



2024

PV Module Index Report

A LETTER FROM OUR CEO



Cherif Kedir is the president and CEO of RETc. He is a solar industry veteran with an extensive background in semiconductors, whose experience spans research and development, manufacturing, reliability testing, field testing, product certification, and bankability.

As RETc publishes its sixth annual *PV Module Index Report*, our organization has never been better positioned to support the global energy transition. As a member of the VDE Group, RETc provides customers worldwide with a one-stop shop for solar and energy storage product testing, inspection, and certification. Moreover, RETc is uniquely positioned to support the nascent US clean energy manufacturing renaissance.

Since the passage of the Inflation Reduction Act in 2022, companies have announced nearly \$17 billion worth of investments in new and expanded solar manufacturing capacity additions in the United States. Given the unprecedented market expansion in the world's second-largest solar market, industry stakeholders must remain vigilant regarding technical risks inherent to supply chain diversification and the accelerated time frames between innovation and mass production.

To better meet the needs of an expanding US clean energy manufacturing ecosystem, RETc recently acquired SolarPTL, a photovoltaic testing laboratory based in Tempe, Arizona, with a dedicated outdoor testing facility. This acquisition does more than simply improve RETc's overall solar, energy storage, and tracker testing throughput capabilities. It also provides manufacturing companies from Arizona to Texas with a regional partner for product testing and certification.

To better support product reliability testing and energy yield characterization, RETc has also expanded its outdoor testing and field forensics capabilities. We now operate a one-acre outdoor testing laboratory—formerly known as known as the Arizona Public Service (APS) Solar Test and Research (STAR) Center—

specializing in reliability and performance characterization in hot, dry, high-irradiance conditions. We are also operating two newly acquired drone cameras with infrared capabilities and will soon be able to support customers with large-scale in-field electroluminescence (EL) testing.

As a highly accredited independent testing laboratory, RETc is privileged to receive a sneak preview of coming solar technologies and trends. Based on this perspective, we can confidently say that the future is largely a sunny and innovative place populated with new and exciting technologies. However, it is not a place without risk or cloudy weather. For example, RETc has long warned industry stakeholders about potential field durability risks intrinsic to ultra-large-format PV modules.

In our laboratory testing, RETc has consistently observed that heat-strengthened solar glass is more prone to breakage than fully tempered solar glass. Unfortunately, we now suspect this vulnerability may also apply to field deployments. We have therefore dedicated the entirety of the "Industry Trends" section (pp. 5–15) to subject matter expert interviews exploring reports of spontaneous glass breakage and catastrophic hail losses in fielded solar assets. Our hope is that this candid discussion will inspire a collective response that ultimately eradicates the problem.

RETc is united with its customers in the belief that our collective work enables a safer and more sustainable future. Thank you for being our partners and collaborators in this endeavor.

—Cherif Kedir, CEO, RETc

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ABOUT RETC

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

RETC IS PROUD TO BE:

- ISO 17025 accredited by A2LA (Certification Number 3038.01)
- Awarded IEC CBTL status
- A VDE Qualified Test Laboratory and VDE PrimeLab®
- Verified by the UL Data Acceptance Program
- An Intertek Recognized Test Laboratory (RTL)
- TÜV SÜD America's CARAT Program recipient
- TÜV Rheinland's Partner Laboratory
- A California Solar and Storage Association (CALSSA) Member



INDUSTRY TRENDS

Innovation is essential to increasing solar PV market penetration. But have module value engineering efforts reached a glass threshold?

In the 2021 edition of the *PV Module Index Report*, RETC explored the benefits and trade-offs associated with a then-novel trend toward large-format PV module designs. On the one hand, we noted that large-area, high-power modules were helping to accelerate the process of lowering the levelized cost of energy (LCOE) of solar, effectively making flat-plate PV technologies more cost-effective compared to other sources of power generation capacity. On the other, we noted that the up-front cost savings associated with these value engineering efforts could come at the cost of reduced resilience to conditions of use, including exposure to elevated wind and snow loads or severe hail impacts.

Some three years later, the early warning efforts documented in our article, "Evaluating Large-Format PV Modules," are simultaneously prescient and naive. While we had clearly identified a signal in our laboratory testing and field forensics—namely, structural vulnerabilities associated with newer module designs—we did not necessarily understand the root cause of the issue. Was the physical size of these new modules a problem? Was solar market proliferation to blame for subjecting modules to previously unaccounted-

for environmental stresses? Were our testing protocols and sequences inadequate to identify potential new failure modes and wear-out mechanisms?

Today, our in-house laboratory and field forensic investigations, not to mention insightful due diligence from esteemed colleagues worldwide, better inform us. With the benefit of this experience and hindsight, we find ourselves asking: Is a decline in the compressive strength of solar module glass partly to blame for some of the unique field failure modes associated with new ultra-large-format module designs?

This is an elephant-sized question that we, like the blind persons in the parable, cannot describe fully by touching only one part of the beast. With that in mind, we interviewed a handful of industry subject matter experts, each of whom brings a unique perspective and area of expertise to the table. By questioning these many authorities—on glass manufacturing, module durability, field forensics, tracker structures, and hail-impact characterization—and sharing those conversations here, we hope to empower industry stakeholders to eliminate a potential technical barrier to solar market advancement.

"Is a decline in the compressive strength of solar module glass partly to blame for some of the unique field failure modes associated with new ultra-large-format module designs?"



GLASS MANUFACTURING, SCIENCE & STANDARDS



DR. JAMES WEBB is a senior research manager for reliability sciences at Corning, a pioneering glass manufacturer founded in 1851. Today, Corning provides state-of-the-art products for a variety of industrial applications, such as

optical communications, mobile consumer electronics, displays, automotive supplies, and life sciences. Dr. Webb's research, development, and engineering activities are foundational to the company's product and process innovations for ceramics and specialty glass.

RETc: What are the challenges associated with using glass as a structural material?

JW: Glass is a unique material that is largely used for two main properties: chemical stability and visual transparency. Certainly, glass is not commonly used as primary beams supporting a building, but people do use it, in a sense, to manage applied loads. What is interesting about glass as a structural material is that its strength is largely an extrinsic property, meaning it is a function of something you do to the glass that changes its strength. The strength of best-in-class commercially available glass optical fiber is on the order of 10 to 14 gigapascals, which approaches theoretical limits. By comparison, the practical strength of plate glass is multiple orders of magnitude lower, on the order of 70 to 100 megapascals (MPa). What dictates glass strength is largely what manufacturers do to the surface. For example, heat tempering adds compressive strength to the surface of the glass. This compressive strength provides protection against surface flaws that would otherwise change the glass's inherent strength. Flaws resulting from manufacturing processes, handling processes, or environmental exposure will reduce structural strength in glass.

"What drives the tempering process is the manufacturer's ability to develop a temperature differential through the thickness of the glass."

—Dr. James Webb, Corning

RETc: How does heat-strengthened glass differ from tempered glass?

JW: The best way to understand these differences is to refer to ASTM C1048 Standard Specification for Heat-Strengthened and Fully Tempered Glass. This standard differentiates between fully tempered and heat strengthened based on surface stress levels and breakage patterns. For example, the standard defines tempered glass as having a minimum surface tension of 69 MPa, whereas heat-strengthened glass will have a surface compressive strength of 24 to 52 MPa. In terms of breakage patterns, the stress level in tempered glass is intended to ensure that for improved safety, the glass breaks into small cube-shaped pieces of glass rather than sharp jagged shards. While fully tempered glass meets building code requirements for safety glass, heat-strengthened glass does not. Annealed glass [ordinary float glass] has a surface compression of less than 24 MPa and may fracture as sharp shards, which can pose a risk of injury.

RETc: Is there a relationship between glass thickness and heat strengthening?

JW: When a piece of glass is tempered, its temperature is raised to between the annealing and softening temperatures, where the glass can adjust its own stress quickly. Then it is quickly cooled. During cooling, the glass surface shrinks first, while the interior of the glass still has the ability to flow. Surface compression then develops as the interior completes its process of cooling, shrinking, and solidifying. This results in tensile stress in the center of the glass and compressive stress on the exterior surface. What drives the tempering process is the manufacturer's ability to develop a temperature differential through the thickness of the glass.

RETc: Is it possible to fully temper thinner sheets of glass?

JW: Yes, it is. However, the temperature differential in the glass decreases as the physical distance between the interior and the exterior decreases. Unless something is done to quickly extract more heat from the surface of thinner glass, the temperature differential is not going to be enough to develop tempering stress. With 2.0-mm [0.08-in.] glass, some form of accelerated cooling—such as forced air—is needed to get it to temper. However, this may require different manufacturing equipment and

potentially creates challenges with respect to cost. When using existing manufacturing infrastructure to manufacture thinner glass for architectural applications, you may only be able to produce heat-strengthened glass.

RETC: Are there practical alternatives to heat strengthening for solar glass?

JW: Chemical tempering is one alternative to heat tempering. Corning uses chemical tempering to produce its Gorilla Glass product, which is used for products in the mobile consumer electronics and automotive spaces. With chemical tempering, you are submerging glass into a molten potassium salt bath and exchanging the sodium ions for potassium. Since potassium is much larger than sodium, the process basically shoves a larger ion into a small hole. Chemical tempering develops compressive stresses that can be much higher than with thermal tempering. While this is an effective process for producing glass with an impressive strength profile, a cost-benefit analysis is required to determine its suitability for solar applications. Thermal tempering provides a good equilibrium between cost and strength. Another option is for manufacturers to maximize glass strength by considering panel, process, and system design strategies that lower glass stress, improve handling, and reduce strength-limiting damage.

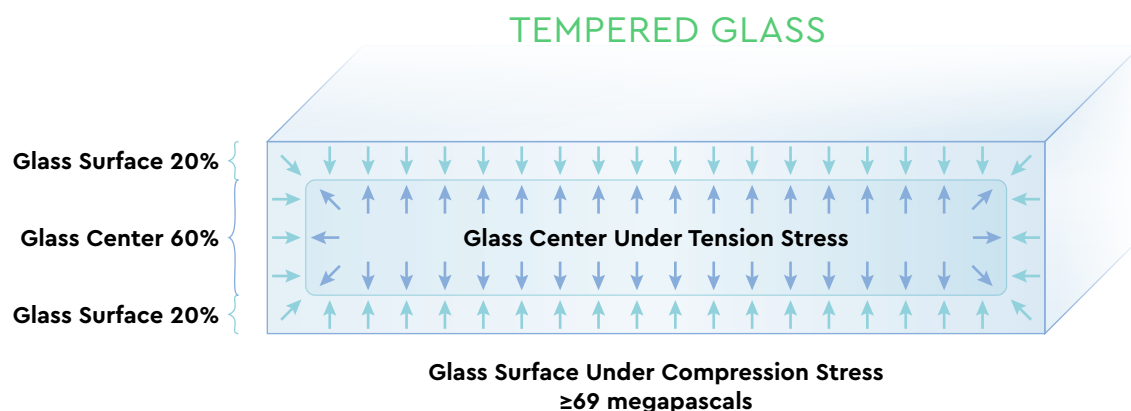
RETC: Is using thinner glass a good way for module companies to reduce costs?

JW: There is often an assumption that glass gets cheaper as it gets thinner, which is not necessarily true. Certainly weight can be reduced by manufacturing with thinner glass. Similarly, more glass can be produced pending the amount of material that goes into the tank. However, the most cost-effective glass thickness is somewhat process dependent.

Manufacturing float glass is a complicated process. The process speed needs to be right. There are rollers involved to stretch the glass out. Rollers are also used to get the AR [anti-reflective] texture utilized on solar glass. As the glass gets thinner, handling requirements also change. Handling, pick and place, and rolling equipment need to be adjusted to account for the increased flexibility of thinner glass. Common adjustments include decreasing the spacing of rollers and suction cups. Thin glass edges will have smaller radii, which can have implications for tolerance to impact events during the manufacturing process. There may be short-term increases in handling issues as solar glass is getting thinner. While it is possible to manufacture thinner glass that is very strong, it is also a learning process.

RETC: How can the solar industry mitigate against glass breakage issues?

JW: All glass manufacturers have a relatively structured process for getting glass off their manufacturing lines and into a box for shipment. They will all have strategies for packing, separating, and delivering the glass to the customer. While there may be some subtle differences from one manufacturer to another, it is reasonable to assume that the glass coming out of those boxes generally meets the compressive strength specifications in ASTM C1048. Unfortunately, simply buying strong glass and putting it into a manufacturing process will not necessarily result in a strong solar module. The glass needs to be kept strong during module assembly, which is not a benign process. If module manufacturers are not paying attention to what they are doing during the module assembly process, they can introduce flaws that reduce the strength of the glass. The same thing is true during installation or operations and maintenance. It is important to pay attention to maintaining the strength of the glass.



