RETC

2023 PV Module Index Report

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A LETTER FROM OUR CEO

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

As RETC publishes its fifth annual *PV Module Index Report,* our work has never been more essential to securing a livable future. Tackling the global climate crisis via mass electrification and deep decarbonization requires massive solar investment, manufacturing, and deployment increases.

Deploying PV power systems at an unprecedented scale across ever-expanding geographies and policy environments using new products or technologies is not without risk—for manufacturers, developers, constructors, investors, and insurers. Looking back at 2022, industry stakeholders navigated supply chain disruptions, systemic inflation, trade investigations, equipment detentions, construction delays, premature field failures, production shortfalls, and severe weather losses.

The 2022 hail season in Texas underscores the challenges and risks facing solar industry stakeholders. According to multiple insurance industry reports, early summer hailstorms in the Lone Star State resulted in more than $300 million in solar project losses. *Power* magazine notes that these hail damages and losses were reportedly "more than twice as severe as other key renewable losses over the last three years combined."

Are these record losses the result of a 1,000-year hail season? Or are they representative of a new normal brought about by a changing climate? Without certainty on this front, insurers are decreasing or declining coverage for solar projects and markets exposed to elevated natural catastrophe risks. Unfortunately, this retrenchment will not eliminate the underlying risks.

Human-induced climate change is an existential threat on a global scale. However difficult it may be to face the challenges of the day on a given front, the climate crisis is a battle we cannot afford to lose. While solar project risks may occasionally seem severe, the risk of inaction—of doing too little too late—is exponentially greater.

In its *Net Zero by 2050* report, the International Energy Agency (IEA) charts a narrow pathway by which the world can avoid the worst effects of climate change. This pathway assumes that solar will become the energy sector's largest power source by the middle of the century. The IEA estimates that meeting this goal requires a twentyfold increase in solar capacity.

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 an independent testing laboratory with the highest level of accreditation, RETC enables data-driven approaches to product and project development, which mitigate sources of risk and uncertainty. These services benefit solar industry stakeholders and the businesses and communities that require reliable power systems.

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 momentous endeavor.

—Cherif Kedir, CEO, RETC

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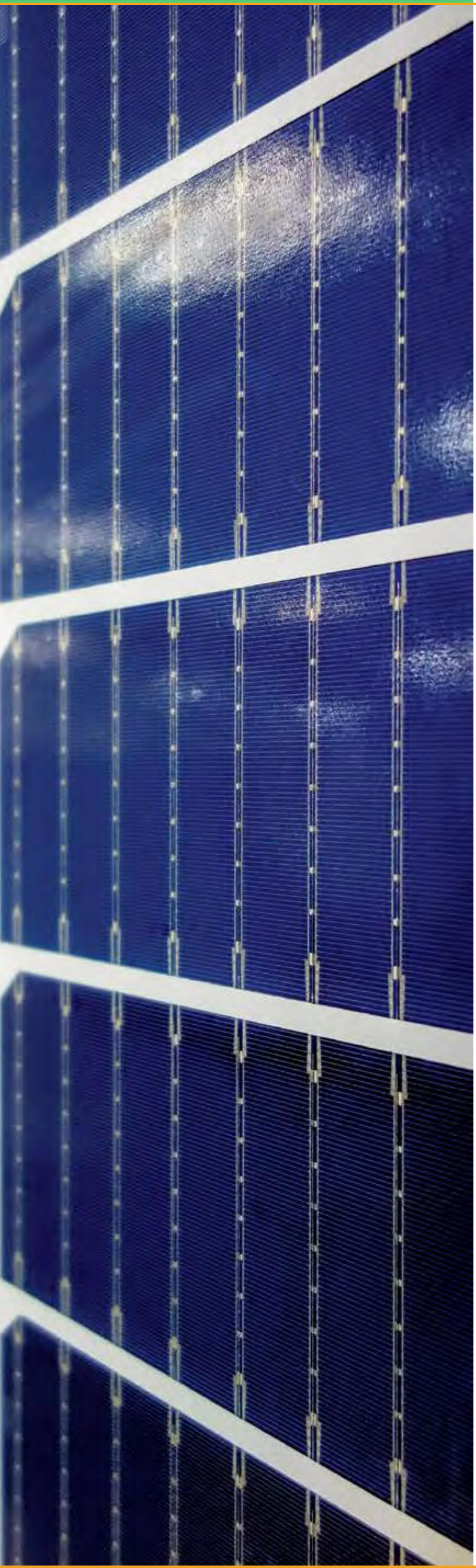

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ABOUT RETC

RETC (Renewable Energy Test Center) is a leading provider of engineering services and certification testing for renewable energy products. Since its founding in 2009, RETC has partnered with manufacturers, developers, and investors to test a wide range of products, including solar photovoltaic (PV) modules, racking, trackers, power electronics, and battery energy storage systems (BESSs). 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

By 2027, solar photovoltaic (PV) power could surpass coal to become the largest source of global electricity generation.

Spurred by global energy security concerns and climate risk mitigation goals, the International Energy Agency (IEA) expects the world to add as much renewable power generation capacity over the next five years as it did over the past two decades combined. These capacity additions will fundamentally transform the global power mix, with renewables becoming the largest source of global electricity generation by 2025.

Solar capacity additions will lead this worldwide energy transformation. As detailed in the IEA's *World Energy Outlook 2022* report, solar project commissioning will account for more than 60% of renewable additions over the next five years, nearly tripling PV power capacity globally. As early as 2027, cumulative solar generating capacity could surpass that of hydropower, natural gas, and coal.

This year's articles and interviews about industry trends explore some of the challenges and opportunities associated with unprecedented solar market expansion. We celebrate sustainable solar development success stories. We review the technical and market factors responsible for increasing solar-plus-storage integration. We highlight the promise and potential pitfalls of novel perovskite-based PV technologies. Lastly, we consider how hail loss events have reshaped the project insurance market.

RESPONSIBLY SCALING SOLAR DEVELOPMENT

The solar industry will play a prominent role in global efforts to mitigate the worst impacts of human-caused climate change. In its *Climate Change 2023* report, the United Nations' Intergovernmental Panel on Climate Change concludes that solar project deployment is the single best option for reducing the energy sector's greenhouse gas emissions. Meeting this moment is both a transformative business opportunity and a cause for reflection.

With great power comes great responsibility. By rising to the occasion, solar industry stakeholders can help save millions of lives, protect against widespread ecosystem collapse, and attract international investment. Doing so requires that the solar industry itself operate sustainably, which it can accomplish by minimizing its carbon footprint, mitigating its environmental impacts, promoting a circular economy, and fielding durable products and systems.

KEY TAKEAWAYS

- Supply chain decarbonization maximizes climate risk mitigation benefits.
- Sustainable land use benefits local communities and the environment.
- Recycling end-of-life equipment facilitates a circular economy.
- Durable products optimize resource utilization and investor returns.

"Proximity not only accelerates the speed of business but also facilitates transparency and decarbonization."

—Nick de Vries, Silicon Ranch

CARBON FOOTPRINT

Maximizing climate risk mitigation benefits while increasing global operations requires that the solar industry align business practices with climate change mitigation goals. The single most important metric of success on this front is reducing net greenhouse gas emissions. In other words, a rapidly expanding solar industry needs to minimize its growing carbon footprint.

Transporting solar modules and other essential supply chain components over long distances contributes to global warming and climate change. Locating manufacturing facilities closer to the point of use can significantly reduce greenhouse gas emissions. As an added benefit, onshoring and nearshoring manufacturing facilities and the ancillary supply chains supports local economies while reducing product delivery lead times and supply chain risks.

"We view all of our projects as an opportunity to distribute economic impact while minimizing embodied carbon," explains Nick de Vries, chief technology officer at Silicon Ranch, a Nashville, Tennessee–based solar project developer. "Today, we own and operate more than 2.3 GW of solar and have signed contracts to increase our portfolio to more than 5 GW nationwide. Part of what is unique about our business model is that we consider carbon when evaluating all products—modules, inverters, and trackers.

"In 2019, when Qcells opened its factory in Dalton, Georgia," de Vries continues, "we bought the first year of production. Why? Because this purchase agreement maximized local economic benefits while minimizing transit times to our Bancroft Station Solar Farm project. Proximity not only accelerates the speed of business but also facilitates transparency and decarbonization."

ENVIRONMENTAL IMPACTS

Sustainable land use is another way for the industry to facilitate a holistic transition to an increasingly solar-powered future. Environmentally conscious practices include relatively simple design adaptations, such as using terrain-following single-axis trackers that minimize topsoil disturbance and erosion. At an even deeper level, state-of-the-art regenerative energy practices and agrivoltaics offer meaningful opportunities for future solar project land use improvements.

The guiding principle behind regenerative energy is identifying and implementing solar development practices that restore and revitalize ecosystems. In other words, its goal is to improve soil, habitat, and biodiversity at solar project sites via strategic land management. This holistic approach enhances soil health, slowing water runoff and improving carbon capture capabilities. It also reduces long-term operating expenses.

Courtesy Silicon Ranch

"Before Silicon Ranch adopted regenerative land management practices," says de Vries, "we had issues with erosion and vegetation. As a result, we were spending a lot of money on civil repairs and vegetation management. We sometimes spent money twice to repair damages resulting from mowers or herbicide overspray.

"Serendipitously, we started development on a project in Georgia and had options to buy the land. We discovered that one of our neighbors was a world-renowned regenerative rancher, Will Harris of White Oak Pastures. After meeting Will and learning more about his approach to land management and soil health, we began to look at the land under our panels as a biological asset rather than as an operational liability. We realized we could integrate regenerative land management practices with solar power production and ultimately deliver better power plants. It was not only technically feasible but also made long-term economic sense when compared to conventional practices."

As solar expands into more rural areas, solar project developers increasingly encounter pushback from farmers and opposition from neighboring communities. Agrivoltaics—a nascent business model that seeks to colocate agricultural land uses with PV power generation—may one day ease these land use conflicts. Today's large-scale agrivoltaic projects generally incorporate sheep grazing or pollinator habitat. Early-stage commercial activities are also underway that combine elevated ground-mounted PV arrays with shade-tolerant row crop cultivation.

CIRCULAR ECONOMY

Equipment recycling and reuse are essential for fostering long-term industry sustainability and owning this narrative in the court of public opinion. Lazard's latest levelized cost of energy (LCOE) index estimates that passage of the Inflation Reduction Act (IRA) may drive the effective LCOE for some solar and wind projects to $0/MWh. In the face of this market advantage, the fossil fuel lobby is increasing its efforts to discredit renewables. A common refrain emanating from the chorus of climate change deniers is that end-of-life solar products generate "mountains of waste."

Though disingenuous, this anti-solar propaganda contains a kernel of truth. In its nascency, the solar industry did not generate waste at a scale adequate to support a specialized recycling ecosystem. Today, industry scale is no longer a bottleneck for recycling investments. Since its founding last year, startup Solarcycle has raised $37 million to scale up its proprietary solar module recycling capabilities.

"Our proprietary recycling technologies and processes can extract up to 95% of the high-value content from crystalline-silicon solar panels."

