation resulting from exposure to sunlight. LID 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 period of time in the field—typically a few hours or days—prior to performance stabilization. As a service to manufacturers, RETC offers LID testing per IEC standards to ensure manufacturing quality control and in-field reliability.

See table p. 22 for a sampling of module performance distribution data based on LID test results.

LIGHT- AND ELEVATED TEMPERATURE-INDUCED DEGRADATION (LeTID) LeTID is a type of long-term in-field degradation that impacts relatively newer cell technologies. The IEC has developed a protocol of light soaking, followed by 75°C temperature exposure for two 162-hour cycles to identify significant degradation (>5%). Subsequently, test samples are subject to 500 hours of 85°C temperature exposure followed by two additional 162-hour cycles, after which measurement should reveal some restoration (regeneration) of module performance. Note that the IEC is drafting an update to the LeTID standard, which is expected to change the test procedures and thresholds.

MODULE EFFICIENCY RESULTS

For the 2021 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 the course of a calendar year. To showcase high performance in manufacturing, we are recognizing those manufactures that achieved conversion efficiencies of 19% or greater based on module area.

MODULE I-V CHARACTERIZATION DATA

Rank	Model	Technology	Pmax (W)	Aperture Area (m^2)	Aperture Area Efficiency
1	P1	Mono-c-Si	359.1	1.69	21.2%
2	P2	Mono-c-Si	440.2	2.11	20.9%
3	P3	Mono-c-Si	439.7	2.12	20.8%
4	P4	Mono PERC	337.7	1.63	20.7%
4	P5	Mono-c-Si	365.2	1.77	20.7%
5	P6	Mono-c-Si	349.4	1.69	20.6%
6	P7	Mono-c-Si	400.6	1.95	20.5%
7	P8	Mono PERC	398.9	1.97	20.3%
7	P9	Mono PERC	439.2	2.17	20.3%
7	P10	Mono-c-Si	420.6	2.08	20.3%
8	P11	Mono-c-Si	420.6	2.08	20.2%
8	P12	Mono-c-Si	398.8	1.98	20.2%
8	P13	Mono-c-Si	356.0	1.77	20.2%
9	P14	Mono-c-Si	324.3	1.61	20.1%
9	P15	Mono-c-Si	418.0	2.08	20.1%
10	P16	Mono-c-Si	389.9	1.95	20.0%
10	P17	Mono-c-Si	351.8	1.76	20.0%
10	P18	Mono-c-Si	331.4	1.66	20.0%
11	P19	Mono PERC	324.5	1.63	19.9%
11	P20	Mono PERC	441.2	2.22	19.9%
12	P21	Mono-c-Si	341.8	1.73	19.7%
12	P22	Mono-c-Si	426.9	2.17	19.7%
13	P23	Mono-c-Si	355.8	1.81	19.6%
13	P24	Mono PERC	349.5	1.79	19.6%
15	P25	Mono PERC	415.3	2.14	19.4%
15	P26	Mono-c-Si	354.4	1.83	19.4%
15	P27	Mono-c-Si	422.8	2.18	19.4%
15	P28	Mono-c-Si	314.4	1.62	19.4%
15	P29	Mono-c-Si	383.6	1.98	19.4%
15	P30	Mono-c-Si	383.6	1.98	19.4%
16	P31	Mono-c-Si	316.6	1.64	19.3%
16	P32	Mono PERC	345.1	1.79	19.3%
17	P33	Mono-c-Si	318.4	1.66	19.2%
17	P34	Mono-c-Si	318.4	1.66	19.2%
17	P35	Mono-c-Si	332.7	1.73	19.2%
18	P36	Mono-c-Si	348.5	1.83	19.1%

HIGH PERFORMANCE IN MODULE EFFICIENCY

RETC proudly recognizes, in alphabetical order, those manufacturers whose modules achieved greater than 20% total area module efficiency based on our CEC characterization test projects: **Hansol Technics, Hanwha Q CELLS, JA Solar, LONGi Solar, REC Solar, Yingli Solar.**

PTC-to-STC RATIO RESULTS

For the 2021 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 are recognizing manufacturers of the Top 10 modules in this list.