SOLAR GLASS DURABILITY & FAILURE MODES



Teresa Barnes, Ph.D., manages the Photovoltaic Reliability and System Performance Group at NREL. She is an expert in accelerated test development, outdoor field testing, energy yield assessment, degradation rate analysis, and

materials science. In addition to working with stakeholders throughout the PV value chain to develop industry standards for reliability testing and energy yield, Dr. Barnes is also the principal investigator and director of the DuraMAT Consortium for module materials research.

RETc: Has NREL noted any changes in glass breakage patterns over time?

TB: Spontaneous glass breakage is an example of a failure mode that we didn't used to see. When I first started working on solar module reliability seven or eight years ago, we mostly heard about glass breakage when there were sloppy O&M [operations and maintenance] practices. Maybe someone is mowing for vegetation management, the mower throws a rock, and you get glass breakage. Occasionally, we would hear about glass breakage in thin-film modules, which use thinner glass that is not tempered; this is known failure mode, one that we would expect to see. Outside of these known issues, we didn't used to hear about glass breakage in silicon modules unless there was a catastrophic storm. That is no longer the case. Now we are regularly hearing about glass breakage in silicon modules. While these reports are anecdotal, there is a definite pattern. People are seeing glass breakage for no apparent reason, often before commissioning. These field reports track what we are hearing from the testing labs. It used to be the case that modules would pass the IEC 61215 static load test with a big safety factor. Today, modules are either barely passing the base static load test or they are not passing with higher safety factors. Some new module designs are simply not passing the minimum static load test.

"As solar glass gets thinner, it takes fewer defects to cause a strength-limiting flaw in the glass."

—Teresa Barnes, Ph.D., NREL

RETc: Do you and your colleagues have any theories about why this is happening?

TB: We have started to hypothesize internally about potential root causes. At DuraMAT, for example, we funded a bunch of projects on cell cracks with the idea that researchers would take PV modules, pre-crack the cells, and then do some sort of stress test to identify the impact of the latent defect. After funding this research, I started receiving phone calls and emails saying: "Hey, I can't break the cells without breaking the glass. It seems like cell cracking is not our problem right now. Can I look at glass breakage or something else instead?" What we believe is happening is similar to how your car windshield breaks, where a small surface defect propagates when exposed to an extreme environmental stress. Think about when you are driving down the road and something hits your windshield. The windshield probably does not shatter on impact. Instead, you might see a small star-shaped defect on the surface of the glass. Here in Colorado, where I go through more windshields than I ever did on the East Coast, that impact damage might not propagate until there is a dramatic change in the weather. But when I walk outside on the first really cold day of winter, suddenly all the windshields in my driveway have a big crack all the way across the glass. We think a similar dynamic could be a root cause of spontaneous solar glass breakage.

RETc: Why do you think this failure mode is increasing now?

TB: Solar glass is thinner today than it was in the past. Because the glass is thinner, it is not fully tempered. According to glass experts like Mike Pilliod from Central Tension, who spoke at NREL's 2024 PV Module Reliability Workshop, any manufacturer can temper glass that is 3 mm [0.12 in.] or thicker because it is relatively easy to get the thermal differential to build the stress profile you need. However, it is more difficult to fully temper glass below a thickness of 3 mm. If you do not have a good temper on the glass, it is relatively easier for the glass to break. In other words, as solar glass gets thinner, it takes fewer defects to cause a strength-limiting flaw in the glass. Moreover, the way we specify glass in the solar industry right now does not account for strength-limiting flaws in glass that is not fully tempered. There might be a ball-drop test on a piece of glass, but people are not necessarily looking at the impacts of defects around the edges of the glass. Also, the way people are cleaning or grinding around the edges of the

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—Teresa Barnes, Ph.D., NREL



glass may be causing more defects rather than fewer defects, perhaps making this thinner glass even more sensitive to breakage. These are the types of things that we are starting to investigate and trying to better understand.

RETc: How does glass breakage relate to module frame and rail designs?

TB: There is undoubtedly an interaction between these different components. A module is really a whole system, often consisting of glass, a perimeter frame, and a mounting rail. When you think about ultra-large modules as a system, the glass may be getting thinner, the frame may be getting thinner, and the mounting rails may be getting closer together. The interaction between these components is where the term "big floppy modules" comes from. While glass has always been an element in the module system, it may be bearing more of the load now, which may be bad because we have made the glass weaker.

RETc: How has the industry responded to reports of spontaneous glass breakage?

TB: At this year's PV Module Reliability Workshop, my colleagues and I started to hear about frames getting thicker again. This was somewhat surprising, given the rapid innovation in recent years focused on making modules cheaper and lighter. The problems we are seeing in the US market may be causing manufacturers to rethink product design strategies. We are starting to hear some chatter

about frames getting a bit more substantial and mounting rails getting a bit wider. As people better understand how the module system interacts, they can work to optimize how loads are balanced out. The pendulum in that balancing act may already be swinging back toward the integrity of the frame and the mounting rail.

RETc: Given the catastrophic scale of recent hail loss events in Texas, do you think the industry needs hail-hardened module designs?

TB: Ten years ago, people would run you out of the meeting on a rail if you mentioned climate-specific module designs. The consensus was that this would simply be too expensive. A decade ago, module cost was really the barrier to entry. Today, solar is a terawatt-scale industry, and we are deploying hundreds of gigawatts of solar capacity annually. Now climate-specific modules and climate-specific testing are starting to look viable because we are seeing more of an emphasis on total system costs. It is entirely possible that we could see hail-hardened modules, especially in a market like the United States, where it could be worth paying more up front for hail resilience. At the end of the day, a lot of these design decisions will come down to the business model. People flipping and selling projects will always have different priorities than those who own and operate projects for the long term. If you are the person who will be caught holding the bag when a hailstorm comes, maybe you are willing to pay a little more for hail-hardened solar modules—because that decision helps make the system pencil over a long lifetime.

LESSONS FROM FIELD FORENSIC INVESTIGATIONS



Ralf Schulze manages field forensics services for RETC. A 15-year veteran in the renewable energy sector, he has worked as a managing engineer at Kaco new energy and Yingli Green Energy Americas and as a quality manager

for Sunrun. A renowned source for end-to-end renewables technology problem-solving and specialized services, Schulze is an expert in quality assurance, failure mode and effects analysis, system diagnostics, and corrective and preventative maintenance.

RETC: What is your experience with glass breakage in fielded PV systems?

RS: Glass breakage in the field is not necessarily a new phenomenon. Over the years, we have documented glass breakage in utility solar due to terrain issues, sinking piles, construction errors, installers using impact tools, and incorrect torque settings—the list goes on and on. Having said that, my personal experience suggests that the leading causes of glass breakage may be changing over time as PV modules become larger, using thinner glass and reduced frame profiles. In more recent glass breakage investigations, we are seeing signs pointing to the glass itself, which is not fully tempered anymore.

RETC: How does module glass specification impact project durability?

RS: Laboratory testing clearly indicates that thin, heat-strengthened glass has higher breakage and failure rates as compared to fully tempered glass. While thinner glass may be an ideal way to keep module costs and weight down, there may be other considerations to balance, especially with large-scale modules. Stress on module glass in the field is substantial, especially in the east and west corners of the array under certain wind or weather conditions. While these

"When breakage patterns are random, that could suggest the glass itself is not suitable for the specific installation environment."

—Ralf Schulze, RETC

environmental stress factors have always been there, they were not the leading cause of glass breakage. Today, we are sometimes being called to investigate glass breakage at sites where modules seem to be failing under normal conditions of use. While I have not seen that many impacted sites, a lot of people within the broader community are seeing similar problems. We know this because NREL and DuraMAT share information regarding field failures relatively quickly. For the few sites I have investigated—which are large utility projects on the order of 100 MW–300 MW in capacity—we are seeing spontaneous glass breakage rates of 2%–5%.

RETC: Is there a typical field forensics process for investigating glass breakage?

RS: When we want to pinpoint a root cause, the first step is to isolate each individual problem, starting with the terrain, tracker, installation process, mounting hardware, torque settings, and so forth. Then we start to look for patterns. Is the glass breaking at the mounting rail locations? Is the glass breaking during the installation process or after the commercial operations date? Has the site experienced a severe weather event and been subjected to pressure ratings beyond the allowable design loads? When there is a pattern that repeats itself—either across a site or based on experience—we can identify a particular issue as the likely root cause. When breakage patterns are random, that could suggest the glass itself is not suitable for the specific installation environment. In other words, if we see breakage inconsistent with anything we have seen in the past, it could be because the glass is not fully tempered.

RETC: Who is most impacted by spontaneous glass breakage?

RS: The parties feeling the pain tend to be the EPC, project owner, or whoever builds the project and then wants to transfer it to a final owner. If glass breakage is documented during the commissioning and handover process, it leads to bigger questions. People will ask, "If spontaneous glass breakage is happening to some modules now, won't it happen to the other modules, too?" This type of scrutiny is uncomfortable for the module manufacturer, who will generally try to help mitigate the problem. From professional experience, I believe PV module manufacturers are aware of these issues, and I suspect some manufacturers are starting to rethink module construction practices.

RETC: How can laboratory testing help prevent these problems?

RS: There are many aspects to this type of technical due diligence. First, you need to investigate and fully test the resiliency of the glass, especially with ultra-large-scale module designs. Hail durability testing is the most likely to identify vulnerabilities associated with the glass itself. Importantly, this testing must exceed the minimum standards for product certification. Second, you need to understand how module frame and tracker mounting rail details impact module resilience to glass breakage. Static and dynamic mechanical load sequences are useful for investigating module glass vulnerabilities related to the frame and rails. This type of testing has consistently shown a tremendous decay in load-bearing capacity whenever module frame profiles drop below 35 millimeters [1.38 in.].

RETC: What additional due diligence measures do you recommend?

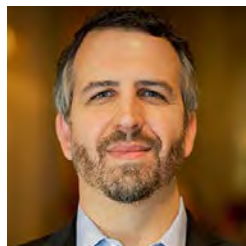
RS: Ideally, laboratory testing is done as part of a systematic vendor qualification program that starts with long-term durability testing—such as RETC's Thresher Test—followed by 12 to 18 months of in-field monitoring. Once you have qualified vendors and identified resilient BOMs [bills of materials], you need to verify that the product leaving the factory matches the BOM you have locked down. So if you are building a 1 GW project over a period of years, you need to require monthly BOM verification inspections and ongoing random sample testing to ensure the product you approved is being delivered to the field. Once the product reaches the project site, look for smart ways to improve installation practices as modules increase in area. For example, you may be able to optimize installation quality using robotic suction-cup machines for module handling.

"Once you have qualified vendors and identified resilient BOMs, you need to verify that the product leaving the factory matches the BOM you have locked down."

—Ralf Schulze, RETC



SINGLE-AXIS TRACKER DESIGN CONSIDERATIONS



Scott Van Pelt is the chief engineer for GameChange Solar, a manufacturer of fixed-tilt and single-axis tracker solar mounting systems. Licensed as a professional engineer in 20 states, he functions as the structural engineer of record

for many of the company's projects and is responsible for the execution, accuracy, and timeliness of its technical deliverables. Van Pelt is an expert in structural engineering who has served as a member of several national and international standards committees.

RETc: How does tracker specification impact PV module resilience?

SVP: When we examine a solar module's load-bearing capacity under mechanical testing in the laboratory, we see that this property is not inherent to the module itself but rather a function of the solar module and the mounting rail acting as an assembly. In other words, the strength of a tracker-mounted solar module is derived in part from the mounting rail. Specifically, the stiffer the rail and the longer the rail—the further the rail extends out from the center of the module—the higher the mechanical support capacity for the assembly. In this context, I am using the term "rail" somewhat ubiquitously. GameChange offers different module mounting rail options, including a bolt-and-nut bottom-mount system and a friction-fit clamping system called SpeedClamp that offers installation speed advantages. Other vendors offer similar products. Regardless of what rail you are using, you typically need to increase length or thickness—or both rail length and thickness—to reach higher mechanical ratings. Interestingly, the module itself is generally the weakest link in this system. We conduct mechanical testing at RETc, and the vast majority of the time, the module is the first component to fail.

"If you put on your forensic engineer's hat, this module breakage pattern is indicative of a failure to account for higher loads on the leading side of the module."

—Scott Van Pelt, GameChange Solar

RETc: What is the goal of mechanical load testing to failure?

SVP: We are testing to identify the lightest rail required to meet the desired mechanical capacity. To better align with wind tunnel test results conducted by our wind engineering consultant, CPP Wind, we conduct unbalanced load testing, which subdivides the module into four different segments. Rather than applying a uniform pressure across the entire surface of the module, which is an under-conservative design assumption, we apply unbalanced loads that reflect how the wind actually loads tracker-mounted modules during operation. If the site and technology details are known, we can conduct this testing using pressures informed by site-specific parameters, such as design windspeed and ground cover ratio. Alternatively, we can calculate pressures for a generic project, based on slightly conservative assumptions informed by building codes and industry practices. RETc will then perform the specified unbalanced load testing, which is highly indicative of module loading during operation.

RETc: How does unbalanced load testing impact single-axis tracker design?