—Suvi Sharma, Solarcycle

"We currently have about half a billion solar panels installed in the United States," notes Suvi Sharma, Solarcycle's cofounder and CEO. "This number is large enough to support a profitable solar recycling business according to our statistical models. Three years ago, aging systems, manufacturing yield losses, shipping breakage, installation breakage, product warranty failures, weather damages, and repowering activities accounted for about half a million end-of-life solar panels in the United States. Today, that number is approaching 2 million—and will increase exponentially.

"Our proprietary recycling technologies and processes can extract up to 95% of the high-value content from crystalline silicon solar panels. We can then return materials such as silver, silicon, aluminum, copper, and glass back to the supply chain to make new solar panels. Recycling these raw materials makes solar more sustainable and scalable. Using recycled aluminum to make new panel frames, as an example, uses 95% less energy than frames made by mining virgin bauxite ore."

Reusing decommissioned solar equipment in good working order can support secondary markets while further improving sustainability. "Before we recycle operating equipment that the original owner deems end of life, it is important that we use it through the end of its working life," explains Kate Collardson, cofounder of SolarRecycle.org and senior manager of residential operations for Omnidian. "There are many options for selling or donating used solar materials. This option maximizes a product's useful life before permanent decommissioning, which is essential for our industry to be truly sustainable."

PRODUCT DURABILITY

Extending the useful life of solar products and projects is the most impactful way to improve industry sustainability. Product durability minimizes the frequency of repair and maintenance activities while reducing waste and conserving raw materials throughout the supply chain. In the process, it optimizes energy yields, financial performance, investor confidence, and decarbonization.

Imagine two functionally equivalent PV power systems installed adjacent to one another, both with the expectation of a 25-year operating life. In a low product durability scenario, the modules on Project A suffer from premature degradation and are replaced under warranty in Year 12. In a high product durability scenario, the modules on Project B degrade less than expected and remain in service until Year 50.

In the downside scenario, stakeholders must deploy modules twice to meet baseline performance expectations, limiting product availability for other sites. In the upside scenario, deferred decommissioning preserves modules for new project sites, which increases cumulative PV capacity and reduces net greenhouse gas emissions. In practice, the only difference between these very different outcomes might be a seemingly insignificant bill of materials (BOM) change—and the rigor of the project stakeholders' technical due diligence.

RETC's best-in-class testing and engineering due diligence serve, first and foremost, to mitigate project-level risks associated with product durability and asset performance. Benefits of this work accrue at the portfolio level, ensuring investment returns for project sponsors and insurers and an unimpeded flow of investment capital. By facilitating continued solar market growth, these products and services are foundational to efforts to promote energy security and effective decarbonization.

RISE OF SOLAR-PLUS-STORAGE SYSTEMS

Energy storage is foundational to collective efforts to avert a global climate crisis via electrification and decarbonization. To maintain power quality and system reliability, grid operators must continuously maintain a balance between generation sources and served loads. As variable renewable resources displace dispatchable fossil fuel plants as inputs to the bulk power system, energy storage deployments will provide system operators with a flexible new source of grid-firming capacity.

Today, this market trend is most evident in the United States, which leads the world in the adoption of battery energy storage systems (BESSs). According to American Clean Power's *Annual Market Report 2022*, cumulative BESS operating power capacity (MW) and cumulative energy storage capacity (MWh) increased by 80% and 93% respectively, last year, a record-setting upward trajectory. BESS integration in the United States is rising across all market segments—residential, commercial, and utility—and most fielded BESS capacity is colocated with solar.

BEHIND THE METER

California is ground zero for residential solar-plus-storage integration in the United States—accounting for 47% of the country's residential BESS installations in 2022—and a harbinger of things to come in other state markets. Due to generous net-energy metering policies and relatively high electricity rates, the Golden State has long been the country's top residential solar market. In recent years, solar-

KEY TAKEAWAYS

- Solar-plus-storage integration is rising across all U.S. market segments.
- Regulatory and tax policy changes are driving BESS adoption.
- Colocated BESSs supports higher renewable energy penetration levels.
- Rigorous testing programs mitigate technical, financial, and safety risks.

"Without batteries, the payback period for standard solar installations in California will double for most customers."

—Barry Cinnamon, Cinnamon Energy Systems

plus-storage integration has also increased as the state's grid resilience has suffered due to global-warming–induced wildfires and heatwaves, driving consumer demand for backup power.

Given the state's ambitious carbon neutrality goals and first-of-its-kind residential solar mandates for new construction, the California Public Utilities Commission's unanimous vote to eliminate net-energy metering confounded stakeholders in solar trade associations and environmental organizations. The state's new Net Billing Tariff slashes payments for solar exports.

"Under the Net Billing Tariff, solar customers get reimbursed for excess power at the 'avoided cost' rate, which is less than $0.05 per kWh—and often zero—during peak daytime generation hours," explains Barry Cinnamon, CEO of Cinnamon Energy Systems. "Without batteries, the payback period for standard solar installations in California will double for most customers. Adding one or more batteries increases up-front costs but recovers some savings from the loss of net metering by reducing solar exports and increasing self-consumption."

Though this regulatory change surprised many Californians, other high-penetration solar markets—such as Hawaii and Germany—have charted a similar course. By reducing the value of solar exports, California's new residential rate structure sends a strong price signal to the market in favor of zero-export self-consumption schemes that pair rooftop solar with behind-the-meter energy storage. Analysts expect the state's residential storage attachment rates to increase to over 80% by 2027—up from about 11% today—as companies such as Sunrun launch new hybrid solar-plus-storage product offerings.

IN FRONT OF THE METER

BESS adoption in the United States is also increasing in utility-scale applications. Wood MacKenzie estimates that the U.S. market installed 4.0 GW of grid-scale energy storage in 2022, accounting for more than 83% of new operating capacity across all market segments. While stand-alone storage installations account for some of these capacity additions, aggregated market data indicate that hybrid solar-plus-storage projects are increasing in popularity.

"In 2022, the market pivoted from pilot-stage storage projects with tens of MWhs of capacity to GWh-scale battery systems," says Bill Reaugh, head of power conversion technologies at engineering advisory firm VDE Americas. "We are currently supporting financing for roughly 3 GW of DC- and AC-coupled solar-plus-storage capacity scheduled to come online over the next 18 months. These systems are significantly larger than anything the industry has seen historically."

Over the next five years, analysts expect the U.S. market to deploy 60 GW of battery energy storage capacity in grid-scale applications. Changes to the U.S. tax code resulting from the passage of the Inflation Reduction Act (IRA) will drive these BESS additions. Specifically, batteries no longer need to be coupled with renewable generation such as solar or wind to qualify for the Investment Tax Credit (ITC).

"Before the IRA, energy storage was eligible for the ITC only if the system primarily used PV generation to charge the battery," Reaugh explains. "With the passage of the IRA, storage systems are eligible for a 30% ITC regardless of the energy source used to charge the batteries. Typical use cases for utility-scale solar-plus-storage projects include fixed-shape hedge applications, where the battery fills gaps in the solar power curve and extends its shoulders to help meet offtake agreement obligations, and more-traditional energy delivery power purchase agreements. Developers also install batteries in purely merchant market applications, where energy storage operates as an alternative to natural gas peaker plants for late afternoon duck curve mitigation or ancillary voltage and frequency control support services."

"With the passage of the IRA, storage systems are eligible for a 30% ITC regardless of the energy source used to charge the batteries."

—Bill Reaugh, VDE Americas

RISK MANAGEMENT

BESS adoption trends will shape project risk profiles in the coming years. The proliferation of new market entrants post-IRA will tend to increase supplier risk and bankability considerations. Operational risks will increase due to system and application complexity. Stored energy raises life and fire safety concerns. While these risks are manageable, the rate of technical change and innovation is daunting.

Solar-plus-storage system integration is considerably more complex than standard grid-tied PV power systems, requiring a battery, a battery management system, energy management software, and additional power electronics and monitoring. These products must not only work correctly but also work together. Components that perform well when tested individually may have issues when integrated with products from other vendors. The financial impacts of these reliability and availability problems are often consequential due to utility rate sensitivities when moving energy in time or dispatching power in parallel with a momentary spike in demand.

In addition to posing bankability and performance concerns, batteries also present unique safety considerations for owners and integrators. If a solar module or power optimizer fails, a corresponding amount of energy production is lost. When a battery goes into thermal runaway and fails, the fire hazards present a clear and present danger to persons and property.

As a highly accredited testing services provider, RETC works at the forefront of emerging technology markets and has seen these challenges firsthand. We are actively expanding our BESS testing capabilities, facilities, and throughput capacity to best support the next phase of the global energy transition. We will share lessons learned from these investigations in future technology reports.

PEROVSKITE-BASED PV TECHNOLOGIES

The adage that what has been done will be done again largely holds true for a terrestrial solar market dominated by crystalline silicon (c-Si) PV technologies. To date, only cadmium telluride (CdTe) thin-film modules, popularized by First Solar, have challenged the c-Si hegemony at scale, claiming roughly 5% market share worldwide and 40% in the U.S. utility sector. Emboldened by the promise of high module performance at low production costs, companies developing perovskite-based solar cells hope to deploy something new under the sun.

As an independent testing laboratory, RETC tests next-generation solar products and technologies to qualify product designs and provide value to market entry activities. Based on its unique and privileged perspective on the industry, RETC believes the event horizon for commercial solar products using perovskite-based materials may be nearer than some industry stakeholders realize. With that in mind, this article provides a technical primer and an overview of the disruptive market potential and potential pitfalls of perovskite-based PV modules.

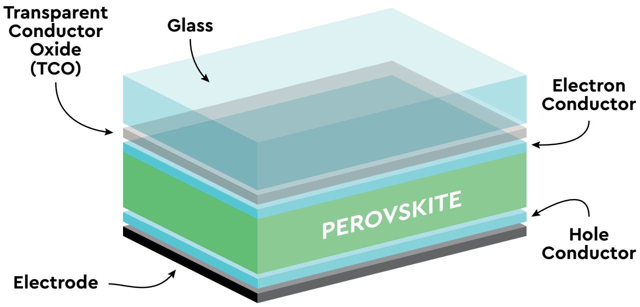
MATERIALS AND APPLICATIONS

Named after Russian mineralogist Lev Perovski, the term "perovskites" describes a class of chemical compounds with a crystalline lattice structure similar to that of naturally occurring calcium titanium oxide. As a semiconductor material, the mineral perovskite can absorb light and generate the photovoltaic effect. Perovskite compounds generally have a chemical formulation of ABX3, where *A* and *B* represent divalent and tetravalent cations and *X* is an anion that bonds to both.

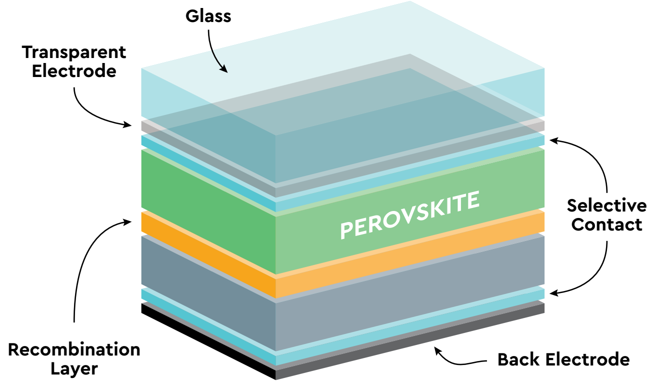
KEY TAKEAWAYS

- Next-generation thin-film technologies are nearing commercialization.
- Perovskites have multiple paths to market and disruptive market potential.
- Novel PV cell technologies can degrade and fail in novel ways.
- Beyond-qualification testing can mitigate emergent technology risk.