In order to qualify for California solar incentive programs, solar modules must be included on an eligible equipment list maintained and regularly updated by the CEC. 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. Rather, CEC listing data are based on test reports from accredited third-party laboratories. Among these, RETC is one of the accredited laboratories most active in terms of testing modules for CEC listing.

The data used to calculate PVUSA Test Conditions (PTC) ratings are of particular interest to manufacturers. As compared to the standard test conditions (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	21.2%	370	351.8	95.1%
2	P2	Mono-c-Si	20.6%	365	345.8	94.8%
3	P3	Mono-c-Si	19.3%	320	302.7	94.6%
4	P4	Mono-c-Si	20.0%	395	373.1	94.5%
5	P5	Mono-c-Si	19.4%	360	339.8	94.4%
6	P6	Mono-c-Si	19.4%	425	400.3	94.2%
6	P7	Mono-c-Si	19.4%	320	301.3	94.2%
7	P8	Mono PERC	19.9%	440	412.9	93.8%
7	P9	Mono-c-Si	20.7%	365	342.4	93.8%
7	P10	Mono-c-Si	20.9%	440	412.5	93.8%
7	P11	Mono-c-Si	20.2%	425	398.5	93.8%
8	P12	Mono PERC	20.3%	405	379.6	93.7%
8	P13	Mono PERC	20.3%	440	412.3	93.7%
9	P14	Mono-c-Si	20.8%	445	416.7	93.6%
9	P15	Mono-c-Si	20.1%	330	308.8	93.6%
9	P16	Mono-c-Si	19.7%	345	322.8	93.6%
10	P17	Mono-c-Si	20.5%	400	374.2	93.5%
11	P18	Mono-c-Si	20.2%	360	336.4	93.4%
11	P19	Mono-c-Si	19.6%	360	336.3	93.4%
11	P20	Mono-c-Si	20.3%	420	392.3	93.4%
12	P21	Mono-c-Si	20.0%	330	307.8	93.3%
13	P22	Mono-c-Si	20.1%	415	386.9	93.2%
13	P23	Mono-c-Si	19.7%	430	400.8	93.2%
13	P24	Mono-c-Si	19.1%	360	335.5	93.2%
14	P25	Mono PERC	19.4%	415	386.4	93.1%
14	P26	Mono PERC	19.3%	335	311.8	93.1%
15	P27	Mono-c-Si	20.2%	395	366.7	92.8%
15	P28	Mono PERC	20.7%	340	315.4	92.8%
15	P29	Mono-c-Si	19.2%	345	320.0	92.8%
16	P30	Mono-c-Si	20.0%	355	329.1	92.7%
16	P31	Mono PERC	19.9%	325	301.1	92.7%
17	P32	Mono PERC	19.6%	340	314.8	92.6%
17	P33	Mono-c-Si	19.4%	390	361.0	92.6%
17	P34	Mono-c-Si	19.4%	390	361.0	92.6%
17	P35	Mono-c-Si	19.2%	325	300.8	92.6%
17	P36	Mono-c-Si	19.2%	325	300.8	92.6%

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, LONGi Solar, REC Solar, Yingli Solar.**

PAN FILE RESULTS

For the 2021 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 are recognizing those manufacturers with products that achieved a PVsyst-modeled performance ratio of 85% or greater.

As a service to project developers, IEs, operators, asset managers, insurers and financiers, RETC generates third-party validated PAN files that allow for 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 theoretical 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.