SVP: There is no meaningful difference from the torque tube down. However, this testing could cause us to use heavier components for the torque tube and rails. All single-axis trackers have a torque tube that rotates the modules, which are attached to the tube using some type of mounting rail system. When we analyze this mounting rail structure, we idealize it as two cantilevers extending out to the east and west sides of the torque tube. Based on our wind tunnel test results, we know that the wind pressures on these cantilevers are not uniform. The wind pressures are greatest on the cantilever supporting the leading edge of the modules and lower on the cantilever on the leeward side. Unbalanced load testing ensures that our tracker component designs can support the applied pressure on the more heavily loaded side of this cantilever. While unbalanced load testing could possibly cause us to use more heavy mounting rails, the additional cost for these heavier components is minuscule compared to the remediation costs in the event of a field failure.

RETC: Does this design approach help mitigate glass breakage in the field?

SVP: Absolutely. You may recall Hurricane Ian in 2022. This made landfall as a Category 4 hurricane, tied for the fifth strongest to ever to strike the United States. GameChange had 16 sites in the path of Hurricane Ian, including one site located very close to, if not within, the eyewall of the storm. As I recall, 99.95% of our trackers were operational within days of the storm. Our customers conducted plant walkdowns to identify any storm damage, and then our trackers were right back up and running. While our sites all fared very well, the EPC [engineering procurement and construction] firms we work with did experience some failures with other tracker systems. For example, we heard about failures where the leading edge of the modules had been pushed down and in. If you put on your forensic engineer's hat, this module breakage pattern is indicative of a failure to account for higher loads on the leading side of the module.

RETC: Does the proliferation of big, floppy PV modules make it more difficult to achieve higher mechanical ratings?

SVP: This type of module exacerbates problems associated with unbalanced loading. With ultra-large-format product designs, we are more restricted in how we can support the modules. Smart clamping systems that improve installation speed are not appropriate for ultra-large-format modules for a number of reasons. We can certainly design systems to support these types of modules, but it is important to recognize that these types of module designs will often require a heavier rail system. Typically, what we see is that you need more mounting locations per module to achieve the desired mechanical load. So you might need eight or even 12 bolts per module, which increases installation costs. You not only have to buy more bolts, but also you will incur labor hours to install the bolts. We do a lot of work in the Gulf Coast of Texas and Florida, places where the standard 2,400-pascal static wind load rating for most modules could be exceeded. By conducting unbalanced mechanical load testing with RETC, we can understand how much more capacity we can get out of a specific module by adding more points of support or more structural steel. This is money well spent, as it gives us an accurate idea of what design we need to reach a certain load level.



HAIL IMPACT CHARACTERIZATION & MITIGATION



Jon Previtali is a technical due diligence specialist at advisory firm VDE Americas, where he supports utility-scale solar and storage project financing. He also manages the company's natural catastrophe advisory services, which leverage

state-of-the-art meteorological models developed by Central Michigan University's Dr. John Allen and financial loss models developed by VDE Americas co-founder Dr. Peter Bostock. Previtali is an expert on hail risk assessment for utility-scale solar projects.

RETc: Is spontaneous glass breakage something the engineering community is tracking?

JP: We have heard reports of a couple of incidents of spontaneous glass breakage from credible sources. While it's unclear why it's happening, we have some theories. One possibility is that the length of the rails that connect the tracker torque tubes to the modules is too short to provide enough support for the design wind load, which allows the modules to bend in the wind and causes the glass to crack. Another theory is that glass is breaking due to manufacturing defects, which could be inclusions, particles of pollutants in the glass, or other manufacturing process problems. Glass breakage could also be a construction issue, such as module clamps being torqued down with too much force during installation.

RETc: How can project stakeholders prevent spontaneous glass breakage?

JP: To address this risk, you can ask the engineer of record and independent engineer to check the length of the rails. We often see letters from PV module manufacturers confirming that rails are long enough, but without providing any supporting calculations. Since this issue isn't covered under the PV module warranty, it's important to get an

"We are seeing more glass breakage due to hail because of the expansion of projects into hail-prone regions like Texas and the Midwest."

—Jon Previtali, VDE Americas

independent third-party engineering review. To prevent manufacturing process issues, you can use a combination of accelerated lifetime testing and factory production oversight. For example, dynamic mechanical load tests done on a randomly selected group of modules can help identify issues before modules are produced and shipped. Also, production oversight inspections can monitor the glass manufacturing and handling process or verify whether testing has taken place for glass delivered to the module factory.

RETc: What is your experience with catastrophic glass breakage due to severe hail?

JP: We are seeing more glass breakage due to hail because of the expansion of projects into hail-prone regions like Texas and the Midwest. The risk is exacerbated by larger, bifacial modules that use 2.0-mm [0.08-in.] glass for both front and back sides. The benefit of 2.0-mm double-glass bifacial modules is that they are not subject to the Section 201 tariff, and their larger format provides economies of scale cost reductions. The downside is that 2.0-mm glass is too thin to be fully tempered in most mass-production glass manufacturing lines. Because 2.0-mm glass is heat strengthened or semi-tempered only, it's softer and more vulnerable to hail damage as compared to fully tempered glass, which is what we have with 3.2-mm [0.13-in.] front glass products. Unfortunately, modules of all kinds are being deployed in hail-prone regions without sufficient hail monitoring and stow protocols in place.

RETc: Is it possible to prevent catastrophic losses due to hail?

JP: Buying modules manufactured with fully tempered front glass will increase first costs but decrease financial exposure due to hail risk over the investment hold period. Module glass that is 3.2 mm or thicker is fully tempered and roughly twice as resilient to hail impacts as thinner heat-strengthened glass. We are aware of manufacturers evaluating different hail-hardened module design approaches, such as using thicker 4.0-mm [0.16-in.] front glass or using much thinner chemically treated front glass layers, like Gorilla Glass. While using hail-hardened modules is the best solution to the problem, all is not lost if you cannot. You can significantly reduce the risk of hail damage by using trackers that can put the modules into a steep stow position prior to a hailstorm. For material hail risk mitigation, we are talking about

trackers that can stow at or beyond a 50° tilt angle under high wind conditions. This hail stow strategy significantly reduces the risk of glass breakage by reducing the glass area exposed to hail impacts and converting direct blows with a high kinetic impact energy into glancing blows with a far lower impact energy. While our recommended hail stow scenario is to tilt the trackers at a maximum tilt angle away from the wind, it's very difficult—impossible even, using available technology—to know which direction the wind will be coming from when the hail falls. When there is a hail alert, we recommend that you put the modules into the closest maximum tilt position to avoid going through the flat position, which is most susceptible to hail damage. One of the ways that we support customers is by providing a hail stow protocol document that can be attached to an operating agreement.

RETC: Do you think the industry needs better ways to characterize impact resiliency?

JP: Currently, module hail resiliency testing follows the IEC 61215 standard, which requires 11 freezer ice ball impacts at different locations often on just one or two PV modules. Testing to this pass-fail standard does not provide enough data to accurately characterize module hail resiliency. It also doesn't do a good job of picking up possible glass defects that would show up in a larger sample size of modules. To reliably characterize module hail resiliency, we need more than 11 data points, and we need to test modules to failure so that we know the probability of failure under different hailstone size conditions. To solve this

problem, VDE Americas is working with RETC, our sister company, on a new hail impact characterization test that will use many more ballistic impacts and kinetic energy levels—representing a range of hailstone sizes and wind conditions—on approximately 30 randomly selected PV modules. Unlike IEC 61215, this new testing protocol will be a test to failure, meaning it will really show us what impacts modules are able to withstand. Importantly, this new test is designed to be not much more expensive than the typical IEC 61215 testing.

RETC: How are you able to control costs while generating more data?

JP: One issue with the IEC 61215 hail test is that it is difficult to make and maintain freezer ice balls that meet the testing requirements. You need special water and highly controlled freezer conditions, and you can't store the freezer ice balls for more than a few days because they will sublime, losing density and size. This complexity adds cost. To reduce cost and complexity, we will use synthetic ice balls instead of freezer ice balls. The synthetic materials we are evaluating have densities similar to those of freezer ice balls but are more consistent as a laboratory testing tool. So, by using a synthetic material as an ice proxy, we can develop an information-rich, cost-effective, and low-uncertainty test. Initially, the new test will be available only through RETC. However, once we have validated and defined this new hail impact characterization test protocol, our plan is to have VDE standards developers in Germany submit a proposed testing standard for IEC review.



CATEGORIES for HIGH ACHIEVEMENT

RETC presents the 2024 *PV Module Index Report*. This annual publication presents performance distribution data for highly accelerated stress tests, empowering project stakeholders to mitigate site- and product-specific technical risks.

Our sixth annual *PV Module Index Report* compiles the results of beyond-certification bankability tests conducted at our highly accredited independent testing laboratories over 12 months, spanning Q2 2023 through Q1 2024. As with previous editions of the report, we catalog testing sequences and data according to three interrelated and equally influential disciplines: module reliability, performance, and quality.

The bankability tests underlying this report are foundational to a science- and engineering-based approach to technical risk mitigation. Industry stakeholders can use these comparative test results to identify product or project designs best suited to a specific environment, location, or portfolio, as determined by RETC's Thresher Test results.



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

—Hugh Kuhn, Thresher Test Program Lead



Introduced at the 2011 PV Module Quality Assurance Forum, the Thresher Test is the solar industry's first-ever commercial reliability and durability analysis standard for PV modules. The program takes its name from a type of farm equipment used to separate high-quality seed and grain from low-quality straw and chaff. Much as a threshing machine beats plants to separate organic materials according to utility and desirability, the Thresher Test uses highly accelerated stress sequences to separate high-quality PV module designs from low-quality ones.

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

The bankability tests underlying this report are foundational to a science- and engineering-based approach to technical risk mitigation.

Longtime readers of the *PV Module Index Report* may notice a realignment of our testing data reporting and evaluation criteria in this 2024 edition. Specifically, we have reengineered our high-achievement categories by adding granularity and raising the bar for our most prestigious awards. These structural changes reflect our internal commitments to continuous improvement, optimization of stakeholder value, and quality assurance.

Starting this year, manufacturers must successfully complete RETC's rigorous Thresher Test program and excel across multiple tests within the reliability and performance disciplines to receive "Overall Highest Achiever" recognition. Stepping down from our top honor, RETC will recognize manufacturers that excel across multiple testing sequences within one specific discipline for either "High Achievement in Reliability" or "High Achievement in Performance." To recognize manufacturers of products that excel in one or more individual testing sequences, we have added a new award, "Test Category High Achiever."

2024 PVMI AWARD CATEGORIES

Award

Criteria for Recognition



- Complete RETC's full Thresher Test program
- Meet high achievement requirements in the reliability and performance disciplines
- Meet criteria for recognition in the quality discipline



- Meet high achiever requirements for at least three of the seven test sequences within the reliability discipline only*



- Meet high achiever requirements for at least three of the seven tests sequences within the performance discipline only



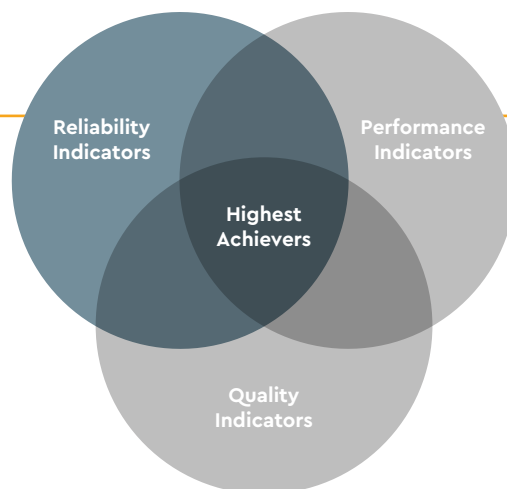
- Meet the high achiever requirements for one or more individual test sequences only

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



MODULE RELIABILITY

Reliable PV plant operation over a 25- or 30-year service is not an accident, but rather a testament to rigorous laboratory testing.



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

Informed by the comparative results of highly accelerated stress testing, diligent project developers, owners, and insurers can take science- and engineering-based steps to mitigate severe weather risks and prevent catastrophic loss events. Laboratory testing data clearly show that some PV modules are more resilient to severe hail impacts, for example, whereas other products are more vulnerable. At the same time, products that test well for hail durability may be at an elevated risk of degradation when installed in a hot, humid location.

Intelligent solar project development eschews an oversimplified solar-as-a-commodity approach to project

design and product procurement. All solar modules and installation environments are not the same. Success or failure in the field could come down to this simple question: What is the right tool for the job? Successful solar project deployment demands differentiated products and design approaches. These strategic design adaptations ensure that fielded projects can withstand site-specific risks while optimizing investor returns.