THIN-FILM PEROVSKITE SOLAR CELL



PEROVSKITE-ON-SILICON TANDEM SOLAR CELL



As a compound, perovskites offer excellent compositional flexibility, allowing for perovskite structures combined from many different atoms and molecules. This flexibility has made perovskites an exciting new field for material scientists, chemists, and physicists. Depending on the combination of elements, perovskite compounds offer different optical and electrical properties. There are many potential applications for synthetic perovskites, including X-ray detectors, lasers, nano-scale antennas, super-high-resolution displays—and solar cells.

Harnessing the tunability of perovskites, scientists have succeeded in creating semiconductor materials with properties akin to those of silicon. Halide perovskites have shown great promise for PV applications, offering excellent light absorption, photoexcitation properties, and charge-carrier mobility. Best of all, one can tune these materials for an ideal match with the spectrum of solar radiation.

MARKET OPPORTUNITY

Perovskite-based PV technologies fit the profile of an insurgent technology capable of disrupting the solar market as we know it today. Meeting the world's climate risk mitigation goals will require a rapid expansion in solar manufacturing capacity. To address energy security concerns and bolster regional economic benefits, policymakers in the United States and European Union are supporting clean energy investments at unprecedented levels. These market forces could help perovskites level up from research and development to commercialization.

The fundamental value proposition of perovskites in solar applications is multifaceted and undeniably compelling. In terms of performance, perovskite-only PV cells have rapidly evolved from conversion efficiencies of 3% in 2009 to almost 26% today. This unprecedented learning curve allows small-area perovskite hero cells to achieve efficiency levels that outperform those of other single-junction thin-film solar technologies. Moreover, manufacturers can combine thin-film perovskites with conventional c-Si PV cells. Record efficiencies for perovskite-on-silicon tandem PV cells surpass 33%.

Regarding manufacturability, perovskites are thin-film materials suitable for either vacuum deposition on a rigid base or roll-to-roll processing on a flexible base. Though continuous roll-to-roll processing is relatively novel in solar applications, manufacturers have long used this approach to produce photographic and chemical film. Perovskite fabrication at scale could one day look like newspaper printing, with affordable ink-like coatings ushering in a transformative era of terawatt-scale solar development.

"Part of what makes perovskites compelling is the streamlined supply chain," notes Brian Grenko, vice president of VDE Americas, a firm specializing in technical due diligence. "Consider all the steps required to make conventional crystalline silicon PV modules. We process silica at high temperatures to refine it into polysilicon, which is very energy intensive. We typically ship polysilicon over long distances to another manufacturing location where we remelt it in another high-temperature operation to form ingots, which are later sliced into wafers. Those wafers may be shipped to yet another facility for conversion into solar cells prior to PV module assembly.

"Roll-to-roll manufacturing would be revolutionary from a cost-per-watt standpoint—and it is not the only path to market for perovskites."

—Brian Grenko, VDE Americas

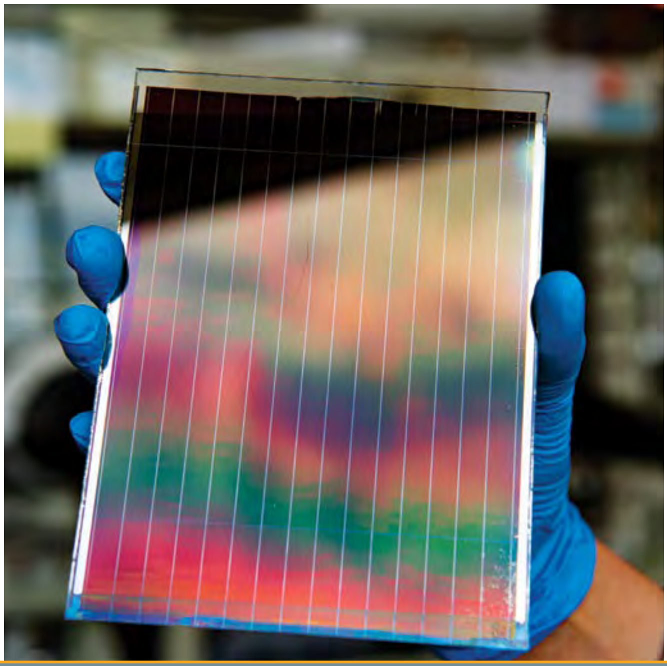
"Now imagine a perovskite-based PV module manufacturing process where raw materials enter one end of the factory and finished products exit the other. Roll-to-roll manufacturing would be revolutionary from a cost-per-watt standpoint—and it is not the only path to market for perovskites. Manufacturers are also working on innovative ways to deposit perovskites on silicon. With manufacturers nearing efficiency limits for conventional single-junction crystalline-silicon PV cells, tandem silicon-plus-perovskite cells are one way the industry can extend its existing technology roadmap."

BANKABILITY CONSIDERATIONS

The path to commercial adoption for perovskite-based solar products poses meaningful technical challenges and performance risks. Compared to conventional PV cell technologies, perovskites are more susceptible to light-, temperature-, and voltage-induced degradation, presenting potential problems associated with long-term product durability. Some promising perovskite compounds include trace amounts of lead, adding environmental concerns associated with lead toxicity.

Beyond materials science considerations, perovskites present manufacturing challenges. Scaling from laboratory equipment and processes to high-volume commercial operations is inherently difficult. Doing so with a novel cell technology while maintaining high conversion efficiencies in large-area product designs is even more challenging.

Courtesy Dennis Schroeder / NREL



"It's one thing to have a better, more efficient cell technology. Convincing customers to buy it is another thing."

—Benjamin Lemkau, RWE

"There is also a commercial aspect to new technology that makes it hard to integrate," says Benjamin Lemkau, senior director of solar PV systems technology for RWE. "It's one thing to have a better, more efficient cell technology. Convincing customers to buy it is another thing. Stakeholders sitting on the other side of the table from us are often very conservative. It's hard to sell a utility on a 25- or 30-year power purchase agreement using technology with limited history in the field."

RETC's expertise with beyond-qualification and bankability testing programs will be invaluable to scaling perovskite-based PV module technologies. On the one hand, product qualification standards—such as IEC 61215 for c-Si PV modules or IEC 61646 for thin-film modules—are an excellent way to identify design, materials, and process flaws already known to lead to premature field failures. On the other hand, minimum requirements will not characterize long-term field durability or performance. Moreover, minimum test standards are generally blind to as-yet-undiscovered field failure modes.

In a best-case scenario, today's minimum product qualification tests could characterize the durability of emerging PV cell technologies over a 5- to 7-year period. In a worst-case scenario, novel cell technologies could degrade or fail in novel ways within a shorter timeframe. Beyond-qualification testing, by contrast, uses highly accelerated extended test sequences to probe for known and unknown wearout mechanisms and failure modes. As such, RETC's Thresher Test—so named for its ability to separate the wheat from the chaff—can help manufacturers and project stakeholders characterize the long-term durability and performance of next-generation perovskite-based PV cells and modules.

HAIL RISK AND SOLAR PROJECT INSURANCE

The insurance industry is the proverbial canary in the coal mine when it comes to climate risk. A century ago, caged canaries provided miners with an early warning that carbon monoxide or other toxic gases were present in harmful quantities. Today, insurance market destabilization is an early indication that carbon dioxide emissions are intensifying severe weather events and increasing climate risk to natural ecosystems and human economies.

Demonstrating the scale of insurance market instability, two top property and casualty insurance companies in the United States—State Farm and Allstate—recently announced that they will no longer provide new home insurance policies in California. The reason for this abrupt pullback from the nation's most populous state is that eight of the 10 largest wildfires in state history have occurred since December 2017. Modeled attribution studies indicate that anthropogenic greenhouse gas emissions are the primary cause of the rising temperatures and declining precipitation fueling an increase in wildfire activity.

Insurance market destabilization is also taking place in Texas, a state whose solar market has national and international implications. Though best known for its oil and gas production and dubious distinction as the country's largest annual emitter of carbon dioxide, Texas is also a renewable energy powerhouse. The Lone Star State not only leads the country in terms of wind power capacity, but also is poised to overtake California as the top solar market. Whether the United States does its part to avert a global climate crisis could very well hinge on the solar industry's ability to weather Texas hailstorms—and insurers' ability to quantify hail risk in fielded assets.

RISK TRANSFER MISMATCH

For the better part of a decade, solar project development benefited from a soft insurance market characterized by low rates and generous terms and conditions. In mid-2019, a severe hailstorm in West Texas shattered this age of innocence when it crossed directly over a West Texas solar farm. The resulting insured losses exceeded $70 million—a previously unimaginable amount, which contributed to the onset of a hardened insurance market and increased the costs of renewable energy project insurance.

"This one hail event in Texas is not entirely responsible for the subsequent market shift," explains Sara Kane, practice

KEY TAKEAWAYS

- Widespread solar deployment is essential for mitigating climate risk
- Large losses in hail-exposed areas have destabilized insurance markets.
- Hail durability testing provides comparative product resiliency data.
- Probabilistic hail-risk assessments quantify financial exposure.

Courtesy Mike Olbinski

"Underwriters are looking to manage their aggregate exposure to natural catastrophe by limiting their capacity and increasing their pricing."

—Sara Kane, CAC Specialty

leader for power and renewables at insurance brokerage CAC Specialty. "But the event marks the inflection point to the more restrictive insurance terms and conditions that have been the norm for the past four years. Overnight, insurers began to reunderwrite their books, increasing prices and introducing restrictive sublimits and deductibles to keep pace with the losses."

In the wake of the 2022 hail season, the solar insurance in market went from hard to harder. According to insurance industry reports, severe hailstorms in Texas resulted in multiple loss events with cumulative solar project losses exceeding $300 million. Going into the year, it was difficult for brokers to find affordable insurance for projects in hail-prone regions. After these record losses, brokers are struggling to procure sufficient severe convective storm hazard insurance for hail-exposed solar projects at any price.

"After what happened in Texas last year, the challenges for sponsors and their brokers ramped up," says Kane. "Solar project development in hail-prone regions is not slowing down. In fact, the opposite is true, as we continue to see more and bigger hail-exposed projects coming to market. Due to recent loss events, banks want to see higher natural catastrophe limits, whereas insurers want to provide a lower limit.

"The mismatch between what project stakeholders would like to procure and what the insurance market is willing to provide leaves customers stuck in the middle. Banks are evolving in their considerations on how to quantify natural catastrophe risk, which is generally leading to increasing limit requirements. Meanwhile, underwriters are looking to manage their aggregate exposure to natural catastrophe by limiting their capacity and increasing their pricing. And our clients are stuck in the middle trying to negotiate and procure a limit that is affordable and acceptable to financing parties. As a brokerage, we help to guide all those discussions and negotiations."