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, Hyundai Solar, LG, LONGi Solar, Trina Solar, Yingli Solar.**

PAN FILE TESTING DATA

PVSyst Simulation for 10MW Ground Mount in Texas

Rank	Model	Specific Prod kWh/kWp/yr	Performance Ratio [%]
1	P1	1904.9	88.50%
2	P2	1899.1	88.23%
3	P3	1888.3	87.73%
4	P4	1873.0	87.01%
5	P5	1872.7	87.00%
6	P6	1870.4	86.89%
7	P7	1868.	86.80%
8	P8	1867.9	86.78%
9	P9	1865.4	86.66%
10	P10	1861.4	86.47%
11	P11	1859.4	86.38%
12	P12	1856.3	86.24%
13	P13	1853.7	86.12%
14	P14	1853.67	86.11%
15	P15	1853.4	86.10%
16	P16	1849.9	85.94%
17	P17	1849.0	85.90%
18	P18	1848.2	85.86%
19	P19	1847.3	85.82%
20	P20	1843.1	85.63%
21	P21	1842.7	85.60%
22	P22	1841.8	85.56%
23	P23	1837.4	85.36%
24	P24	1825.7	84.82%
25	P25	1818.0	84.46%
26	P26	1811.4	84.15%
27	P27	1806.2	83.91%
28	P28	1805.9	83.90%
29	P29	1804.8	83.85%
30	P30	1801.77	83.70%
31	P31	1798.67	83.56%
32	P32	1798.07	83.53%
33	P33	1794.9	83.38%
34	P34	1794.4	83.36%
35	P35	1791.6	83.23%
36	P36	1789.9	83.15%
37	P37	1788.6	83.09%
38	P38	1784.59	82.90%
39	P39	1779.2	82.66%
40	P40	1776.9	82.55%
41	P41	1765.5	82.02%
42	P42	1764.7	81.98%
43	P43	1762.8	81.89%
44	P44	1757.8	81.66%
45	P45	1753.2	81.45%
46	P46	1740.0	80.84%
47	P47	1736.9	80.69%
48	P48	1729.99	80.37%

LID TEST RESULTS

For the 2021 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.

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 a gain in power or very low power loss after LID test exposure, which is a function of the specific cell or module technology.

LeTID TEST RESULTS

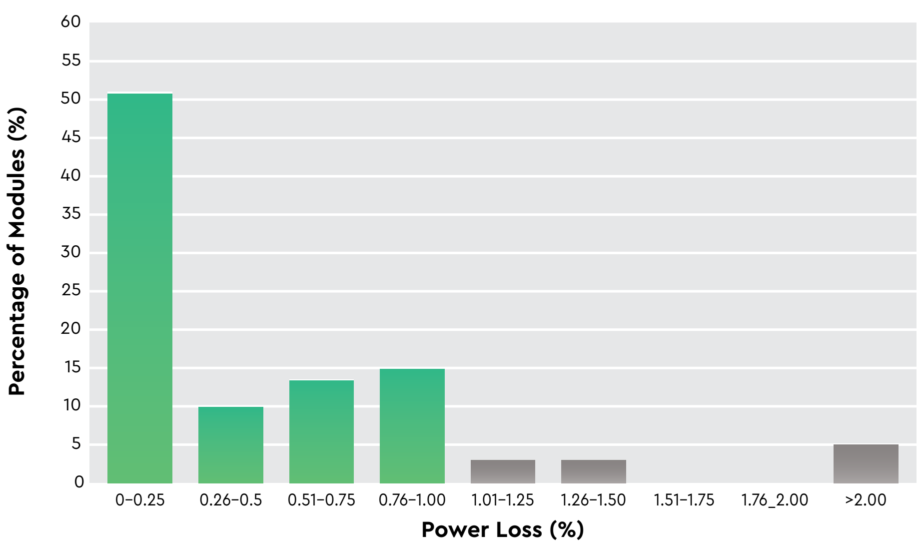
For the 2021 edition of its *PV Module Index Report*, RETC has ranked the top-performing PV modules based on the results of LeTID testing and characterization. To showcase high performance in manufacturing, we are recognizing manufacturers whose modules experienced less than 1% power loss after 486 hours of exposure.

Note that most of the products RETC tested performed well on the basis of LeTID. Greater than 50% of modules tested experienced less than 0.25% power loss; moreover, roughly 90% of the modules tested experienced less than 1% power loss. At the same time, approximately 5% of the models tested experienced power greater than 2% power loss after 486 hours.