RELIABILITY INDICATORS & RESULTS

For the 2024 edition of the *PV Module Index Report*, RETC identified seven important reliability evaluation categories. As summarized in the "Reliability Discipline Criteria" table, each category correlates with a specific extended testing sequence. The source data in this discipline derive from either RETC's Thresher Test or its Hail Durability Test programs. Within individual categories, we recognize manufacturers of products that exceed carefully calibrated reliability indicator thresholds as test category high achievers. In the year-in-review section (p. 35), we further showcase manufacturers of products that consistently exceed our high achiever requirements in the reliability discipline.

RELIABILITY DISCIPLINE CRITERIA		
Category	Evaluation Method	High Achiever
Backsheet Ultraviolet Durability	DH1000 + [3 x (UV65 + TC50 + HF10)] + UV6.5	No backsheet cracking
Damp Heat	DH2000 + B-O LID	<2% degradation
Hail Durability Test	HDT + TC50 + Hot Spot	>20-joule impact
Potential-Induced Degradation	PID192 + UV2	<2% degradation
Static and Dynamic Mechanical Load	SML + DML + TC50 + HF30	<2.5% degradation
Thermal Cycling	TC600	<2% degradation
Ultraviolet-Induced Degradation	UV220	<2% degradation

BACKSHEET ULTRAVIOLET DURABILITY TEST (BUDT)

RETc's Thresher Test program incorporates a durability testing sequence to probe glass-on-backsheet PV module designs for vulnerabilities to UV exposure and prevent backsheet-related failures. This BUDT sequence starts with 1,000 hours of damp heat exposure to weaken polymeric bonds. Subsequently, test samples are exposed to three consecutive rounds of rear-side UV exposure, followed by 50 thermal cycles and 10 humidity-freeze cycles. This Thresher Test sequence improves new product designs and project reliability by screening unreliable or incompatible backsheet materials out of the market before they make it into the field.

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

BUDT* HIGH ACHIEVERS	
Manufacturer (in alphabetical order)	
JA Solar	
LONGi Solar	
SolarSpace	

*Applies to glass-on-backsheet models only.

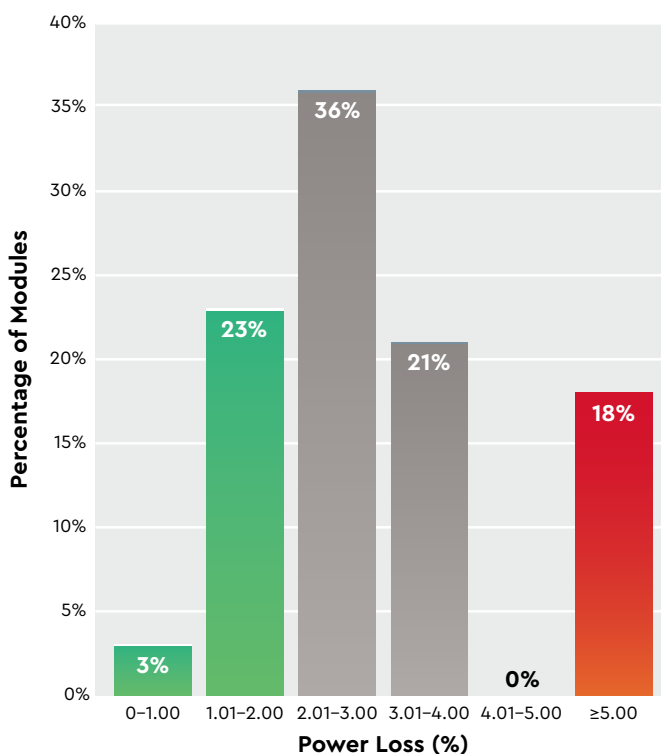
For test category high achiever recognition in the 2024 *PV Module Index Report*, RETc required that all glass-on-backsheet PV module models withstand BUDT exposure without cracking occurring in the polymeric material. We considered evidence of backsheet cracking during visual inspection to be a red-flag result in this sequence because it presents a potential electrical safety hazard. Early results, aggregated here in our preliminary June 2024 report release, are promising, with 100% of test samples meeting our high achiever requirements for BUDT. We will incorporate additional BUDT data into our final September 2024 report release. Note that glass-on-glass module designs, which provide a superior level of UV resistance and PV cell protection, are not subject to the BUDT sequence.

DAMP HEAT (DH)

RETc's Thresher Test includes a DH testing sequence to characterize a PV module's ability to withstand prolonged exposure to humid, high-temperature environments. This sequence takes place inside an environmental chamber and exposes modules to a controlled temperature of 85°C (185°F) and a relative humidity of 85% for a set amount of time. The DH sequence for the Thresher Test has a 2,000-hour duration of exposure (DH2000), which is twice the duration typically required for product certification (DH1000). Subsequently, samples undergo a modified boron-oxygen light-induced degradation (B-O LID) test, as B-O LID can impact certain p-type passivated emitter rear contact (p-PERC) and other advanced PV cells.

Reviewing the aggregated data in this testing sequence, RETc notes that newer high-efficiency PV module technologies appear more susceptible to damp heat as compared to more mature aluminum back surface field (Al-BSF) PV cell technologies. Moreover, these vulnerabilities seem to be increasing over time. This downward trend indicates that module companies must pay better attention to DH test results when qualifying new products for market entry. In double-glass module designs, for example, it is a

DH SEQUENCE



DH SEQUENCE HIGH ACHIEVERS

Astronergy, ES Foundry, LONGi Solar, Runergy, and Trina Solar met our DH test category high achiever criteria.

DH KEY TAKEAWAYS

- DH results trended downward on a year-over-year basis..
- 26% of models tested met DH high achiever criteria.
- 18% of models tested returned a DH red-flag result.
- 5 different manufacturers recognized as DH high achievers.

best practice to use double layers of polyolefin elastomer (POE) encapsulant, as research has shown that single or double layers of ethylene vinyl acetate (EVA) can lead to corrosion due to acetic acid buildup in the field.

With Al-BSF technologies, which still dominated the market as recently as 2018, rear-side aluminum acted as a barrier that helped mitigate moisture-driven damage. Today's market share leader, p-PERC solar cell technology, is more susceptible to damage due to moisture as compared to legacy Al-BSF cells. Meanwhile, the newer high-efficiency cells growing in market share—such as n-type tunnel oxide passivated contact (n-TOPCon) and n-type silicon heterojunction (n-HJT) technologies—are more susceptible than p-PERC to voltage-driven degradation and electrochemical corrosion from moisture ingress.

For the test category high achiever recognition in the *2024 PV Module Index Report*, RETC required that test samples withstand DH2000 exposure with less than 2% degradation in maximum power. We considered maximum power degradation greater than or equal to 5% a red-flag result that could compromise a product's ability to perform reliably over a 25- or 30-year period. Concerningly, 18% of models returned a red-flag result in this sequence.

HAIL DURABILITY TEST (HDT)

Within the context of the Thresher Test program, the HDT is an optional rather than a core sequence. However, recent catastrophic loss events indicate that beyond-certification testing is required to ensure that large-scale solar projects can withstand severe weather events over a 25- or 30-year project life. This is especially true for projects deployed in hail-prone locations, including Texas and other high-growth solar markets in the United States.

Virtually all PV module designs are unscathed by the basic ballistic-impact tests found in IEC certification standards. To pass IEC 61215-2, a module design must withstand 11 impacts of 25-mm (1-in.) ice balls traveling at their terminal velocity,

HDT HIGH ACHIEVERS

Manufacturer (in alphabetical order)

JA Solar

LONGi Solar

which results in a modest kinetic impact energy of 2 joules. While these minimum pass-fail test criteria served the industry well for decades, they have not prevented catastrophic loss events in large-scale projects deployed in hail-prone regions.

To address this gap, RETC's HDT sequence expands upon existing IEC standards to probe vulnerabilities to glass breakage and cell cracking and classify products based on severe hail resilience. This sequence exposes modules to 45-mm diameter (1.8-in.-diameter) freezer iceball impacts, followed by 50 thermal cycles and hot-spot endurance testing per IEC 61215. Final characterization includes visual inspection, electroluminescence testing, and maximum power measurements.

For test category high achiever recognition in the *2024 PV Module Index Report*, RETC required that HDT samples withstand an effective kinetic energy of at least 20 joules while achieving a Class A rating for hail durability. A Class A hail classification indicates that a test sample experienced less than 1% maximum power degradation upon completion



of the HDT sequence without incurring significant visual abnormalities or defects. Modules with fully tempered front glass generally outperform those with heat-strengthened front glass in the HDT sequence.

Because the hail durability test is an optional sequence within the Thresher Test program, RETC did not establish a red-flag threshold in this category. Having said that, catastrophic financial losses to fielded projects resulting from severe hail are clearly a warning sign to the entire industry. To avoid a crisis of confidence, solar projects must be resilient to normal conditions of use. A reliable bulk power system requires durable PV modules and solar assets.

To better assist industry stakeholders with product design and qualification, RETC is working with leading subject matter experts to develop a new and vastly improved hail-impact-characterization testing standard. This new standard will test modules to failure using synthetic hailstone proxies, characterizing impact resilience according to a highly granular staircase methodology. The resulting information-rich hail resiliency curves will improve the fidelity and accuracy of state-of-the-art financial hail risk models that technical advisers, such as VDE Americas, use to inform site selection and product specification to prevent catastrophic module field failures and project financial losses.

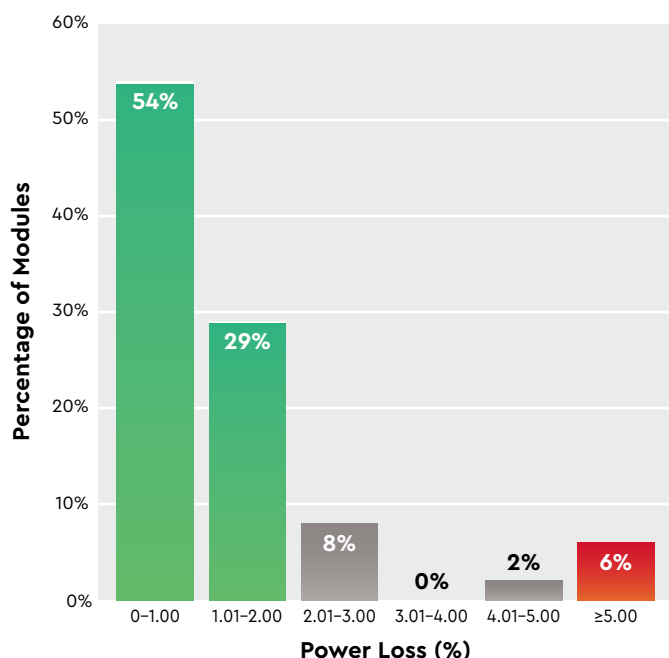
POTENTIAL-INDUCED DEGRADATION (PID)

RETC's Thresher Test includes a PID testing sequence to characterize a PV module's ability to withstand degradation due to shunting (PID-s) and surface polarization (PID-p). This sequence 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. The Thresher Test PID

sequence calls for a 192-hour duration of exposure (PID192), double that required for product certification (PID96).

PID risks vary according to cell technology. Traditional Al-BSF technologies are at risk of PID-s. New high-efficiency cell technologies (such as p-PERC, n-TOPCon, and n-HJT) are vulnerable to both PID-s and PID-p. While some amount of PID is reversible with UV light exposure, NREL has shown that this recovery is not field representative. As a result, we expect that the rear-side post-PID UV light soak step will be removed from both the IEC 61215 standard and the Thresher Test.

PID SEQUENCE



PID SEQUENCE HIGH ACHIEVERS

Astronergy, ES Foundry, GEP VN, Gstar*, JA Solar, LONGi Solar, Qcells*, REC Solar, Runergy, SEG Solar, Silfab Solar, SolarSpace, Talesun, Trina Solar, VSUN Solar, and Yingli Solar* met our PID test category high achiever criteria. (*Positive bias only.)

For test category high achiever recognition in the 2024 *PV Module Index Report*, RETC required that PV module models withstand PID192 exposure with less than 2% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 5% a red-flag result. While the percentage of red-flag results was relatively low (6%), PID results have trended downward on a year-over-year basis due to PID-p in n-TOPCon and n-HJT technologies.

PID KEY TAKEAWAYS

- 83% of models tested met PID high achiever criteria.
- 6% of models tested returned a PID red-flag result.
- 16 different manufacturers were PID high achievers.