PARAMETRIC INSURANCE

Some specialty insurance companies such as Descartes Underwriting offer parametric insurance products to help bridge the gap between the needs of traditional insurers and the finance community. Parametric policies pay out based on the occurrence of a specific event, such as severe hail. Moreover, payout amounts are indexed to a specific parameter, such as hailstone diameter.

"For severe convective storms, and hail in particular, we set up payout coefficients that correspond to specific hailstone diameters coupled with the amount of area impacted," explains Brenden Beeg, Descartes Underwriting's business development manager for North America. "As an example, 2.5-inch [63.5 mm] hail might pay out 25% of the limit at risk, which we then multiply by the impacted area percentage. As hailstone diameter increases, so does the payout percentage. So, 3-inch [76.2 mm], 3.5-inch [88.9 mm], and 4-inch [101.6 mm] hail might have payout coefficients of 50%, 75%, and 100%, respectively. The parameters and coverage amounts are highly customizable based on the client's needs."

In the wake of a qualifying hail event, parametric insurance providers use mutually agreed upon data sources—such as third-party weather data or on-site hail sensors—to quantify the magnitude of the parametric trigger. If the trigger value exceeds a predetermined threshold, the policyholder is entitled to a corresponding payout, independent of incurred losses.

"Parametric insurance is an extremely liquid kind of payout," notes Beeg. "In the traditional property market, insureds likely go through burdensome forensic accounting during the claims adjustment process, leading to a lengthy period of time before receiving a claims payout. This can result in a very frustrating experience in the wake of a catastrophic loss. Index-based insurance is much cleaner that way. Following a triggering event, money typically flows within 10 to 15 business days after the parties execute a simple loss declaration statement."

MITIGATING HAIL RISK

Deploying hail-resilient PV modules in hail-prone regions is an ideal way to mitigate a leading cause of severe weather losses. As a specialist in technical risk mitigation, RETC designed the industry's first commercial beyond-qualification test program for severe hail. Recognizing that virtually all PV module designs pass the basic ballistic-impact tests required for product qualification, RETC's Hail Durability Test (HDT) program exposes PV modules to impacts with higher kinetic energies.

By probing impact resistance at the threshold of damage, just over this threshold, and at the point of material failure, comparative HDT data can help project stakeholders differentiate PV product designs based on hail resilience and better understand real-world hail effects. As evidence, RETC recently conducted a statistical analysis of more than three years of HDT results—a data set that includes many different module sizes, power ratings, bills of materials, and manufacturers—analyzing the probability of module glass breakage as a function of effective kinetic impact energy.

The results in the accompanying data visualization characterize hail resilience for two standard crystalline silicon (c-Si) PV module packages: 1) 3.2 mm (0.13 in.) glass superstrate with a polymer substrate, and 2) 2.0 mm (0.08 in.) glass superstrate with a 2.0 mm glass substrate. These resiliency curves indicate that PV modules with 3.2 mm front glass over a polymer backsheet are roughly twice as resilient to hail impact as dual-glass modules with 2.0 mm glass. The delta between the two probability is largely a function of glass thickness and strengthening. Whereas 3.2 mm solar glass is usually *heat tempered,* 2.0 mm solar glass is often *heat strengthened* only, to control material costs.

"As the decision-makers on solar glass specification and procurement," says Cherif Kedir, president and CEO of RETC, "manufacturers are uniquely positioned to improve module hail resilience. Companies selling or buying hail-resistant products can use our HDT program to quantify module hail resilience. These differentiated products can mitigate financial risk in Texas and other locations that experience severe convective storms."

"Our engineering advisory services can help owners and developers understand financial risk exposure over a specific hold period."

—Jon Previtali, VDE Americas

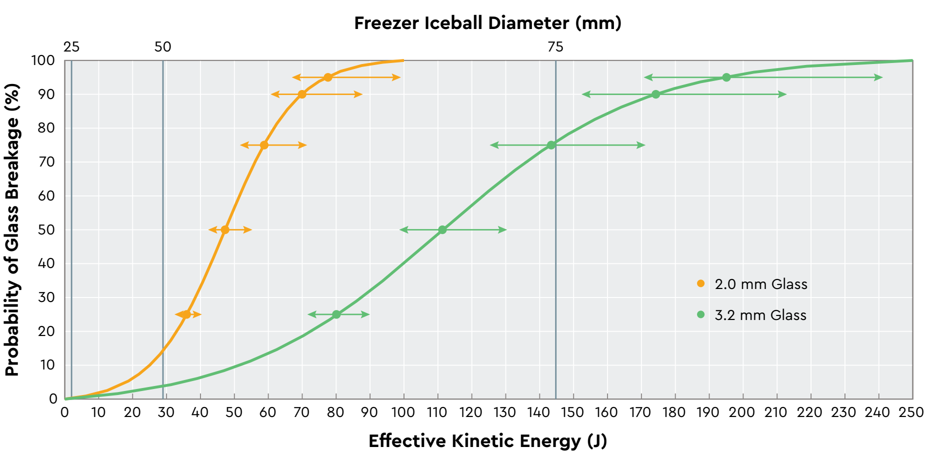
TAKING IT TO THE LIMIT

Using RETC's HDT data to identify and select hail-resilient modules, project stakeholders can significantly reduce financial risk exposure in hail-prone regions. Moreover, hail-risk mitigation specialists can use ballistic-impact resiliency data to inform probabilistic financial loss estimates.

"Quantifying a PV module's impact resistance is the first step toward a holistic understanding of hail risk in fielded assets," notes Jon Previtali, head of natural catastrophe consulting at engineering advisory firm VDE Americas. "It is equally important to quantify hailstorm frequency and severity at the specific project location, which requires novel risk assessment approaches. Hail risk is also a function of the tracker's defensive stow capabilities and the remote operation center's emergency response capabilities.

"Science- and engineering-based assessments account for all these variables and characterize hail risk at the local scale of a solar power plant. In addition to providing probable maximum loss and average annual loss estimates to facilitate insurance discussions, our engineering advisory services can help owners and developers understand financial risk exposure over a specific hold period. The results of these financial models are useful not only for characterizing the benefits of hail-resilient system design approaches, but also for determining reasonable insurance coverage terms and convective storm sublimits."

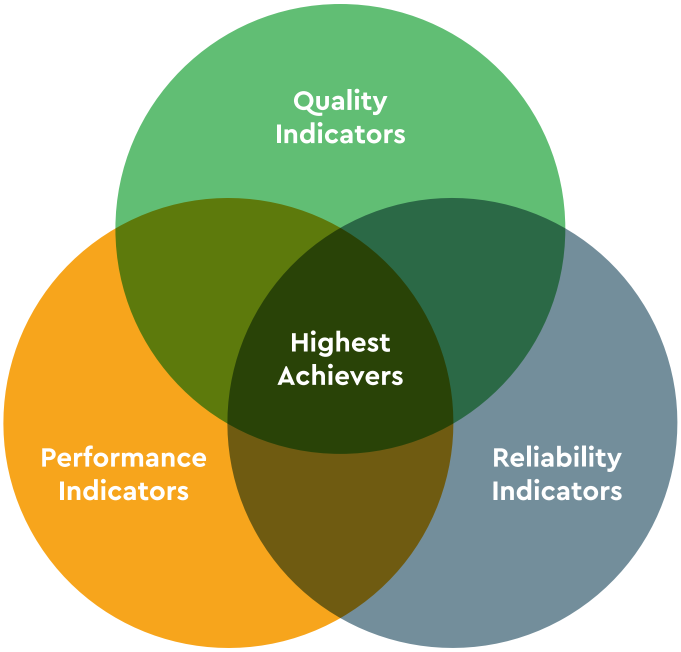
COMPARATIVE RESILIENCY



Comparative single-impact freezer iceball resiliency curves for common c-Si PV module packages.

CATEGORIES for HIGH ACHIEVEMENT

RETC proudly presents the 2023 *PV Module Index Report*. Our annual publication showcases industry-leading technologies and manufacturers. The collected data empower project stakeholders to make strategic product selection and system design decisions.



The 2023 edition of the *PV Module Index Report* compiles the results of bankability and beyond-qualification tests conducted at RETC's accredited laboratories over 12 months, spanning Q2 2022 through Q1 2023. Like previous editions, this year's report catalogs testing sequences and data according to three interrelated and equally influential manufacturing disciplines: module quality, performance, and reliability.

Within each of these three disciplines, we present performance distribution data for specific highly accelerated stress tests. Project stakeholders can use comparative test results to specify products or project designs best suited to a particular environment, location, or portfolio. Entities looking to procure high-performing products within a certain category or sequence can request RETC's test report from the manufacturer.

"The goal of the PV Module Index Report *is not to vilify a product, technology, or manufacturer while endorsing another, but rather to enable data-driven development approaches that identify, quantify, and mitigate project-specific technical risks."*

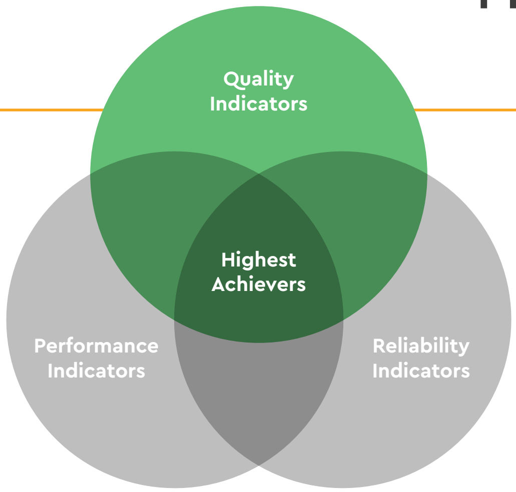
—Cherif Kedir, RETC

When reviewing the results compiled herein, recall that the goal of comparative testing is not to disparage or favor specific technologies, products, or manufacturers. Project development is rarely suited to a solar-as-a-commodity approach. 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.

Intelligent project design eschews oversimplified pass-fail models in favor of sophisticated comparative analyses. Products that perform well in tests that simulate high wind speeds may not perform well in tests that simulate high humidity. PV module designs resilient to severe hail or snow may not be cost-effective in large utility-scale applications in California's Central Valley, which rarely experiences these perils.

The goal of a data-driven approach to project development is not to eliminate every risk at any cost but rather to balance risk mitigation based on a holistic cost-benefit analysis. The bankability testing that underlies this report is foundational to these science- and engineering-based approaches to technical risk mitigation.

MODULE QUALITY



Reliable in-field operation over a 25- or 40-year warranty period is a testament to rigorous manufacturing quality and product testing programs.

Funded by the U.S. government and led by the Jet Propulsion Laboratory (JPL) from 1975 to 1986, the Flat-Plate Solar Array (FSA) Project marks the genesis of collective efforts to produce cost-competitive PV modules capable of supporting a large-scale terrestrial solar market. To facilitate the development of long-life PV modules that would perform cost-effectively in future large-scale power generation applications, JPL quantified the environmental stresses associated with two or three decades of field exposure. Subject matter experts also developed detailed application-specific PV module functional requirements and reviewed long-term operations and maintenance (O&M) considerations for fielded systems.