LID TESTING DATA

Rank	Model	Technology	Average LID
1	P1	Bifacial PERC	0.31%
1	P2	Mono	0.31%
2	P3	Mono	0.17%
3	P4	Mono	0.06%
4	P5	Mono PERC	-0.01%
5	P6	Mono PERC	-0.03%
6	P7	Mono	-0.05%
7	P8	Bifacial	-0.06%
8	P9	Mono	-0.07%
9	P10	Bifacial PERC	-0.12%
9	P11	Mono	-0.12%
10	P12	Mono PERC	-0.15%
10	P13	Mono PERC	-0.15%
11	P14	Mono PERC	-0.17%
12	P15	Mono PERC	-0.19%
13	P16	Poly	-0.20%
13	P17	Bifacial	-0.20%
14	P18	Mono	-0.24%
15	P19	Mono PERC	-0.26%
16	P20	Bifacial	-0.29%
17	P21	Mono PERC	-0.46%
18	P22	Mono PERC	-0.50%
19	P23	Mono PERC	-0.52%
20	P24	Bifacial PERC	-0.53%
21	P25	Bifacial PERC	-0.54%
22	P26	Mono	-0.63%
23	P27	Bifacial PERC	-0.68%
24	P28	Mono	-0.71%
25	P29	Mono	-0.84%
26	P30	Mono	-0.91%
27	P31	Mono	-1.10%
28	P32	Mono PERC	-1.33%
29	P33	Mono PERC	-1.61%
30	P34	Mono PERC	-1.64%
31	P35	Mono PERC	-1.69%

486-HOUR LeTID EXPOSURE



HIGH PERFORMANCE IN LID RESISTANCE

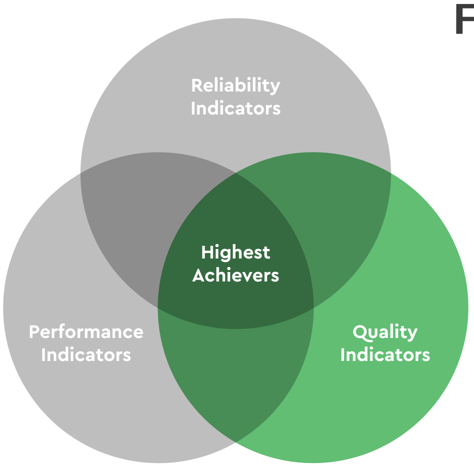
RETC proudly recognizes, in alphabetical order, those manufacturers that achieve a Top 10 ranking, among all modules tested, based on LID performance ratio: **Hanwha Q Cells, JA Solar, Jinko Solar, LONGi Solar, Trina Solar.**

HIGH PERFORMANCE IN LeTID RESISTANCE

LeTID PERFORMANCE RETC proudly recognizes, in alphabetical order, those manufacturers with modules that achieve less than 1% power loss after 486 hours of LeTID test exposure: **Hanwha Q Cells, JA Solar, Jinko Solar, LONGi Solar, Trina Solar, Yingli Solar.**

MODULE QUALITY

Product quality is a function of its ability to meet user standards. Especially with PV modules, there is a strong relationship between quality and time. In order 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.



Products that appear very similar on paper may perform very differently in the real world. A manufacturing commitment to quality often accounts for these differences. Studies have consistently shown a strong positive correlation between quality and return on investment and other indicators of profitability. Moreover, experience has shown that simply meeting minimum certification requirements does not ensure a quality product for all project stakeholders.

To address in-field module quality over a 25- or 30-year timeframe, RETC provides a variety of quality assurance (QA) and quality control (QC) services. Our Thresher Test, for example, is a beyond-qualification test protocol that allows manufacturers to identify potential wearout and failure mechanisms prior to volume manufacturing. Downstream project stakeholders—such as financiers, insurers, IEs, developers and EPCs—can also use these Thresher Test results as a comparative screening tool.

Fielding increasing numbers of higher-capacity solar projects in widespread locations around the globe is not without risk. Mitigating site-specific risk requires the strategic application of products and technologies. While it is tempting to assume commoditization goes hand-in-hand with project and market scale, this overlooks substantive differences in environmental exposure. An indiscriminate belief in one-size-fits-all solutions increases project risk.