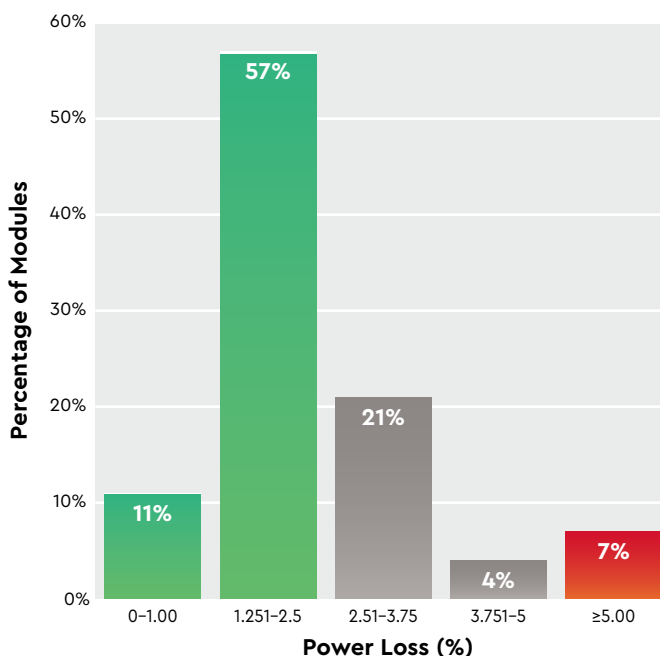
STATIC & DYNAMIC MECHANICAL LOAD (SDML)

The Thresher Test includes an SDML sequence to characterize a PV module's ability to withstand transportation stressors, snow and ice loads, and dynamic push-pull loads associated with hurricanes, typhoons, and other high-wind events. After static mechanical loading, dynamic mechanical loading subjects PV modules to 1,000 cycles of +1,000 pascal (Pa) 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 HF30 testing. Measurements taken upon completion capture post-SDML performance characteristics.

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

For test category high achiever recognition in the 2024 *PV Module Index Report*, RETC required that PV module models withstand SDML exposure with less than 2.5% degradation in maximum power. At the other end of the spectrum, we

SDML SEQUENCE



SDML SEQUENCE HIGH ACHIEVERS

Aptos Solar, Astronergy, ES Foundry, Gstar, JA Solar, LONGi Solar, Runergy, Silfab Solar, SolarSpace, Trina Solar, and Yingli Solar met our SDML test category high achiever criteria.

considered maximum power degradation greater than or equal to 5% to be a red-flag result. In this testing category, we note that 68% of samples qualified as high achievers whereas 7% returned red-flag results.



SDML KEY TAKEAWAYS

- 68% of models tested met SDML high achiever criteria.
- 7% of models tested returned an SDML red-flag result.
- 11 different manufacturers were SDML high achievers.

THERMAL CYCLING (TC)

The Thresher Test includes a TC testing sequence to characterize a PV module's ability to withstand stresses associated with diurnal and annual temperature fluctuations. This sequence calls for cycling modules in an environmental chamber between two temperature extremes—85°C (185°F) on the high end and -40°C (-40°F) on the low end. The Thresher Test calls for a 600-cycle TC sequence (TC600), triple that required for product certification (TC200). The goal of TC testing is to probe module designs for thermal fatigue failure modes, ensuring a long operational lifetime. TC sequence results are especially relevant for project deployment in operating environments characterized by wide diurnal-to-nocturnal temperature swings.

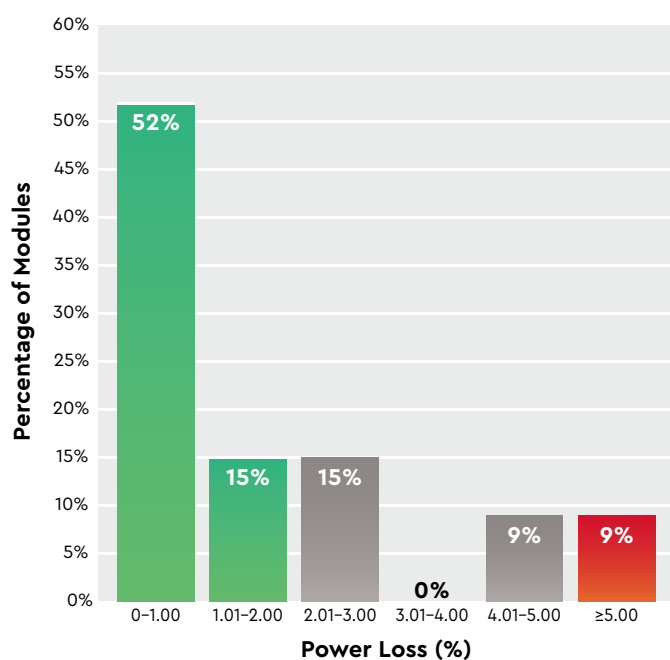
Historically, a best PV module design practice for TC resilience was to use all-silver paste and lead-based soldering. As the industry switched from all-silver pastes to silver-aluminum-based ones and, in some cases, unleaded solder coatings, researchers and testing laboratories have noted some variations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



the amorphous silicon layer(s). All else being equal, p-PERC and n-TOPCon tend to perform reasonably well in the TC sequence, though perhaps not as well as traditional Al-BSF cell technologies. Having more busbars on the PV cells tends to lead to better TC results, assuming the pastes and solder coatings are robust.

For test category high achiever recognition in the 2024 *PV Module Index Report*, RETC has required that PV module models withstand TC600 exposure with less than 2% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 5% a red-flag result. In this test category, we note that 67% of samples qualified as high achievers whereas 9% returned red-flag results.

TC SEQUENCE



TC SEQUENCE HIGH ACHIEVERS

Aptos Solar, Astronergy, ES Foundry, Gstar, JA Solar, LONGi Solar, Qcells, Runergy, SolarSpace, Trina Solar, and Yingli Solar met our TC test category high achiever criteria.

TC KEY TAKEAWAYS

- 67% of models tested met TC high achiever criteria.
- 9% of models tested returned a TC red-flag result.
- 11 different manufacturers were TC high achievers.

ULTRAVIOLET-INDUCED DEGRADATION (UVID)

The Thresher Test includes a UVID testing sequence to characterize a PV module's ability to withstand ultraviolet-induced degradation. This optional testing sequence exposes test samples to 220 kWh/m² of UV exposure (UV220), nearly 15 times the UV exposure required for product certification (UV15). For context, UV15 equates to roughly 70 days of field exposure, meaning that UV220 approaches 2.8 years of UV exposure in the field. The latter is notably still well within the wear-in period of the Weibull bathtub curve that basic PV module certification testing is intended to cover.

In the 2022 edition of the *PV Module Index Report*, RETC noted that some new cell technologies—most notably, n-TOPCon—appeared susceptible to UVID. To test the potential for UV degradation in novel cell technologies, we worked with technical subject matter experts at NREL and elsewhere to develop a rigorous beyond-certification UVID testing sequence. The initial results of our study indicate there is indeed cause for alarm. The level of UVID susceptibility in commercial PV cell technologies merits industrywide discussion and dialogue.

Specifically, surface passivation and antireflective coating dielectric layers in p-PERC, n-TOPCon, and n-HJT cell technologies appear susceptible to permanent and irreversible breakdown under UV exposure. This effect happens and reaches saturation during the first few years of operation, when predictable investor returns are most critical. Notably, the effect signature is indicative of short-circuit current and open-circuit voltage degradation rather than fill factor degradation.



UVID KEY TAKEAWAYS

- UVID is a high risk in new PV cell technologies and irreversible under normal field conditions.
- 40% of models tested met UVID high achiever criteria.
- 40% of models tested returned a UVID red-flag result.
- 10%–16% degradation was noted in some products, and both sides degraded.

For Thresher Tests conducted between Q2 2023 and Q1 2024, RETC did not require that manufacturers submit samples for the UVID sequence. However, many module companies elected to do so voluntarily. For test category high achiever recognition in the 2024 *PV Module Index Report*, we required that PV module models withstand UV220 exposure with less than 2% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 5% a red-flag result. Trina Solar and VSUN Solar met our test category high achiever criteria.

In the UVID category, we note that 40% of samples qualified as high achievers, while 40% of samples returned red-flag results. Alarming, we observed double-digit power loss in some mass-produced, commercially available PV modules, indicating that these products could degrade 10%–16% in the first three years of in-field operation. A double-digit degradation in maximum power would far exceed the allowable limits found in module warranty terms and PV system power guarantees.

Without immediate and collective action, UVID has the potential to become a major reliability issue for industry stakeholders. To do its part, RETC is now requiring the UVID sequence as a core component of its Thresher Test program. We also support industry efforts to include UVID as an input to the energy simulations that inform solar project financial models. Industry stakeholders may need to consider whether a reduction in module nameplate ratings is required to account for this degradation mode, similar to the early-onset degradation deratings applied to some thin-film technologies.

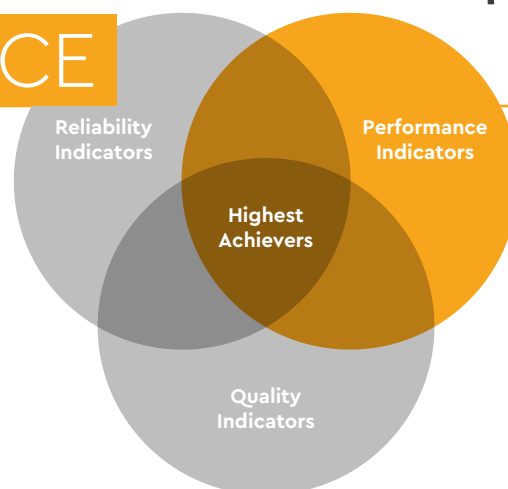
MODULE PERFORMANCE

A bankable solar project financial pro forma relies on independent third-party PV module performance characterization.

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

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

As a highly accredited provider of product certification and bankability testing, RETC plays an essential role in PV performance characterization and optimization. Our laboratory and outdoor testing services help manufacturers identify cell-level degradation mechanisms and module-level failure modes



during product development. In parallel, our work assures owners, insurers, financiers, and independent engineers that mass-produced PV products will perform as expected during commercial operations. Our state-of-the-art testing laboratories use calibrated and certified equipment under audited and controlled conditions. Performance characteristics captured under these rigorous testing conditions represent the true measure of PV module performance.

PERFORMANCE INDICATORS & RESULTS

For the 2024 PV Module Index Report, RETC identified seven important performance evaluation categories. As summarized in the "Performance Discipline Criteria" table, the categories include specific extended testing sequences as well as important figures of merit. The source data in this discipline derive from either RETC's Thresher Test or our California Energy Commission (CEC) testing. Within individual categories, we recognize manufacturers of products that exceed thoughtfully calibrated performance indicator thresholds as test category high achievers. In the year-in-review section (p. 35), we further showcase manufacturers of products that consistently exceed our high achiever requirements in the performance discipline.

PERFORMANCE DISCIPLINE CRITERIA

Category	Evaluation Method	High Achiever
Module Efficiency	CEC testing	>21%
Incidence Angle Modifier	CEC or Thresher Testing	>88% at 70° AOI
Light- and Elevated Temperature-Induced Degradation	B-O CID + LETID486	<0.5% degradation
Light-Induced Degradation	Outdoor light soaking per IEC 61215-2	≤0.5% degradation
PAN File Characterization	IEC 61853-1 and Performance Ratio (PR)	>85% PR
PTC-to-STC Ratio	CEC testing	≥94%
Temperature Coefficient of Power	CEC or Thresher Testing	<0.3%/°C (abs)

MODULE EFFICIENCY

RETC captures PV module conversion efficiency data as part of its CEC testing for manufacturers. To qualify for various solar incentive programs around the United States, PV module models must be included on an eligible equipment list that the CEC maintains. Importantly, the CEC does not accept manufacturers' self-reported data. RETC is one of the accredited third-party laboratories most active in CEC testing.

Nominal module conversion efficiency is determined by dividing a product's nameplate maximum power rating under standard test conditions by its total aperture area. While conversion efficiency is a key figure of merit for PV modules, it is also in many cases a function of PV module cell technology. For example, the p-type passivated emitter rear contact (p-PERC) PV cells that are popular today offer improved initial efficiency at time zero as compared to legacy aluminum back surface field (Al-BSF) technologies. Meanwhile, n-type tunnel oxide passivated contact (n-TOPCon) and n-type silicon heterojunction (n-HJT) PV cell technologies provide manufacturers with a roadmap for even higher-efficiency product designs in the future.

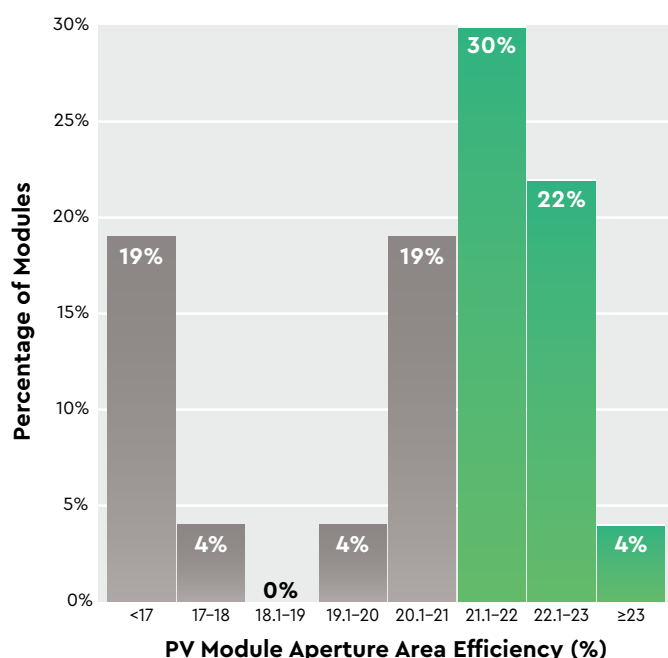
While conversion efficiency advancements provide value throughout the industry and contribute to the widespread adoption of solar energy, project stakeholders must remain diligent regarding performance risk. High conversion



efficiency in Year 0—or during a factory or laboratory flash test—is a meaningful metric only if it correlates with high efficiency over a 25- to 30-year operating life. As the red-flag results in the reliability section of this report have shown, ensuring that operating solar assets provide expected financial returns requires significant technical due diligence. Over the life of a PV power system, module conversion efficiency has as much to do with the materials that make up the module's laminate stack as it does with cell efficiency. Chasing high-efficiency solar cell designs is a fool's errand if device-level maximum power output degrades in the field due to material incompatibilities, poor-quality materials, or poor manufacturing processes related to the laminate stack.