Based on these investigations, the JPL-led team defined, among other things, module hail-impact probabilities, cell and module operating temperatures, humidity and soiling levels, ultraviolet (UV) exposure, and wind pressure loading.

Critical areas of investigation included interconnect fatigue, optical surface soiling, hail-impact resistance, glass- and cell-fracture strength, cell and module temperature and humidity endurance, hot-spot heating, bypass diode reliability, electrical insulation breakdown, and electrochemical erosion. Applying reliability physics principles, the FSA Project defined prototypical design standards and analytical test methods that are still in use today.

When JPL's work began in earnest, state-of-the-art PV modules, which cost more than $200/W in today's dollar, had a conversion efficiency of 5%–6% and an operational life of 1–2 years. By comparison, today's high-performing commercial PV modules, which cost less than $0.40/W, have a conversion efficiency of 22%–23% and an expected useful life of 30–40 years.

These dramatic improvements in PV module prices (>99.8% decrease), performance (>267% increase), and lifespan (>1,400% increase) are not simply the result of continual technological improvements related to cell technologies and module manufacturing. In parallel, industry stakeholders used analytical approaches pioneered by JPL to identify in-field failure modes and quantify warranty risk prior to mass-market adoption.

QUALITY TESTS AND METRICS

While a manufacturing commitment to quality can take many forms, essential components of a quality program include product conformity analyses, random sampling programs, third-party factory audits, and beyond-qualification testing. Simply meeting minimum certification requirements does not ensure a quality product for all project stakeholders in every application.

"As the decision-makers on solar glass specification and procurement, manufacturers are uniquely positioned to improve module hail resilience."

—Cherif Kedir, RETC

To help project stakeholders better evaluate module quality over a 25- or 30-year time frame in the field, RETC has taken a leadership role in industry efforts to develop and implement beyond-qualification testing standards. These enhanced test sequences and programs identify wearout mechanisms and failure modes, allowing stakeholders to compare products based on quality.

HAIL DURABILITY TEST (HDT) In late 2019, the industry suffered a collective crisis in confidence after a hailstorm damaged more than 400,000 PV modules in West Texas. Recognizing that basic safety and qualification test standards were inadequate to characterize risk in hail-exposed locations, RETC developed the industry's first-ever commercial beyond-qualification test program for severe hail. Our HDT program expands upon existing UL and IEC standards to probe vulnerabilities to glass breakage and cell cracking and classify products based on hail resilience.

Virtually all PV module designs are unscathed by the basic ballistic impact tests found in UL and IEC standards. To pass UL 1703, a module design must withstand the impact of a 50 mm (2 in.) steel sphere dropped from a height of roughly 130 cm (51 in.), which results in a modest impact energy of roughly 7 joules. To pass IEC 61215–2, a module design must withstand 11 impacts of 25 mm (1 in.) ice balls traveling at their terminal velocity, which results in a meager impact energy of 2 joules. These pass-fail test programs will not ensure that modules can withstand severe hailstorms in the real world.

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

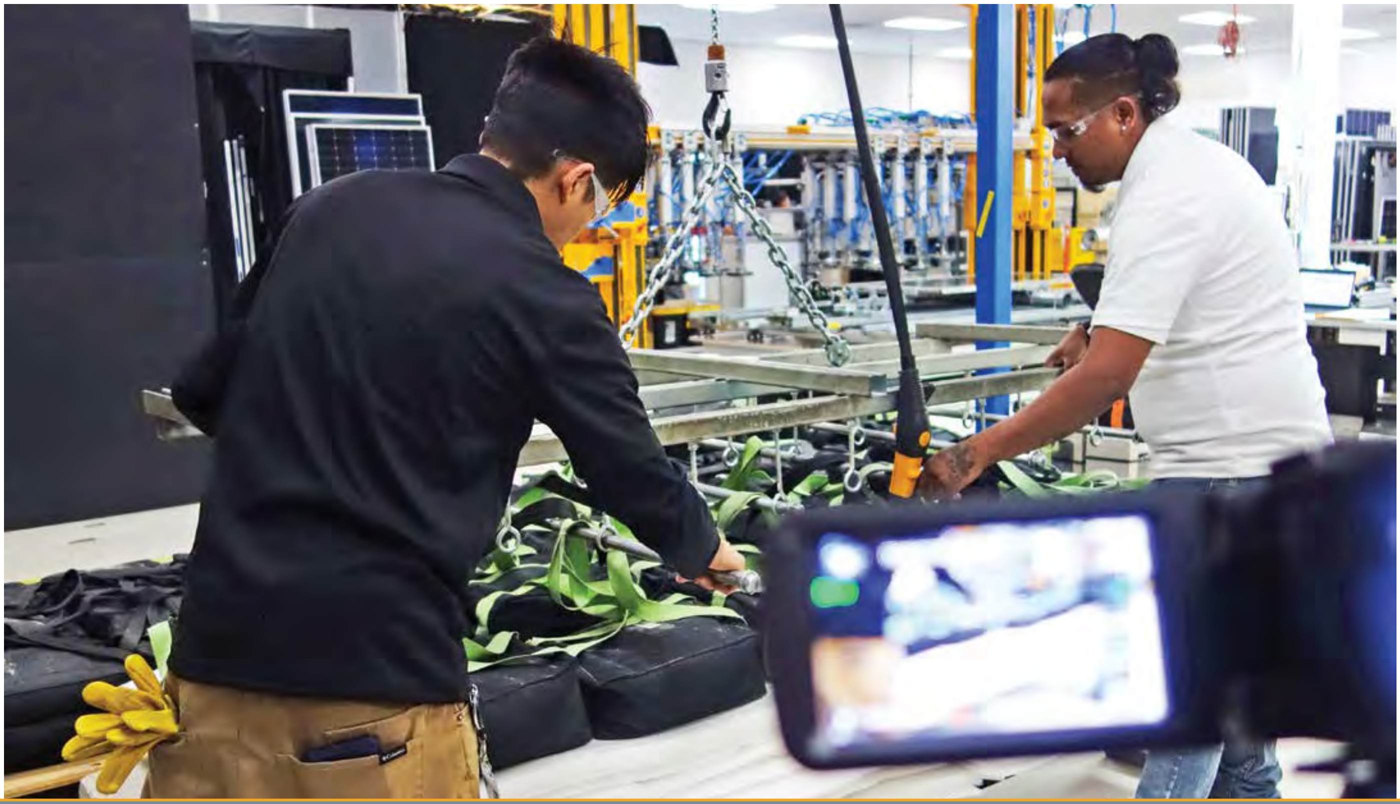
See the results on p. 20 for a table ranking product performance and classification in RETC's Hail Durability Test.

THRESHER TEST Developed by and for industry stakeholders, the first consensus reliability and durability test standard for PV modules has been separating the wheat from the chaff since 2011. Much as the FSA Project marked the genesis of the terrestrial solar industry, the introduction of the Thresher Test marked a pivotal moment of market maturation, the birth of a science- and engineering-based approach to bankability. Though both initiatives relied on similar analytical methodologies, the delivery processes could not have been more different. Whereas the FSA Program was a top-down initiative led by government-funded scientists, the Thresher Test was the product of a bottom-up collaboration involving an ad hoc team of industry stakeholders led in part by a startup independent testing laboratory.

Circa 2009, the global proliferation of module manufacturing meant that purchasers had more procurement options than ever before. At the same time, it was difficult for buyers to identify quality products that would meet or exceed durability and performance claims. Many manufacturers used proprietary accelerated testing regimens to evaluate product designs and benchmark competitors' products based on long-term performance and reliability. However, developers, engineers, and investors could not use these in-house test data to evaluate long-term investment risk on an apples-to-apples basis due to fundamental differences in test methodologies and the self-reported nature of the data.

A critical mass of industry stakeholders favored the adoption of a consensus reliability and degradation testing standard. This stakeholder group included multiple module manufacturers and subject matter experts from the National Renewable Energy Laboratories (NREL) and Sandia National Laboratories. Since the goal was to develop a protocol that any independent testing laboratories could implement, the group also included RETC, PV Evolution Labs (PVEL), TÜV Rheinland, and TÜV SÜD. Collectively, program members selected Hugh Kuhn to serve as the project leader, since he had an interest in technical due diligence to support bankability assessments for Solar Power Partners, an independent solar power producer that NRG Energy later acquired.

RETC played a critical role as the program coordinator due to manufacturer concerns about intellectual property. Module companies were understandably reluctant to share their internal testing protocols with industry competitors. As a workaround, the manufacturers agreed to share testing program details with RETC under a nondisclosure agreement. RETC could then review these testing protocols against an NREL database of failure modes observed in fielded PV power plants or during product certification testing. This analysis allowed the working group to isolate the test sequences that most effectively identified known failure modes.



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

As the program coordinator, RETC was the first independent testing laboratory to offer the Thresher Test. Other laboratories, such as TÜV SÜD, followed suit, making the Thresher Test the solar industry's original commercial test standard for characterizing PV module designs based on long-term performance, reliability, and durability. In the years since the Thresher Test's introduction and adoption as the de facto standard for comparative PV module testing, RETC has adapted or added test sequences to better align test outcomes with the latest field-failure data. However, the core extended test sequences—thermal cycling, humidity-freeze, damp heat, and damp heat with system voltage bias—are still used today to characterize product-specific design vulnerabilities, wearout and failure modes, and long-term degradation patterns.

See the results on p. 21 for a matrix detailing product performance across the multiple accelerated test sequences in RETC's Thresher Test.

HAIL DURABILITY TEST RESULTS

For the 2023 edition of its *PV Module Index Report*, RETC presents a table ranking module performance in our state-of-the-art HDT program. We recognize as high achievers those products that achieved a Class A hail rating while withstanding an effective kinetic energy of at least 20 joules. Products that receive a Class A rating in RETC's HDT program experience less than 1% power degradation and do not display any meaningful abnormalities upon completion of the test sequence.

Fielding hail-resilient PV modules in hail-exposed locations helps mitigate a leading natural catastrophe hazard. Resistance to kinetic impact energy is the ultimate measure of a hail-hardened PV module. Products that withstand kinetic energy of at least 20 joules have effectively demonstrated resistance to a 45 mm (1.8 in.) iceball traveling at a terminal velocity of 30.7 m/s (68.7 mph).

Note that front glass thickness strongly correlates to ballistic-impact resistance. Reflecting these differences, modules with 3.2 mm glass modules should survive the impact of a 55 mm (2.2 in.) iceball to demonstrate a meaningful level of hail resistance. By comparison, modules with 2.0 mm glass modules should survive the impact of a 45 mm (1.8 in.) iceball to demonstrate a commensurate level of hail resistance.

HIGH QUALITY IN HAIL DURABILITY TEST

RETC proudly recognizes, in alphabetical order, the manufacturers whose modules resisted an effective kinetic impact energy greater than 20 joules, experienced less than 1% power degradation, and achieved a Class A hail-resistance rating: JA Solar, JinkoSolar, Trina Solar.