Projects in hail-prone regions, such as parts of Texas and the Central Region of the Continental U.S., require hail-resistant products and project designs. Projects in high-wind locations, such as parts of the East Coast, require products and project designs resistant to dynamic wind effects. Projects in extreme-snow locations require products and project designs that resist high static mechanical loads. Projects in coastal locations require products that resist corrosion.

"Financiers are becoming more attuned to our industry and asking more relevant questions. To address these questions, manufacturers utilize reliability testing through highly qualified labs to understand how a solution will perform over time."

—Ryan Simpson, Trina Solar

QUALITY TESTS & METRICS

A manufacturing commitment to quality takes many forms. Here we provide an overview of some of the most important components of a successful quality program. Following this overview, we provide a summary of Thresher Test results and showcase OEMs according to high achievement in manufacturing.

"We pursue comprehensive testing on multiple combinations of BOMs within each product to reduce risk and build confidence for our customers on their projects."

—Vikash Venkataraman, Jinko Solar

BEYOND-QUALIFICATION TESTING Over the past decade, industry stakeholders and committees have worked continuously to develop more stringent testing protocols designed to better identify long-term module wearout mechanisms and failure modes. Products that have passed RETC's beyond-qualification Thresher Test protocols are less likely to experience short-term failures and performance degradation in the field.

PRODUCT CONFORMITY To improve product performance, reliability and cost, module manufacturers are continually making bill of material (BOM) and other engineering changes to products and product lines. Since seemingly small process changes could impact long-term reliability and performance, RETC works with customers to help them analyze BOM and engineering changes to determine whether additional testing should take place. Coupled with 24/7 BOM control at the factory, these quality control measures increase confidence that a design change does negatively impact in-field reliability.

RANDOM SAMPLING Randomized sampling is a statistical method of ensuring quality control during volume production. As the name suggests, samples are selected at random and inspected or tested to specific standards. Random sampling not only ensures consistency in manufacturing production equipment performance, but also in the upstream material supply chain. A successful random sampling program will specify sample testing frequency and define the sample selection methodology. Random sampling of lot-specific modules is a best practice for volume purchasers.

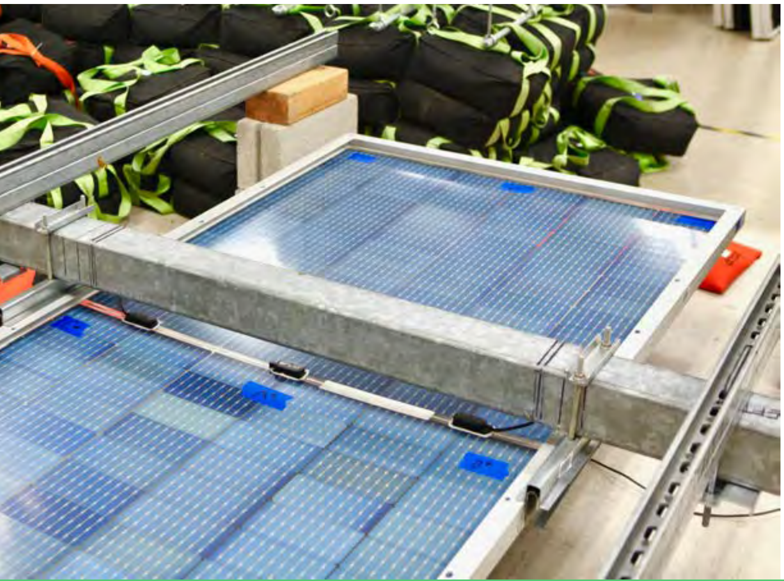
FACTORY INVESTIGATIONS Third-party solar factory audits and inspections are another way for volume purchasers to mitigate supply-chain risk. Factory auditors typically review factory certifications, resource training, production processes, materials, finished products and logistics. Factory inspections review product lines, incoming materials, BOM conformity, in-line manufacturing and warehousing. These factory investigations are increasingly important in a manufacturing ecosystem that is at once global and regionalized. High-quality manufacturers not only establish stringent quality QA and QC standards for first factories, but also propagate these program elements successfully to any other factories manufacturing the same products or module families.