In the *2024 PV Module Index Report*, RETC has recognized manufacturers of PV module models with conversion efficiencies greater than 21% as test category high achievers. This level of performance is indicative of sophisticated high-efficiency cell designs. We have not applied red-flag criteria in this category. In this testing category, we note that 56% of samples qualified as high achievers.

MODULE EFFICIENCY SEQUENCE



MODULE EFFICIENCY HIGH ACHIEVERS

Astronergy, Mission Solar, Qcells, REC Solar, and Silfab Solar met our module efficiency test category high achiever criteria.

MODULE EFFICIENCY KEY TAKEAWAYS

- 56% of models tested met efficiency high achiever criteria.
- 4% of models tested achieved $\geq 23\%$ efficiency.
- 5 different manufacturers were efficiency high achievers.

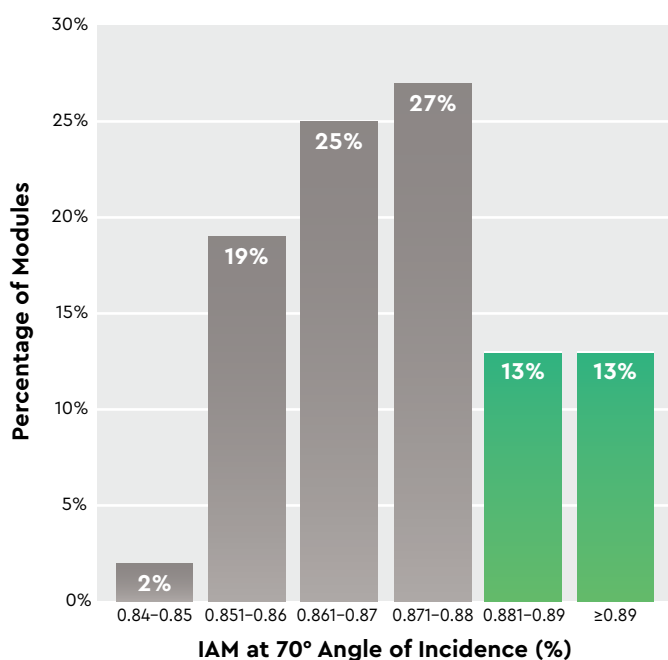
INCIDENCE ANGLE MODIFIER (IAM)

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

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

In the *2024 PV Module Index Report*, RETC has recognized manufacturers of PV module models with an IAM greater than

IAM SEQUENCE



IAM HIGH ACHIEVERS

Dehui Solar, ES Foundry, JA Solar, JinkoSolar, LONGi Solar, Meyer Burger, Qcells, Runergy, Silfab Solar, and SolarSpace met our IAM test category high achiever criteria.

IAM KEY TAKEAWAYS

- 27% of models tested met IAM high achiever criteria.
- 10 different manufacturers were IAM high achievers.

88% at a 70° angle of incidence (AOI) as test category high achievers. This level of performance is indicative of a low-loss optical design under typical conditions of use. We have not applied red-flag criteria in this category. In this testing category, we note that 27% of samples qualified as high achievers.

LIGHT- & ELEVATED TEMPERATURE-INDUCED DEGRADATION (LETID)

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

LETID HIGH ACHIEVERS

Manufacturer (in alphabetical order)
Astronergy
Gstar
JinkoSolar
LONGi Solar
Runergy
SEG Solar
Silfab Solar
SolarSpace
Talesun
Trina Solar
VSUN Solar
Waaree
Yingli Solar

LETID KEY TAKEAWAYS

- LETID results trended upward on a year-over-year basis.
- 82% of models tested met LETID high achiever criteria.
- 0% of models tested returned a LETID red-flag result.

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

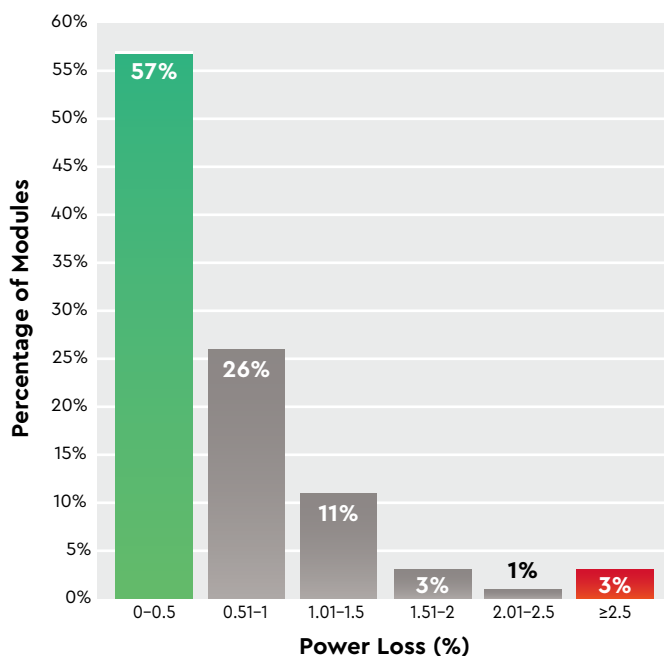
For test category high achiever recognition in the 2024 *PV Module Index Report*, RETC required that PV module models withstand B-O CID plus LETID486 exposure with less than 0.5% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 2.5% a red-flag result. In this testing category, we note that 82% of the test samples qualified as high achievers whereas 0% returned red-flag results.

LIGHT-INDUCED DEGRADATION (LID)

The Thresher Test program requires a LID sequence to investigate a product's susceptibility to light-induced degradation. LID is a type of degradation resulting from initial 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—ranging from a few hours to a few weeks, depending on the PV cell technology—before performance stabilizes. This LID test sequence consists of outdoor light soaking in accordance with IEC 61215-2.

LID affects advanced PV cell technologies. For example, LID risk is low in gallium-doped p-type PV cell technologies but high in boron-doped p-type PV cells. While manufacturers can use advanced hydrogenation processes to reduce B-O LID risk in boron-doped p-PERC cells, this introduces LETID

LID SEQUENCE



LID HIGH ACHIEVERS

Astronergy, GEP VN, Gstar, JA Solar, JinkoSolar, LONGi Solar, Meyer Burger, Qcells, Runergy, SEG Solar, Silfab Solar, SolarSpace, Talesun, Trina Solar, VSUN Solar, Waaree, and Yingli Solar met our LID test category high achiever criteria.

risks. So module designers need to balance B-O LID versus LETID risk exposure. Cadmium telluride thin-film devices and n-type PV cell technologies are not susceptible to LID.

For test category high achiever recognition in the 2024 *PV Module Index Report*, RETC required that PV module models withstand the LID sequence with less than or equal to 0.5% degradation in maximum power. At the other end of the spectrum, we considered maximum power degradation greater than or equal to 2.5% a red-flag result. In this testing category, we note that 57% of the test samples qualified as high achievers whereas 3% returned red-flag results.

LID KEY TAKEAWAYS

- 57% of models tested met LID high achiever criteria.
- 3% of models tested returned an LID red-flag result.
- 17 different manufacturers were LID high achievers.

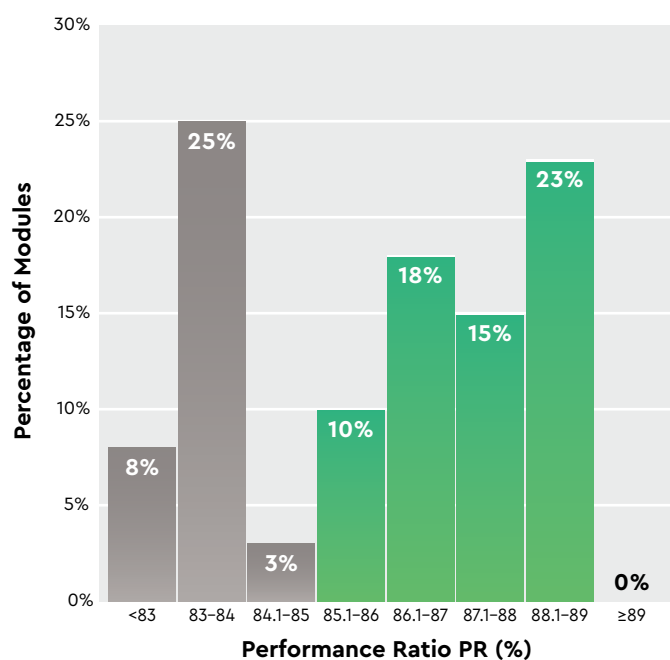
PAN FILE CHARACTERIZATION

PAN files are text-only software files that characterize PV module performance parameters in accordance with IEC 61853-1. RETC uses state-of-the-art equipment under controlled conditions to generate its third-party PAN files, which provide an independent and bankable characterization of PV module performance. These small files do a lot of heavy lifting in the context of the PV performance modeling used to inform project bankability assessments. Once imported into industry-standard software, such as PVsyst, these independently verified module-specific performance parameters allow for accurate and bankable energy production estimates.

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



PAN FILE SEQUENCE



PAN FILE HIGH ACHIEVERS

Astronergy, Gstar, JinkoSolar, LONGi Solar, Qcells, Runergy, SolarSpace, Trina Solar, VSUN Solar, and Yingli Solar met our PAN file test category high achiever criteria.

In the *2024 PV Module Index Report*, RETC has recognized manufacturers of PV module models that returned a performance ratio greater than 85% in our PVsyst simulations. We have not applied red-flag criteria in this category. Key drivers of PAN file performance include low-light performance and bifaciality factor. In this testing category, we note that 65% of the test samples qualified as high achievers.

PAN KEY TAKEAWAYS

- 65% of models tested met PAN file high achiever criteria.
- 23% of models tested achieved a >88% performance ratio.
- 10 different manufacturers were PAN file high achievers.

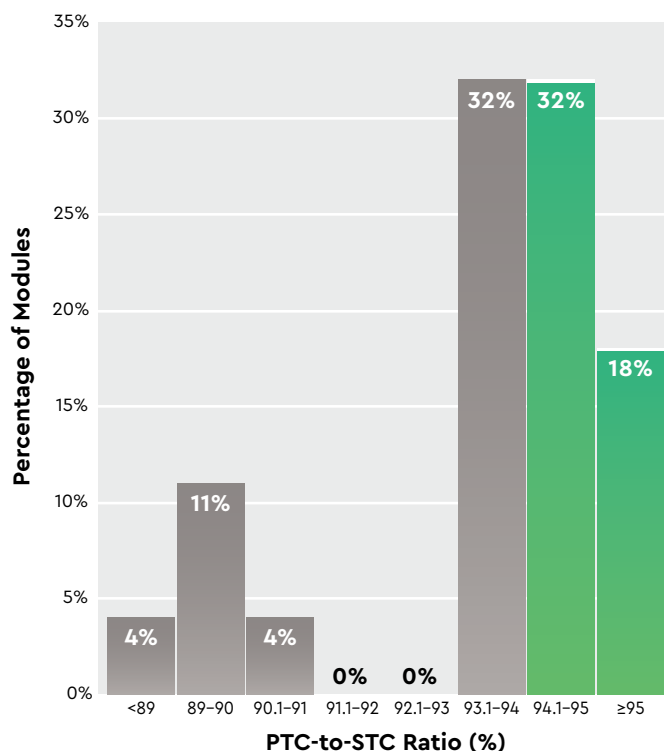
PTC-TO-STC RATIO

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

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

In the *2024 PV Module Index Report*, RETc has recognized manufacturers of PV module models that achieved a PTC-to-STC ratio greater than or equal to 94% as test category high achievers. We have not applied red-flag criteria in this category. In this testing category, we note that 50% of the test samples qualified as high achievers.

PTC-TO-STC RATIO SEQUENCE



PTC-TO-STC HIGH ACHIEVERS

Astronergy, Auxin Solar, Qcells, REC Solar, Silfab Solar, and Trina Solar met our PTC-to-STC ratio test category high achiever criteria.