HAIL DURABILITY TEST

Rank	Model	Effective Kinetic Energy (J)	HDT Case	HDT Class
1	P1	29	2	A
2	P2	27	2	A
3	P3	27	2	A
4	P4	22	2	A
5	P5	22	2	A
6	P6	21	2	A
7	P7	21	2	A
8	P8	21	2	A
9	P9	20	1	A
10	P10	20	1	A
11	P11	20	1	A
12	P12	18	1	A
13	P13	15	1	A
14	P14	15	1	A
15	P15	15	1	A
16	P16	15	1	A
17	P17	15	1	A
18	P18	15	1	A
19	P19	13	1	A
20	P20	13	1	A
21	P21	8	1	A
22	P22	8	1	A
23	P23	21	2	B
24	P24	32	3	C
25	P25	22	2	C
26	P26	21	2	C
27	P27	21	2	C
28	P28	19	1	C
29	P29	32	3	N/A

THRESHER TEST RESULTS

For the 2023 edition of its *PV Module Index Report*, RETC presents a Thresher Test performance matrix. To showcase high performance in manufacturing, we recognize those manufacturers that achieve high performance across a diverse set of accelerated test sequences. As proof of quality, products must consistently achieve less than 2% power degradation per accelerated aging test sequence.

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

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

HIGH QUALITY IN THRESHER TEST

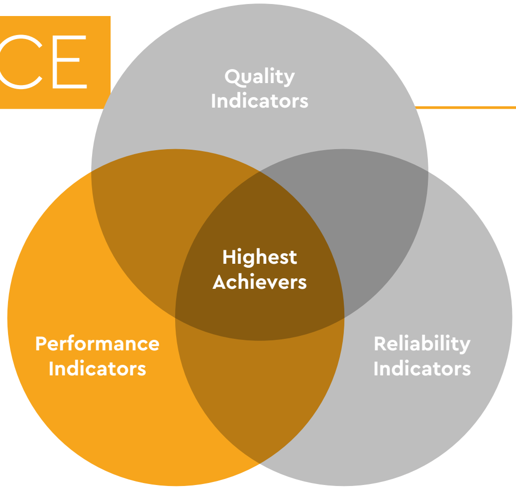
RETC proudly recognizes, in alphabetical order, those manufacturers whose products experienced less than 2% power degradation after exposure to a wide range of beyond-qualification test sequences for demonstrating a commitment to quality: Astronergy, JA Solar, LONGi Solar, Runergy.

THRESHER TEST

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

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

MODULE PERFORMANCE



PV module performance directly impacts energy generation and consequently financial returns and investor confidence.

Investors want to ensure that solar assets yield expected investment returns. High-performing PV modules facilitate this by improving energy output and financial performance. To the extent that developers can ensure reliable and predictable energy generation, they can reduce risk and improve the odds that a proposed project will receive funding. Over time, high-performing assets improve investor confidence and public trust—and foster continued solar market growth.

As an independent testing laboratory with the highest level of accreditation, RETC plays an essential role in ensuring that module performance characterization is as accurate and reliable as possible. Testing laboratories use calibrated and certified equipment under audited and controlled test conditions. Characteristics captured under these rigorous conditions represent the proper measure of PV module performance and provide value to multiple project stakeholders.

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

PERFORMANCE TESTS AND METRICS

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

CEC CERTIFICATION In the 1990s, researchers working on the Photovoltaics for Utility-Scale Applications (PVUSA) project developed a set of performance rating parameters intended to simulate environmental conditions a module might experience in the real world. The primary differences between PVUSA test conditions (PTC) and STC are cell temperature and wind speed. Specifically, PTC parameters call for an elevated cell temperature of 45°C (113°F), an ambient temperature of 22°C (72°F), and a wind speed of 1 m/s (2.2 mph). PTC ratings are foundational module performance characteristics required by the California Energy Commission (CEC).

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

See the table on p. 24 for a sampling of high-achieving PV modules based on PTC-to-STC ratio.

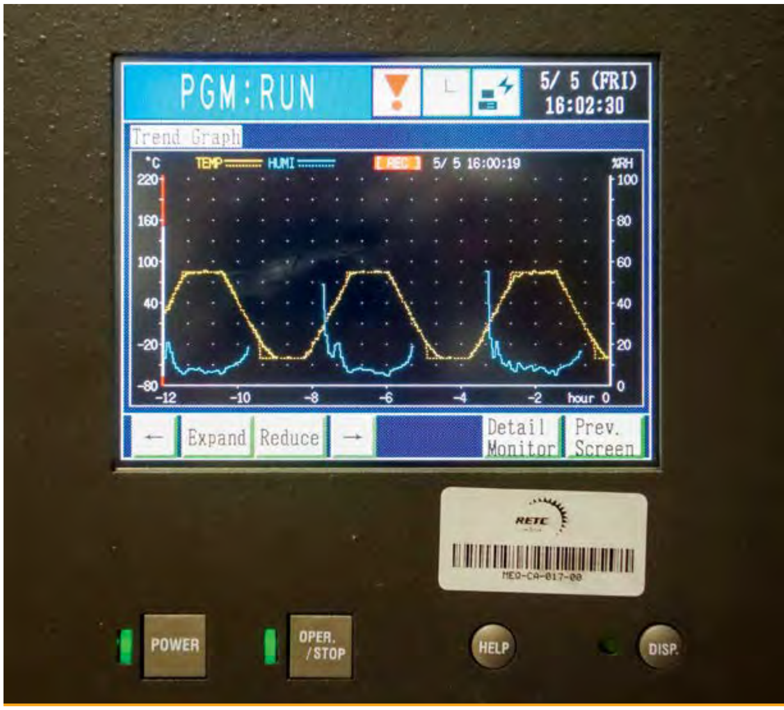
CONVERSION EFFICIENCY The percentage of incident solar energy converted to electrical energy is an essential figure of merit for PV modules and cell technologies. Nominal module conversion efficiency is determined by dividing a product's nameplate STC-rated power by its total aperture area. Cell technology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

See the table on p. 25 for the maximum module efficiency ratings calculated and ranked per manufacturer based on a year's worth of RETC's module characterization test data.

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

LIGHT- AND ELEVATED TEMPERATURE–INDUCED DEGRADATION (LeTID) Relatively newer cell technologies may experience a type of long-term in-field degradation associated with exposure to light and elevated temperatures. To characterize LeTID susceptibility, the IEC has developed a protocol of light soaking, followed by 75°C (167°F) temperature exposure for two 162-hour cycles to identify significant degradation (>5%). Subsequently, test samples are subject to 500 hours of 75°C temperature exposure followed by two additional 162-hour cycles, after which measurement should reveal some restoration of module performance (regeneration).

See the table on p. 25 for module performance distribution data based on LeTID test results.



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

See the table on p. 26 for module performance distribution data based on LID test results.

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

See the table on p. 27 for module-specific PVsyst performance estimates for a 10 MW ground-mounted application in Texas, simulated based on RETC's third-party validated and optimized PAN files.

PTC-TO-STC RATIO RESULTS

For the 2023 edition of its *PV Module Index Report*, RETC has ranked the high-achieving PV modules according to the PTC-to-STC ratio. To showcase high performance in manufacturing, we recognize the manufacturers of the Top 10 modules in this summary table.

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

HIGH PERFORMANCE IN PTC-TO-STC RATIO

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

CEC TESTING DATA

Rank	Model	Cell Technology	Efficiency	STC	PTC	PTC Ratio
1	P1	Mono-c-Si HJT	21.9%	410	393.56	96.0%
2	P2	Mono PERC	21.5%	410	392.72	95.8%
3	P3	Mono-c-Si	22.3%	415	396.53	95.5%
	P4	Mono PERC	21.4%	380	362.83	95.5%
4	P5	Mono-c-Si	22.1%	720	686.93	95.4%
	P6	Mono-c-Si	21.6%	370	352.99	95.4%
5	P7	Mono PERC	21.8%	385	366.10	95.1%
6	P8	N type-TOPCon	25.8%	680	644.86	94.8%
7	P9	Mono-c-Si HJT	22.4%	410	388.20	94.7%
8	P10	Mono-c-Si	20.7%	400	375.85	94.0%
	P11	Mono-c-Si	20.9%	530	497.99	94.0%
9	P12	Mono PERC	21.6%	500	469.71	93.9%
	P13	Mono PERC	20.8%	400	375.52	93.9%
10	P14	Mono PERC	21.4%	535	502.01	93.8%
11	P15	Mono-c-Si	21.9%	660	618.36	93.7%
12	P16	Mono PERC	20.7%	400	373.56	93.4%
	P17	Mono-c-Si	20.8%	400	373.53	93.4%
13	P18	Mono-c-Si	21.7%	590	550.59	93.3%
	P19	Mono-c-Si	19.7%	395	368.45	93.3%
	P20	Mono PERC	21.7%	565	526.96	93.3%
	P21	Mono PERC	19.7%	425	396.34	93.3%
14	P22	Mono PERC	19.6%	400	372.93	93.2%
15	P23	Mono PERC	21.3%	540	502.84	93.1%
16	P24	Mono PERC	21.8%	415	386.08	93.0%
17	P25	Mono PERC	15.8%	400	371.62	92.9%
	P26	Mono PERC	21.5%	415	385.43	92.9%
	P27	Mono PERC	20.0%	395	366.85	92.9%
18	P28	Mono PERC	16.3%	330	306.29	92.8%
19	P29	Mono PERC	21.9%	545	503.80	92.4%
20	P30	Mono-c-Si	16.0%	360	326.64	90.7%
	P31	Mono PERC	16.1%	180	163.22	90.7%
21	P32	Mono PERC	15.5%	120	108.68	90.6%
22	P33	Mono PERC	12.0%	68	61.12	89.9%
23	P34	Mono PERC	15.2%	175	156.77	89.6%
24	P35	Mono PERC	15.3%	117	104.68	89.5%

MODULE EFFICIENCY RESULTS

For the 2023 edition of its *PV Module Index Report*, RETC has ranked the recorded maximum module efficiency values—as well as other relevant product attributes—per manufacturer based on third-party I-V characterization measurements conducted at our accredited testing laboratories over a 12-month period. To showcase high performance in manufacturing, we recognize those manufacturers with products that achieved conversion efficiencies of 20% or greater based on total module area.