THRESHER TEST RESULTS

For its 2021 edition of the *PV Module Index Report*, RETC has compiled a Thresher Test performance matrix. To showcase high performance in manufacturing, we are recognizing those manufacturers that achieve high performance across multiple accelerated test sequences. For the purposes of this matrix, high product quality is demonstrated by achieving power degradation of less than 2% for a given test across the greatest number of discrete accelerated aging tests.

Fielded PV modules are exposed to a wide variety of environmental stresses. To address these various stresses, the Thresher Test protocol includes humidity-freeze cycling (HF30); thermal cycling (TC600); damp heat exposure (DH2000); dynamic mechanical loading; and UV soaking.

Note that some products are subjected to one or two accelerated reliability tests only, which provides limited insight into in-field performance. Module companies that demonstrate a commitment to quality characterize modules based on an exhaustive set of accelerated stress tests. Ideally, beyond-qualification testing will cover multiple products as well as assess changes to individual module families.



THRESHER TEST PERFORMANCE

Model	HF30	TC600	DH2000	DML	UVSoak
P1	Excellent	Excellent	Excellent	Excellent	No Data
P2	Excellent	Excellent	Excellent	Excellent	No Data
P3	Excellent	Excellent	Excellent	Excellent	No Data
P4	Excellent	Excellent	Excellent	Excellent	No Data
P5	Excellent	No Data	Excellent	Excellent	No Data
P6	Excellent	No Data	Excellent	Excellent	No Data
P7	No Data	No Data	No Data	No Data	Excellent
P8	No Data	No Data	No Data	No Data	Excellent
P9	No Data	No Data	No Data	No Data	Excellent
P10	No Data	No Data	No Data	Excellent	No Data
P11	No Data	No Data	No Data	Excellent	No Data
P12	No Data	No Data	No Data	Excellent	No Data
P13	No Data	No Data	No Data	Excellent	No Data
P14	No Data	No Data	No Data	Excellent	No Data
P15	No Data	No Data	No Data	Excellent	No Data
P16	No Data	No Data	No Data	Excellent	No Data
P17	No Data	No Data	No Data	Excellent	No Data
P18	No Data	No Data	No Data	Excellent	No Data
P19	No Data	No Data	No Data	Excellent	No Data
P20	No Data	No Data	No Data	No Data	Excellent
P21	Excellent	No Data	Excellent	Excellent	No Data
P22	Excellent	Excellent	Average	Excellent	No Data
P23	Excellent	Excellent	Average	Excellent	No Data
P24	Excellent	Excellent	Average	Excellent	No Data
P25	Excellent	Excellent	Average	Excellent	Excellent
P26	Average	Excellent	Average	Excellent	Excellent
P27	No Data	Excellent	Average	Excellent	No Data
P28	Average	No Data	No Data	Excellent	No Data
P29	No Data	Average	Average	Excellent	No Data
P30	No Data	No Data	Average	No Data	No Data
P31	Average	No Data	No Data	Excellent	No Data
P32	Excellent	Average	Average	Excellent	Excellent
P33	No Data	No Data	Average	Excellent	No Data
P34	No Data	Average	Average	Excellent	No Data
P35	Average	Average	Average	Excellent	Excellent
P36	Average	Excellent	Average	Excellent	Average
P37	Average	No Data	Average	Excellent	No Data
P38	Fail	Excellent	Fail	Excellent	No Data
P39	No Data	No Data	Fail	No Data	No Data
P40	Excellent	Fail	Excellent	Excellent	No Data
P41	Average	Average	Fail	Excellent	No Data
P42	Average	Fail	Fail	Excellent	Excellent
P43	Fail	No Data	Fail	Excellent	No Data
P44	Fail	Fail	Fail	Excellent	Excellent

Key	<2% Excellent	2–5% Average	>5% Fail	No Data

HIGH QUALITY IN THRESHER TEST

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

OVERALL HIGH ACHIEVEMENT IN MANUFACTURING SUMMARY

In the 2021 edition of the *PV Module Index Report*, RETC has recognized 11 different manufacturers in the process of showcasing 42 examples of high achievement in manufacturing. To identify the best of the best, we reviewed and ranked the overall data distributions across all three disciplines: reliability, performance and quality. The results of this analysis are summarized in the Overall Results Matrix at right.