PTC-TO-STC KEY TAKEAWAYS

- 50% of models met PTC-to-STC ratio high achiever criteria.
- 18% of models achieved a $\geq 95\%$ PTC-to-STC ratio.
- 6 manufacturers were PTC-to-STC ratio high achievers.

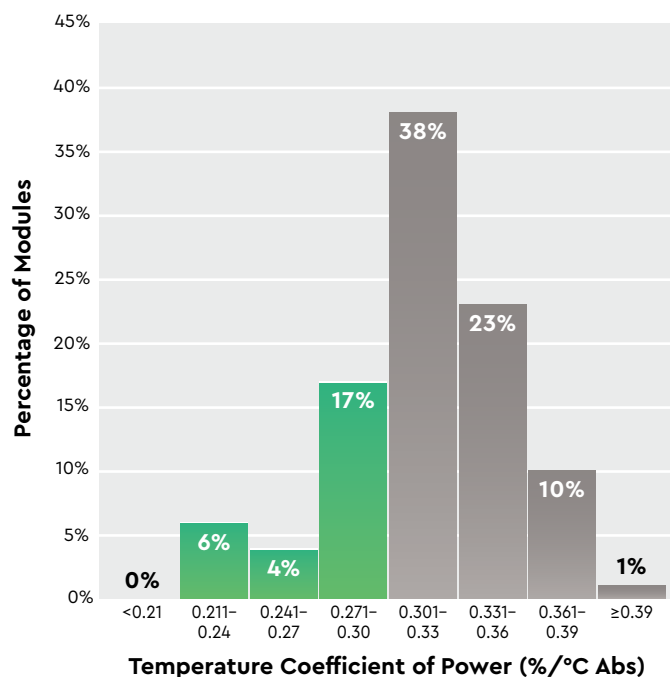
TEMPERATURE COEFFICIENT

RETC captures temperature coefficient data as part of the Thresher Test program or during its CEC testing for manufacturers. This performance characteristic accounts for changes in PV module maximum power, current, and voltage based on changing cell temperature conditions. Specifically, the temperature coefficient describes the percentage change in power for each degree Celsius ($\%/^{\circ}\text{C}$) relative to standard test conditions (25°C).

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

In the 2024 PV Module Index Report, RETC has recognized manufacturers of PV module models with temperature coefficient values less than $0.3\%/^{\circ}\text{C}$ (absolute) as test category high achievers. We have not applied red-flag criteria to temperature coefficient results. In this category, we note that 27% of the test samples qualified as high achievers.

TEMP COEFFICIENT SEQUENCE



TEMPERATURE COEFFICIENT HIGH ACHIEVERS

Astronergy, JinkoSolar, Meyer Burger, Qcells, REC Solar, Runergy, and Silfab Solar met our temperature coefficient test category high achiever criteria.



TEMPERATURE COEFFICIENT KEY TAKEAWAYS

- 27% of models met temperature coefficient high achiever criteria.
- 6% of models achieved a temperature coefficient $\leq 0.24\%/^{\circ}\text{C}$ (absolute).
- 7 manufacturers were temperature coefficient high achievers.

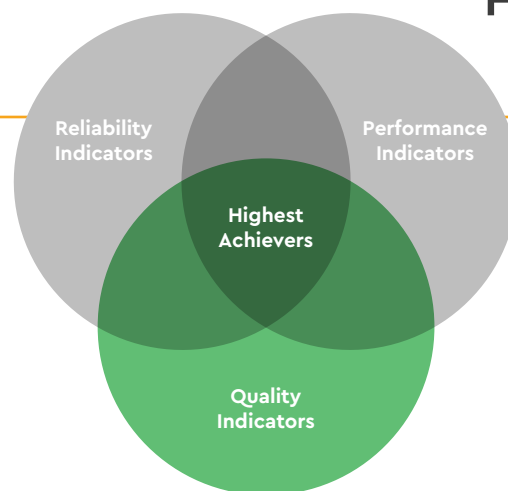
MODULE QUALITY

Sourcing high-quality PV modules optimizes energy yields, investor confidence, decarbonization benefits, and energy security.

To meet the expectations of solar project stakeholders, fielded PV modules and systems must withstand harsh operating conditions while meeting or exceeding performance predictions over a 25- to 30-year service life. Products and materials that appear very similar on paper may perform, wear out, or break down very differently under actual conditions of use. A commitment to quality often accounts for these differences.

Fielding high-quality PV modules is a complex and interconnected undertaking, especially in the context of a terawatt-scale market. A commercially viable product design must exceed beyond-certification bankability testing requirements. Module companies must manufacture such products at high volumes without any reduction in durability and performance. Inspectors and auditors must verify that factories are controlling quality in their supply chain management, material handling, and manufacturing processes. Accredited laboratories must analyze and test random product samples leaving the factory and arriving at the project site.

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



with third-party factory witness BOM verification, RETC's comparative Thresher Test program data helps to ensure that fielded projects meet the expectations of stakeholders by empowering them to discriminate between high- and low-quality products.

QUALITY INDICATORS & RESULTS

For the 2024 edition of the *PV Module Index Report*, RETC applied three evaluation categories for the quality discipline. As summarized in the "Quality Discipline Criteria" table, these categories include third-party factory BOM verification and cross-disciplinary reliability and performance evaluations. These criteria reflect the fact that commercial PV modules must excel in both reliability and performance to meet stakeholder expectations. A product's ability to meet user expectations is the ultimate measure of quality.

In the year-in-review section (p. 35), we celebrate manufacturers of products that check all quality discipline boxes as "Overall Highest Achievers." Note, however, that due diligence for project procurement is considerably more complex than simply entering into a supply agreement with a manufacturer we have recognized for high achievement in PV module manufacturing. Even the best module manufacturers sometimes make PV modules that underperform in Thresher Test sequences. Buyers who want to source high-quality BOMs and avoid low-quality ones should request a copy of RETC's Thresher Test report from the manufacturer.

QUALITY DISCIPLINE CRITERIA

Category	Evaluation Method
Bill of Materials	Third-party factory bill of materials verification
High Achievement in Reliability	Product recognized as high achiever in three or more reliability categories*
High Achievement in Performance	Product recognized as high achiever in three or more performance categories

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

RED FLAGS

Throughout the *2024 PV Module Index Report*, RETC has highlighted red-flag results for specific testing sequences. These red flags are measured values that raise questions about whether a product design can perform reliably in the field and meet stakeholder expectations over a 25- or 30-year lifetime. A red flag result in a specific testing sequence could be indicative of an immature cell technology, an incompatible BOM, a departure from quality during a manufacturing or assembly process, or an expected statistical variance in mass manufacturing.

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

RETC's summary data analysis comparing test category outcomes across this report indicates that individual test



samples are more likely to experience a red-flag result (14% of test samples) than to meet our "Overall Highest Achiever" standards (8% of test samples). These overall results underscore the importance of technical due diligence throughout the industry value chain. Achieving overall excellence in PV module manufacturing requires rigorous product design qualification and continuous quality management. Moreover, sourcing these high-quality products requires an adherence to best practices for product procurement.

SUMMARY DATA & RED FLAGS BY MODEL

PV Module Index Report Test Category	High Achievement		Red Flag	
	Threshold	Percentage	Threshold	Percentage
Backsheet Ultraviolet Durability	No cracking	100%	Backsheet cracking	0%
Potential-Induced Degradation	<2% degradation	83%	≥5% power degradation	6%
Light- and Elevated Temperature-Induced Degradation	<0.5% degradation	82%	≥2.5% power degradation	0%
Static and Dynamic Mechanical Load	<2.5% degradation	68%	≥5% power degradation	7%
Thermal Cycling	<2% degradation	67%	≥5% power degradation	9%
PAN File Characterization	>85% PR	65%	—	—
Light-Induced Degradation	≤0.5% degradation	57%	≥5% power degradation	3%
Module Efficiency	>21%	56%	—	—
PTC-to-STC Ratio	≥94%	50%	—	—
Ultraviolet-Induced Degradation	<2% degradation	40%	≥5% power degradation	40%
Temperature Coefficient of Power	<0.3%/°C (abs)	27%	—	—
Incidence Angle Modifier	>88% at 70° AOI	27%	—	—
Damp Heat	<2% degradation	26%	≥5% power degradation	18%
Hail Durability Test	>20-joule impact	17%	—	—
OVERALL	See p. 17	8%	—	14%

BILL OF MATERIALS (BOM) VERIFICATION

Holding PV modules to a higher standard by probing manufacturing and material quality is the fundamental concept behind our Thresher Test program. Basic IEC and UL certification tests focus primarily on ensuring performance and safety over the wear-in phase of the product's lifetime, meaning the first few years of outdoor operation. More rigorous testing is required to ensure PV modules can withstand the expected 25- to 30-year service life implied by modern PV module warranties. The Thresher Test—and the heuristic thresholds applied to its various testing sequences—are intended to identify high-quality module types and models, much as a thresher machine separates the wheat from the chaff.

Though beyond-certification testing is essential for identifying high-quality PV modules, it is only the first of many technical due diligence steps required to construct a long-lifetime solar project. After entering into a high-volume supply agreement, stakeholders must remain vigilant to deviations from quality product designs. This

BOM VERIFICATION HIGH ACHIEVER

Manufacturer (in alphabetical order)
Astronergy
ES Foundry
GEP VN
Gstar
JA Solar
JinkoSolar
LONGi Solar
Qcells
Runergy
SEG Solar
SolarSpace
Talesun
Trina Solar
VSUN Solar
Waaree
Yingli Solar



is the role of third-party factory BOM verification, which ensures that products delivered to the project site will continuously meet the high bar established by the rigorous Thresher Test.

As a placeholder for on-site sample witness and BOM verification, RETC has elected to recognize in the 2024 *PV Module Index Report* those manufacturers who used an independent third party to randomly select PV modules from inventory for the Thresher Test. Random sampling ensures that manufacturers do not cherry-pick only the highest-quality PV modules for the Thresher Test. This practice demonstrates that a module company is committed to transparency and has full confidence in its manufacturing quality programs.

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

—Cherif Kedir, RETC

A YEAR IN REVIEW

Analyzing our annual PV module test results, 8% of models tested met RETC's rigorous standard for our top accolade—namely, recognition as an "Overall Highest Achiever"—whereas 14% of models tested showed some sort of red flag.

In this preliminary June 2024 release of the *PV Module Index Report*, RETC has recognized 23 module manufacturers for some form of high achievement across the 14 different testing sequences included within the reliability and performance disciplines. To capture the results of any remaining long-duration testing sequences, we will publish a final report release in September 2024.

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

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

Based on a thorough review of these data and results, we have identified nine manufacturers that met our rigorous 2024 *PV Module Index Report* criteria for our "Overall Highest Achiever" recognition.



While we applaud high achievement in solar manufacturing, the red-flag results presented and discussed in this report demonstrate the importance of technical due diligence. After all, 75% more test samples returned a red-flag result (14% of models) compared to overall highest achiever results (8% of models). This discrepancy should be a red flag for underinformed buyers, owners, independent engineers, and investors. Without beyond-certification test data, you are more likely to procure modules that test poorly in one or more reliability or performance sequences than modules that excel across multiple disciplines.

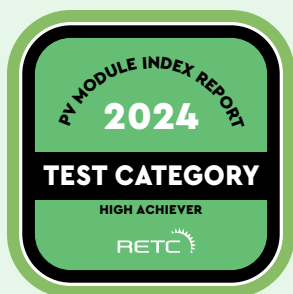
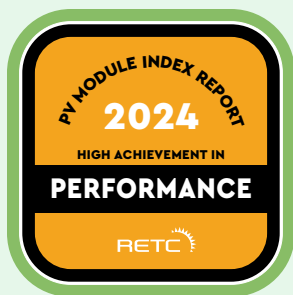
Representing an extreme downside scenario, one of the PV module models submitted to RETC for the Thresher Test last year returned red-flag results in both a reliability and a performance test sequence. Upon further investigation, we learned that these test samples had not come directly out of a factory but rather had been resold at a discount out of a warehouse, where they had been stored for an unknown period. This double red-flag result is a reminder that the bitterness of poor quality remains long after the sweetness of low price is forgotten. If a deal seems too good to be true, it usually is.

While outlier results make for excellent cautionary tales, industry stakeholders must also remain vigilant to pervasive and systemic problems, as these tend to be difficult to see in real time. As early as Q1 2022, RETC provided industry stakeholders with an early warning about the potential for ultraviolet-induced degradation in advanced n-type PV cells. Two years later, the industry at large has finally acknowledged that UVID is not only a real problem but also potentially a widespread one—and third-party testing laboratories around the world have largely adopted our UVID testing recommendations.

Novel technologies tend to degrade in novel ways. Collectively, we need to anticipate and test new products and technologies accordingly. As the solar market grows in scale and sophistication, industry stakeholders must remain vigilant regarding the technical risks inherent to an accelerated pace of change and the short time frames between innovation and mass production. As long as the solar industry continues to innovate and evolve, there will be a need for data-driven technical due diligence. Caveat emptor. Let the buyer beware.