I-V CHARACTERIZATION DATA

Rank	Model	Cell Technology	Pmax (W)	Aperture (m^2)	Aperture Efficiency
1	P1	N type-TOPCon	679.96	2.63	25.8%
2	P2	Mono-c-Si HJT	402.15	1.79	22.4%
3	P3	Mono-c-Si	400.17	1.79	22.3%
4	P4	Mono-c-Si	733.94	3.33	22.1%
5	P5	Mono-c-Si HJT	413.06	1.88	21.9%
	P6	Mono PERC	545.22	2.49	21.9%
	P7	Mono-c-Si	667.94	3.05	21.9%
6	P8	Mono PERC	385.87	1.77	21.8%
	P9	Mono PERC	412.62	1.90	21.8%
7	P10	Mono-c-Si	589.81	2.72	21.7%
	P11	Mono PERC	570.53	2.63	21.7%
8	P12	Mono-c-Si	373.43	1.73	21.6%
	P13	Mono PERC	499.17	2.31	21.6%
9	P14	Mono PERC	407.40	1.90	21.5%
	P15	Mono PERC	402.93	1.88	21.5%
10	P16	Mono PERC	379.68	1.77	21.4%
	P17	Mono PERC	538.14	2.52	21.4%
11	P18	Mono PERC	536.06	2.52	21.3%
12	P19	Mono-c-Si	525.99	2.51	20.9%
13	P20	Mono PERC	399.67	1.92	20.8%
	P21	Mono-c-Si	397.80	1.92	20.8%
14	P22	Mono PERC	385.78	1.86	20.7%
	P23	Mono-c-Si	391.92	1.90	20.7%
15	P24	Mono PERC	389.51	1.95	20.0%
16	P25	Mono PERC	421.58	2.14	19.7%
	P26	Mono-c-Si	385.70	1.96	19.7%
17	P27	Mono PERC	383.16	1.96	19.6%
18	P28	Mono PERC	315.94	1.93	16.3%
19	P29	Mono PERC	175.94	1.09	16.1%
20	P30	Mono-c-Si	342.78	2.14	16.0%
21	P31	Mono PERC	397.59	2.52	15.8%
22	P32	Mono PERC	118.13	0.76	15.5%
23	P33	Mono PERC	117.05	0.76	15.3%
24	P34	Mono PERC	166.43	1.09	15.2%
25	P35	Mono PERC	66.16	0.55	12.0%

HIGH PERFORMANCE IN MODULE EFFICIENCY

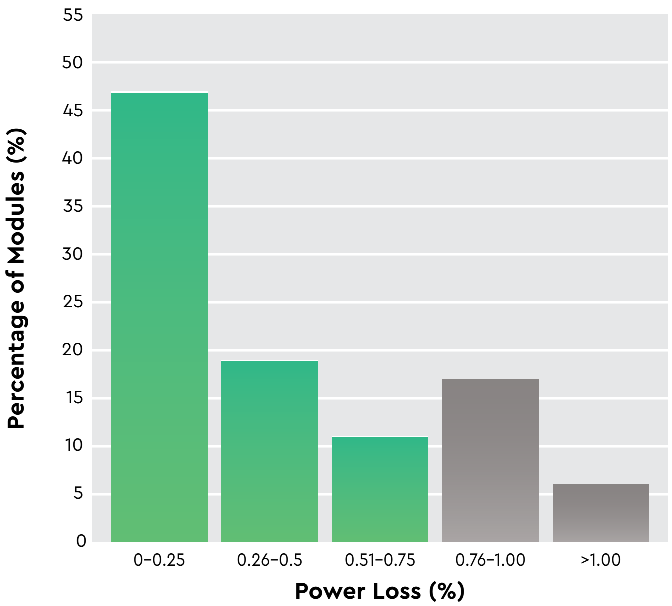
RETC proudly recognizes, in alphabetical order, those manufacturers whose modules achieved greater than 20% total area module efficiency: Auxin Solar, JA Solar, LONGi Solar, Meyer Burger, Mission Solar, Qcells, REC Solar, Silfab Solar, Trina Solar, Yingli Solar.

LETID TEST RESULTS

For the 2023 edition of its *PV Module Index Report*, RETC has ranked the high-achieving PV modules based on the results of LeTID testing and characterization. To showcase high performance in manufacturing, we recognize manufacturers whose products experienced less than 0.75% power loss after 486 hours of exposure.

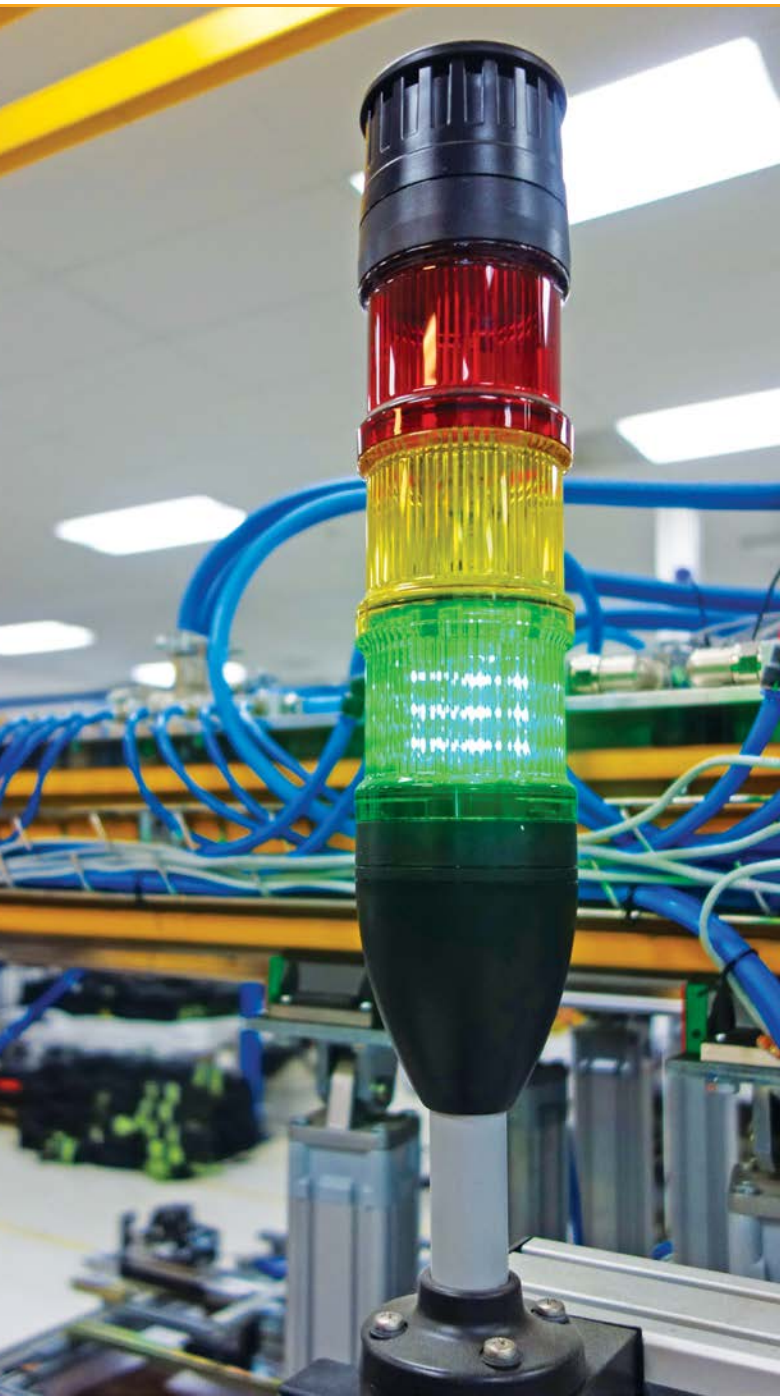
On a year-over-year basis, RETC's LeTID test results are mixed. On the one hand, RETC notes a significant improvement in the percentage of modules tested that experienced less than 0.25% power loss. On the other hand, the percentage of modules that experience greater than 0.75% power loss also increased.

486-HOUR LeTID EXPOSURE



HIGH PERFORMANCE IN LeTID RESISTANCE

RETC proudly recognizes, in alphabetical order, those manufacturers of modules that experienced less than 0.75% power loss after 486 hours of exposure: Aptos Solar, Astronergy, JA Solar, JinkoSolar, Runergy, SEG Solar, Silfab Solar, Solar Space, Trina Solar, Yingli Solar.



LID TEST RESULTS

For the 2023 edition of its *PV Module Index Report*, RETC has ranked the high-achieving PV modules based on the results of LID testing and characterization. To showcase high performance in manufacturing, we are recognizing the manufacturers of the Top 10 modules in this list.

RETC notes a correlation between cell technology and average LID values in some of these results, as certain technologies experience an increase—rather than a decrease—in measured power after LID test exposure. The high-achieving products based on LID performance ratio experience an increase in power or very modest power loss after test exposure, in many cases due to their specific cell technology.

LID TESTING DATA

Rank	Model	Cell Technology	Performance Ratio
1	P1	Mono	0.49%
2	P2	Mono	0.34%
3	P3	Mono	0.33%
4	P4	Mono	0.19%
5	P5	Mono	0.14%
6	P6	Mono	0.12%
7	P7	Mono	0.11%
8	P8	Mono	0.06%
9	P9	Mono	-0.03%
10	P10	Mono	-0.04%
11	P11	Mono	-0.10%
12	P12	Mono	-0.11%
13	P13	Mono	-0.13%
14	P14	Mono	-0.14%
15	P15	Mono	-0.15%
16	P16	Mono	-0.16%
17	P17	Mono	-0.17%
18	P18	Mono	-0.18%
	P19	Mono	-0.18%
19	P20	Mono	-0.19%
	P21	Mono	-0.19%
	P22	Mono	-0.19%
	P23	Mono	-0.19%
20	P24	Mono	-0.20%
	P25	Mono	-0.20%
	P26	Mono	-0.20%
21	P27	Mono	-0.23%
	P28	Mono	-0.23%
22	P29	Mono	-0.27%
23	P30	Mono	-0.29%
	P31	Mono	-0.29%
24	P32	Mono	-0.30%
25	P33	Mono	-0.31%
	P34	Mono	-0.31%
	P35	Mono	-0.31%
26	P36	Mono	-0.36%
	P37	Mono	-0.36%
	P38	Mono	-0.36%
27	P39	Mono	-0.37%
28	P40	Mono	-0.38%
29	P41	Mono	-0.39%
30	P42	Mono	-0.40%
31	P43	Mono	-0.41%
	P44	Mono	-0.41%
32	P45	Mono	-0.42%
33	P46	Mono	-0.46%
	P47	Mono	-0.46%
34	P48	Mono	-0.47%
35	P49	Mono	-0.49%
36	P50	Mono	-0.52%

HIGH PERFORMANCE IN LID RESISTANCE

RETC proudly recognizes, in alphabetical order, those manufacturers of products that achieved a Top 10 ranking, among all modules tested, based on LID performance ratio: Dehui Solar, LONGi Solar, Merlin Solar, Qcells.

PAN FILE RESULTS

For the 2023 edition of its *PV Module Index Report*, RETC has ranked the high-achieving PV modules based on the results of plant-level PVsyst production estimates that use our third-party validated PAN files. To showcase high performance in manufacturing, we recognize those manufacturers with products that achieved a PVsyst-modeled performance ratio of 85% or greater.

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

These simulations assume a 10 MW utility-scale solar plant in Midland, Texas, deployed using fixed-tilt ground mounts and 500 kVA–rated central inverters. While minor design details may vary per simulation based on product-specific capacity ratings, the DC-to-AC inverter loading ratios are functionally equivalent.