RETC compiles its annual *PVMI Report* as a means of showcasing and recognizing industry-leading PV module companies and technologies. RETC compiled the data and results presented in this white paper at its accredited testing facilities during the 2020 calendar year.

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.

OVERALL RESULTS MATRIX

Model	Reliability	Performance	Quality
P1	Good	Good	Good
P2	Good	Good	Good
P3	Good	Good	Good
P4	Good	Good	Good
P5	Good	Good	Good
P6	Good	Good	Good
P7	Good	Good	Good
P8	Good	Good	Good
P9	Good	Good	Good
P10	Good	Good	Good
P11	Good	Good	Good
P12	Good	Good	Good
P13	Average	Good	Good
P14	Average	Good	Good
P15	Average	Good	Good
P16	Average	Good	Good
P17	Average	Good	Good
P18	Average	Good	Good
P19	Average	Good	Good
P20	Average	Good	Good
P21	Average	Good	Good
P22	Average	Good	Good
P23	Good	No Data	No Data
P24	Good	No Data	No Data
P25	Good	No Data	No Data
P26	Good	No Data	No Data
P27	Good	No Data	No Data
P28	Good	No Data	No Data
P29	Good	No Data	No Data
P30	Good	No Data	No Data
P31	Good	No Data	No Data
P32	Average	Average	No Data
P33	Average	Average	No Data
P34	Average	Average	No Data
P35	Average	Average	No Data
P36	Average	Average	No Data
P37	Average	No Data	No Data

Key	Good	Average	No Data

2021 TOP PERFORMERS OF THE YEAR

RETC congratulates and proudly recognizes, in alphabetical order, five manufacturers with products recognized for high achievement in manufacturing across three essential disciplines—reliability, performance and quality—in the 2021 edition of the *PVMI Report:* Hanwha Q CELLS, JA Solar, Jinko Solar, LONGi Solar, Trina Solar.

A YEAR IN REVIEW

PV Module Index Report 2021 Awardees

OVERALL HIGH ACHIEVEMENT IN MANUFACTURING

Congratulations to our top five performers of the year!

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

HIGH ACHIEVEMENT IN RELIABILITY

DAMP HEAT TEST

JA Solar • LONGi Solar • Trina Solar

DYNAMIC MECHANICAL LOAD SEQUENCE

JA Solar • LONGi Solar • Trina Solar

POTENTIAL-INDUCED DEGRADATION

LONGi Solar

HIGH ACHIEVEMENT IN PERFORMANCE

MODULE EFFICIENCY

Hansol Technics • Hanwha Q Cells • JA Solar • LONGi Solar
REC Solar • Yingli Solar

PTC-TO-STC RATIO

Hanwha Q Cells • JA Solar • LONGi Solar • REC Solar • Yingli Solar

PAN FILE CHARACTERIZATION

JA Solar • Jinko Solar • Hyundai Solar • LG • LONGi Solar
Trina Solar • Yingli Solar

LID RESISTANCE

Hanwha Q Cells • JA Solar • Jinko Solar • LONGi Solar • Trina Solar

LeTID RESISTANCE

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

HIGH ACHIEVEMENT IN QUALITY

THRESHER TEST

Hanwha Q Cells • JA Solar • Jinko Solar • LONGi Solar
Tesla • Trina Solar

RETC

PV MODULE INDEX REPORT 2021 HIGH ACHIEVER RETC

In Alphabetical Order:

Hansol

Hanwha Q CELLS

HYUNDAI corporation

JA SOLAR

Jinko Solar

LG

LONGi Solar

REC

TESLA

Trinasolar

YINGLI SOLAR

LOOKING AHEAD

As we look ahead to the 2022 edition of the *PV Module Index Report,* RETC is paying close attention to requests from Nationally Recognized Testing Laboratories (NRTLs) to implement the latest revisions to IEC 61215, the qualification testing standard for terrestrial solar photovoltaic modules. Whereas most testing laboratories are able to test modules to the 2005 or 2016 versions of the standard only, RETC is able to characterize products to the latest testing standards, IEC 61215: 2021.