2024 AWARDEES



In Alphabetical Order within Award Category

2024 SUMMARY OF RESULTS

RELIABILITY DISCIPLINE HIGH ACHIEVERS

BACKSHEET ULTRAVIOLET DURABILITY TEST (BUDT)

JA Solar • LONGi Solar • SolarSpace

DAMP HEAT (DH)

Astronergy • ES Foundry • LONGi Solar • Runergy • Trina Solar

HAIL DURABILITY TEST (HDT)

JA Solar • LONGi Solar

POTENTIAL-INDUCED DEGRADATION (PID)

Astronergy • ES Foundry • GEP VN • Gstar • JA Solar • LONGi Solar • Qcells • REC Solar • Runergy • SEG Solar • Silfab Solar • SolarSpace • Talesun • Trina Solar • VSUN Solar • Yingli Solar

STATIC AND DYNAMIC MECHANICAL LOAD (SDML)

Aptos Solar • Astronergy • ES Foundry • Gstar • JA Solar • LONGi Solar • Runergy • Silfab Solar • SolarSpace • Trina Solar • Yingli Solar

THERMAL CYCLING (TC)

Aptos Solar • Astronergy • ES Foundry • Gstar • JA Solar • LONGi Solar • Qcells • Runergy • SolarSpace • Trina Solar • Yingli Solar

ULTRAVIOLET-INDUCED DEGRADATION (UVID)

Trina Solar • VSUN Solar

PERFORMANCE DISCIPLINE HIGH ACHIEVERS

MODULE EFFICIENCY

Astronergy • Mission Solar • Qcells • REC Solar • Silfab Solar

INCIDENCE ANGLE MODIFIER (IAM)

Dehui Solar • ES Foundry • JA Solar • JinkoSolar • LONGi Solar • Meyer Burger • Qcells • Runergy • Silfab Solar • SolarSpace

LIGHT- AND ELEVATED TEMPERATURE-INDUCED DEGRADATION (LETID)

Astronergy • Gstar • JinkoSolar • LONGi Solar • Runergy • SEG Solar • Silfab Solar • SolarSpace • Talesun • Trina Solar • VSUN Solar • Waaree • Yingli Solar

LIGHT-INDUCED DEGRADATION (LID)

Astronergy • GEP VN • Gstar • JA Solar • JinkoSolar • LONGi Solar • Meyer Burger • Qcells • Runergy • SEG Solar • Silfab Solar • SolarSpace • Talesun • Trina Solar • VSUN Solar • Waaree • Yingli Solar

PAN FILE CHARACTERIZATION

Astronergy • Gstar • JinkoSolar • LONGi Solar • Qcells • Runergy • SolarSpace • Trina Solar • VSUN Solar • Yingli Solar

PTC-TO-STC RATIO

Astronergy • Auxin Solar • Qcells • REC Solar • Silfab Solar • Trina Solar

TEMPERATURE COEFFICIENT

Astronergy • JinkoSolar • Meyer Burger • Qcells • REC Solar • Runergy • Silfab Solar

QUALITY DISCIPLINE HIGH ACHIEVERS

BILL OF MATERIALS (BOM) VERIFICATION

Astronergy • ES Foundry • GEP VN • Gstar • JA Solar • JinkoSolar • LONGi Solar • Qcells • Runergy • SEG Solar • SolarSpace • Talesun • Trina Solar • VSUN Solar • Waaree • Yingli Solar

HIGH ACHIEVEMENT IN RELIABILITY

Astronergy • ES Foundry • Gstar • JA Solar • LONGi Solar • Runergy • SolarSpace • Trina Solar • Yingli Solar

HIGH ACHIEVEMENT IN PERFORMANCE

Astronergy • ES Foundry • Gstar • JA Solar • JinkoSolar • LONGi Solar • Qcells • REC Solar • Runergy • Silfab Solar • SolarSpace • Trina Solar • Yingli Solar

LOOKING AHEAD

With the emergence of novel PV cell technologies, the industry has entered a new realm of more complex I-V curve characterization.

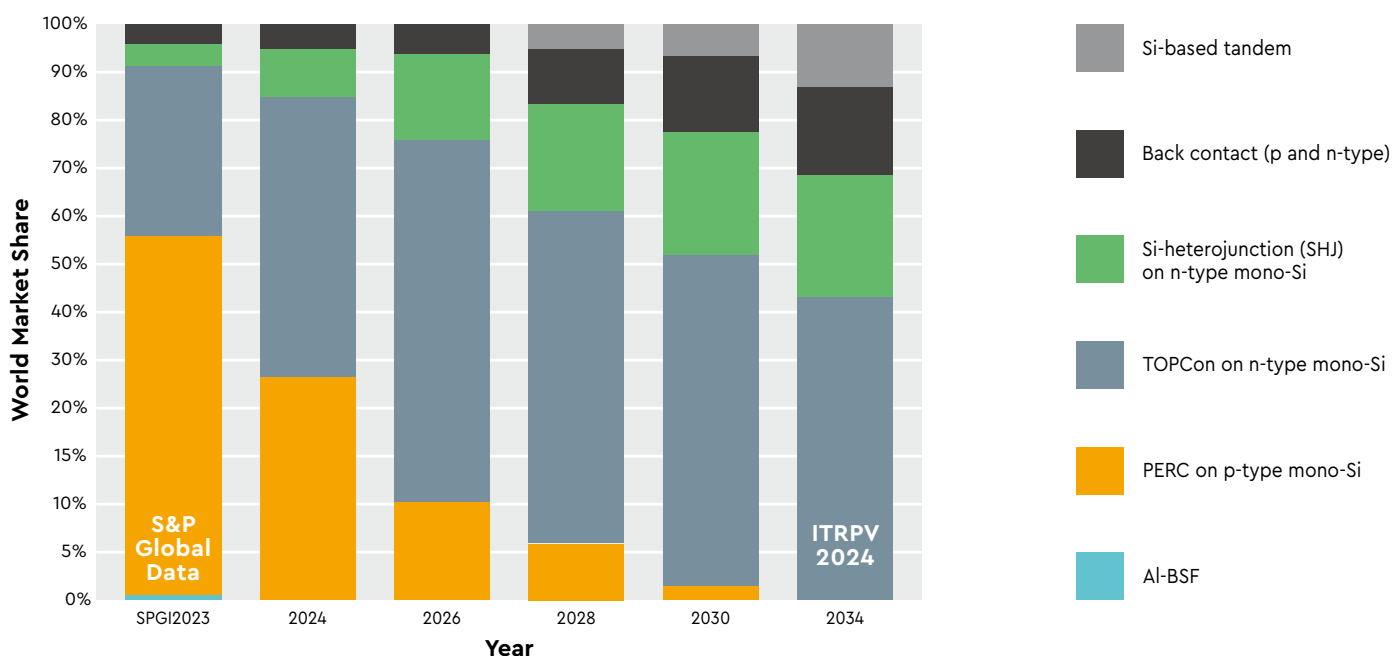
Industry analysts expect that the market share for advanced PV cell technologies—many of which are already in mass production—will rapidly increase over the next five to ten years. Broadly speaking, these emergent PV cell technologies are the result of developments in n-type wafer production and progress in surface passivation and back-contacting methods. These newer technologies include n-type tunnel oxide passivated contact (n-TOPCon), n-type back-contact (n-BC), n-type passivated emitter rear totally diffused (n-PERT), and n-type silicon heterojunction (n-HJT) PV cells. The most mainstream of these novel n-type technologies is the n-TOPCon cell.

In recent years, many module companies have evolved away from traditional aluminum back surface field (Al-BSF) technologies to higher efficiency p-type passivated emitter rear contact (p-PERC) PV cells. Today, manufacturers are converting p-PERC production lines into n-TOPCon lines. This is relatively easy to do, as p-PERC and n-TOPCon share many production processes.

Though it is tempting to view each new cell technology as an advancement over previous technologies, it is also true that novel cell technologies, especially those based on n-type cell designs, present interesting and unique measurement challenges.

Module characterization challenges include the power rating of advanced PV devices. There are many factors that affect the accuracy and uncertainty of power ratings for any PV module, regardless of cell type. However, equipment operators and technicians must adjust their flash-testing measurement and calibration procedures for advanced PV cell technologies to accurately measure power. The intent of these procedural changes is to address metastability issues, spectral mismatch, I-V corrections, device linearity, high capacitance, and hysteresis. Hysteresis and metastability are of particular interest to industry stakeholders, as both have the potential to contribute upward of 1%–2% to maximum power measurements, which are foundational to product benchmarking.

MARKET SHARE FOR DIFFERENT PV CELL TECHNOLOGIES



Data sources: S&P Global (2023); ITRPV 2024 (2024–2034).

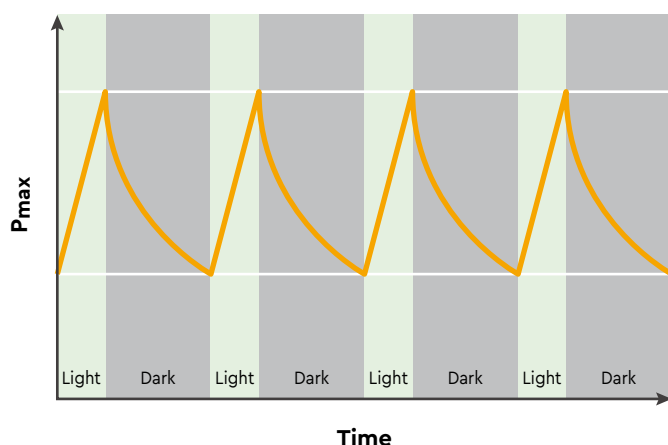
HYSTERESIS

The hysteresis phenomenon presents a challenge for accurate device power measurement of n-type silicon-based PV devices, which have high internal capacitance. During flash testing, this internal capacitance causes charge build-ups and internal delay effects in I-V measurements. Normally, solar simulator (flash tester) technicians use an actively controlled electrical load to measure the I-V curve of a PV module under simulated solar irradiance. Internal device capacitance can result in differences between the load voltage and the PV module output voltage during the sweep, causing hysteresis errors. With n-type PV modules, it is not always possible to fully eliminate the hysteresis effects using multi-slope or other non-linear (and sometimes proprietary) sweep algorithms. Measuring capacitance-free I-V curves requires new, custom test methods that produce stable current values across a range of voltages.

METASTABILITY

Metastability is another phenomenon that presents challenges for PV module characterization. Low-level light soaking can cause power measurements of n-type PV modules to increase by 1% to 2%. Researchers first documented this metastability issue in n-HJT modules, noting that short-circuit current (I_{sc}), fill factor, and maximum power ratings increased with light soaking and then gradually decreased under dark conditions. The fact that I_{sc} changes significantly makes it particularly challenging to work with technologically matched calibration modules. Calibration procedures typically start from a "known" calibrated I_{sc} value, such as I_{sc} at standard test conditions or some other irradiance setpoint. Technicians and operators must consider metastability whenever characterizing I-V curves for n-TOPCon or n-HJT PV modules.

METASTABILITY DEGRADATION & RECOVERY



High-precision and high-accuracy measurements are critical to the entire solar industry ecosystem and value chain.

CUSTOMIZATION

Working at the forefront of technological advancement and adoption, RETC has observed that a traditional one-size-fits-all module power measurement approach is obsolete. Emergent n-TOPCon and n-HJT PV modules are complex devices that require careful characterization—and, in most cases, some measurement customization. The same is true for next-generation Perovskite-based solar cells, not to mention cadmium-telluride thin-film devices. As the industry advances technologically, the measurement complexity required to achieve an essential level of accuracy is increasing. In many cases, additional test steps—such as light soak preconditioning to stabilize metastability in advanced silicon-based devices or annealing normalization in thin-film devices—are increasing the burden on testing laboratories.

High-precision and high-accuracy measurements are critical to the entire solar industry ecosystem and value chain. Researchers, manufacturers, and testing laboratories must now holistically optimize test methodologies—namely, preconditioning methods, flash recipe, spectral mismatch, and I-V correction procedures—on a technology-specific basis. Maintaining quality control requires updating standard operating procedures to capture technology-specific adaptations. Moreover, it is critical to maintain a complete calibration traceability chain and adhere to scientific measurement methods and principles.

To ensure a worthwhile future, RETC is involved in global round-robin efforts to improve the performance characterization of next-generation PV technologies. We are actively contributing to IEC project teams responsible for revising relevant solar product standards. Collaborating with colleagues within the VDE Group, we are writing and publishing new product standards that will improve fielded project resiliency and insurability. This cutting-edge work is foundational to the global power transition. It benefits solar industry stakeholders and all of the businesses and communities relying on clean power. After all, the success of future solar products and projects starts with precise, reproducible, and repeatable PV module performance measurements.



RETC (Renewable Energy Test Center) 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 systems (BESS), and racking assemblies. As a member of the VDE Group, RETC is helping to 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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