The 2021 version of IEC 61215 supersedes the 2005 and 2016 versions, both of which are still actively used. Since the adoption of international standards is not highly synchronized, it is common for testing requirements to vary somewhat in the short term from one NRTL to another. These variations in testing may reflect requirements for different end markets, as well as the perceived criticality of the revised test.

While it is beyond the scope of the *PVMI Report* to summarize all of the changes to IEC 61215, the following are some notable themes from the 2021 version.

COVERAGE OF RECENT TECHNOLOGIES

Previous versions of IEC 61215 lack qualification testing methods for recent PV module technologies, including: very-large modules; bifacial modules; and flexible modules.

Very-large modules: The 2021 version of the test 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). To qualify very-large modules, IEC 61215:2021 allows for the use of reduced-sized test samples (50% of length and width or 1.1 meters-by-0.75 meters, whichever is greater).

Bifacial modules: The 2021 version of IEC 61215 adds bifacial testing requirements, which we detailed in the 2019 edition of the *PVMI Report.* The revisions require solar simulators capable of flash-testing to 1,135 W/m^2. During UV testing, rear-side exposure is required for bifacial modules.

Flexible modules: The 2021 version of the test standard introduces flexible module qualifications tests. These requirements include a bending test. Flexible module product markings must indicate the minimum radius of curvature, as well as bifacial coefficients when applicable. Adhesives and substrates must be evaluated during UV, TC, DH, HF, hail and mechanical load tests.

EXTENDED STRESS TESTS

The 2021 version of IEC 61215 adds extended testing requirements intended to address known issues related to deficiencies in testing or in-field performance, such boron-oxygen (BO) destabilization, breakage of damaged cells, PID and junction-box adhesion.

Boron-oxygen light-induced degradation: BO-LID is a phenomenon that RETC observed and brought to the industry's attention. To address this damp heat artifact, the DHT sequence is followed by a BO-LID sequence for crystalline-silicon (c-Si), whereby a sample is tested for 48 hours at 80°C and injected with its short-circuit current (Isc).

Stress-test related cell damage: To address new findings related to cell damage and breakage due to previous stress tests, the 2021 version of the test standard adds a DML sequence in between UV and TC50 tests. Per IEC 62782, this DML sequence is 1,000 cycles at 1,000 pascal.

PID susceptibility: The revised test standard requires PID testing according to TS 62804–1, whereby the system voltage is applied for 96 hours at 85°C and 85% relative humidity is added. When a sample fails PID, there is a chance to regenerate by UV exposure for 2 kWh/m^2. This final stabilization for c-Si PV modules is meant to reverse the effects of PID-polarization, which results from the movement of charge within the module.

Junction-box adhesion: To better characterize potential in-field failure modes, the TC test sequence must be performed with a 5 Newton weight attached to the module junction box.

OTHER PRODUCT CATEGORIES

The 2021 version of IEC 61215 clarifies the reference standards for other product categories related to elevated-temperature climates, nominal module operating temperature (NMOT) and consumer electronics.

Elevated temperature climates: FFor products intended for use in climates where 98th percentile operating temperatures exceed 70°C, the revised test standard recommends testing to IEC TS 63126.

NMOT: The revised standard no longer includes a method for measuring NMOT. See IEC 61853–2 for details on the NMOT measurement method.

Consumer electronics: The 2021 version of IEC 61215 clarifies that consumer electronics that are not subject to the same amount of outdoor exposure and life expectancies as PV modules manufactured for residential, commercial and utility applications are assessed differently. To qualify PV devices for consumer electronics applications, refer to IEC TS 63163.

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. At RETC, we are united in the belief that our work is enabling a safer and more sustainable world.

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