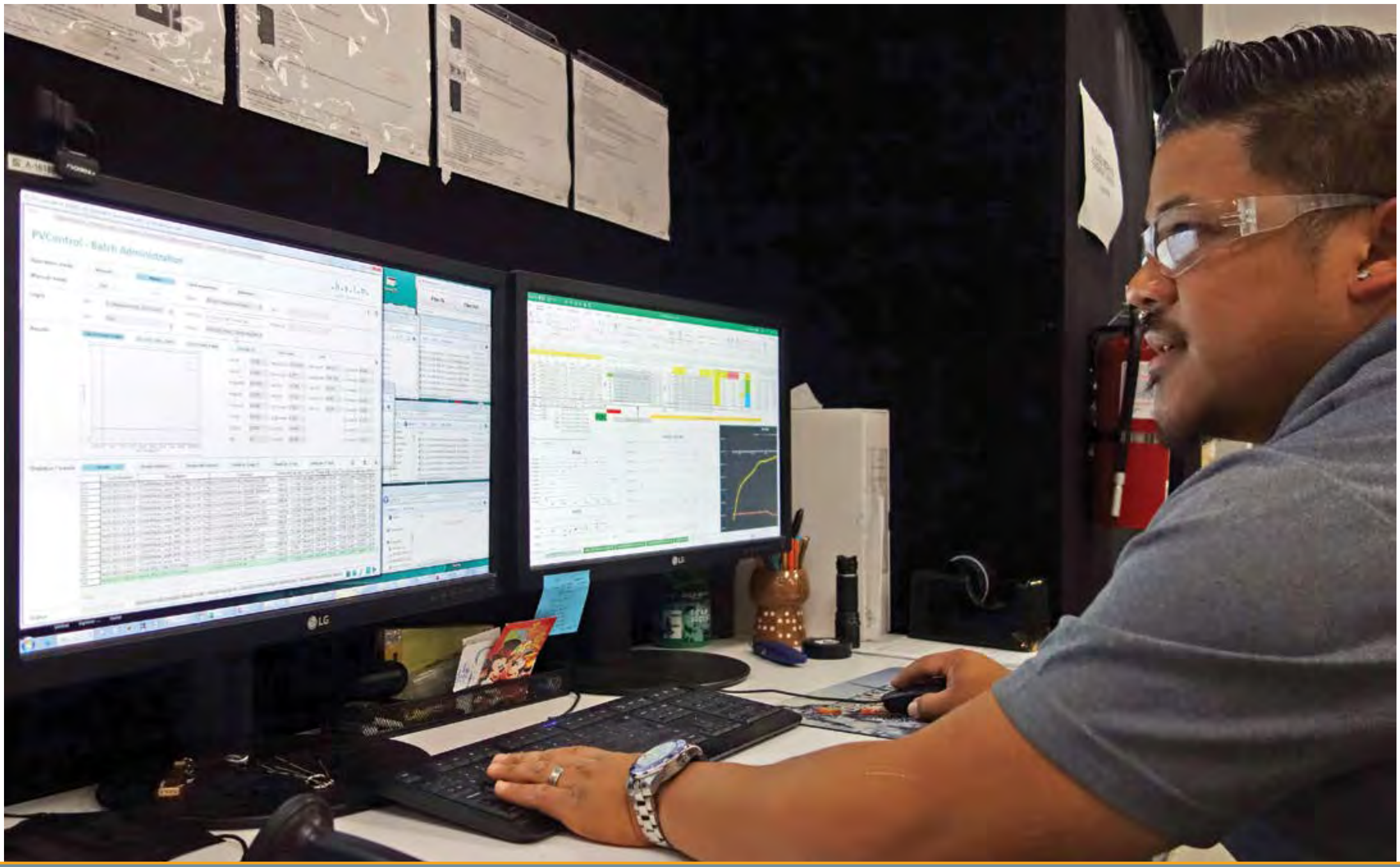
PAN FILE TESTING DATA

PVsyst Simulation for 10 MW Ground Mount in Texas

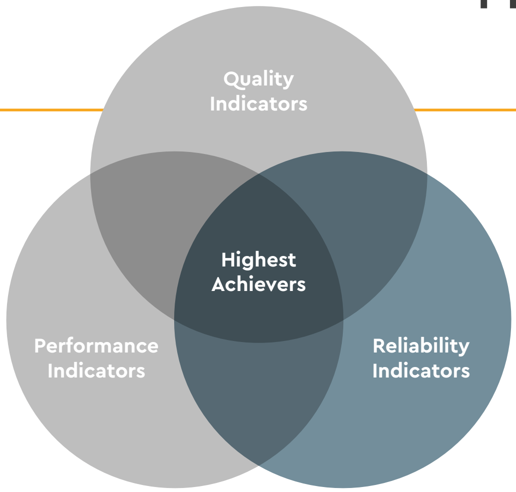
Rank	Model	Specific Yield (kWh/kW)	Performance Ratio
1	P1	1,900	88.27%
2	P2	1,886	87.61%
3	P3	1,877	87.20%
4	P4	1,876	87.13%
5	P5	1,870	86.88%
6	P6	1,868	86.77%
7	P7	1,863	86.56%
8	P8	1,860	86.43%
9	P9	1,859	86.36%
10	P10	1,853	86.06%
11	P11	1,848	85.87%
12	P12	1,794	83.34%
13	P13	1,785	82.91%
14	P14	1,783	82.85%
15	P15	1,779	82.66%
16	P16	1,777	82.57%
17	P17	1,772	82.31%
18	P18	1,742	80.91%
19	P19	1,738	80.74%
20	P20	1,731	80.41%

HIGH PERFORMANCE IN PAN FILE CHARACTERIZATION

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



MODULE RELIABILITY



Achieving high-reliability PV module designs requires a strong reliance on extended test sequences conducted in a laboratory setting.

The best locations for solar are inherently high-stress environments subject to extreme daily and annual temperature variations, high humidity, dynamic mechanical loads, and long-term UV exposure. Given the duration and intensity of these environmental stresses, project stakeholders need to evaluate locational and technical risks on a case-by-case basis.

Beyond-qualification testing is one of the industry's best tools for understanding these differences and adapting project designs in response to location- and product-specific characteristics. Module reliability differs based on environmental exposure, which varies on a site-by-site basis. With comparative testing data, these differences are not random but statistically predictable.

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

RELIABILITY TESTS AND METRICS

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

DAMP HEAT (DH) RETC's Thresher Test includes a DH2000 test, indicating a duration of exposure of 2,000 hours—twice the duration typically required for product certification. DH testing aims to characterize a PV module's ability to withstand prolonged exposure to humid, high-temperature environments. Taking place inside an environmental chamber, the test exposes modules to a controlled temperature of 85°C (185°F) and a relative humidity of 85% for a set amount of time.

See the bar chart on p. 30 for module performance distribution data based on DH test results.

HUMIDITY FREEZE (HF) HF testing characterizes a PV module's ability to withstand the alternating effects of high heat and humidity followed by extreme cold. For this accelerated aging test, modules in an environmental chamber are exposed to a relative humidity of 85% and subjected to temperature cycling from 85°C to −40°C (185°F to −40°F) with no relative humidity control. Certification standards call for a 10-cycle test and allow for no more than 5% degradation. RETC's Thresher Test subjects modules to 30 or more HF cycles.

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

See p. 31 for module performance distribution data based on PID test results.

STATIC AND DYNAMIC MECHANICAL LOAD (SDML) The SDML test sequence subjects modules to 1,000 cycles of +1,000 pascal (Pa) and −1,000 Pa loads at a frequency of three to seven cycles per minute. Subsequently, test samples in an environmental chamber undergo TC50 testing followed by HF30 testing. Measurements taken upon completion characterize electrical performance. SDML testing evaluates a module's ability to withstand static snow and ice loads as well as dynamic push-pull loads associated with hurricanes, typhoons, and other high-wind events.

See the bar chart p. 30 for module performance distribution data based on SDLM, TC, and HF test results.

THERMAL CYCLING (TC) RETC's Thresher Test calls for extended 600-cycle TC600 testing as a means of detecting weaknesses in module designs. TC testing assesses product reliability and identifies thermal fatigue failure modes. The TC test protocol calls for cycling modules in an environmental chamber between two temperature extremes—85°C (185°F) on the high end and −40°C (−40°F) on the low end. Typical certification standards call for a TC200 test, consisting of 200 cycles only.

See the bar chart on p. 31 for module performance distribution data based on TC test results.

ULTRAVIOLET (UV) EXPOSURE The enhanced UV preconditioning test conducted for accelerated reliability assessment exposes modules to two cycles of UV irradiation at 45 kWh/m^2, which is six times greater than the IEC 61215 requirements for product qualification. This test maintains modules at an elevated temperature of 60°C (140°F) while a UV light is tuned to the UVA and UVB regions. UV soaking or preconditioning characterizes a module's susceptibility to degradation and performance loss resulting from exposure to UV light.

DAMP HEAT TEST RESULTS

For its 2023 edition of the *PV Module Index Report*, RETC has compiled performance distribution data for modules exposed to a 2,000-hour DH test (DH2000). As compared to minimum certification requirements, the extended DH2000 test duration better characterizes module durability and robustness. IEC and UL certification standards require only a 1,000-hour DH test (DH1000) and allow for a maximum performance degradation of 5%.

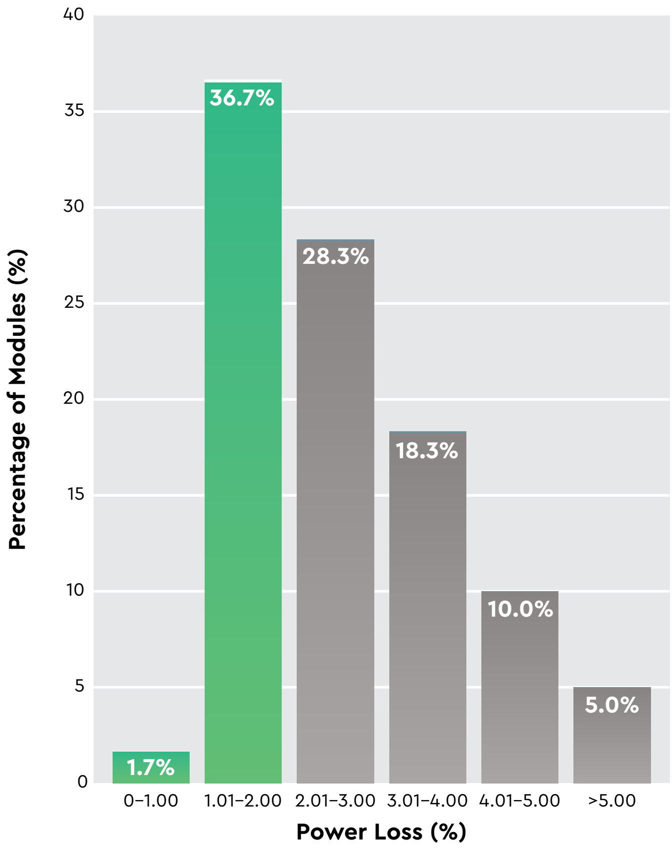
To showcase high performance in manufacturing, RETC has highlighted data for modules that experienced less than 2% power loss after DH2000 exposure. As shown in these results, just over 38% of the modules RETC subjected to DH2000 testing experienced less than 2% power loss. While the overall high-performance percentage is nearly identical to last year's result, RETC notes that the percentage of modules that degraded less than 1% decreased significantly on a year-over-year basis.

PID TEST RESULTS

For its 2023 edition of the *PV Module Index Report*, RETC has compiled performance distribution data for modules exposed to PID testing. To showcase high performance in manufacturing, we have highlighted data for modules that achieved less than 2% of performance degradation through 192 hours of exposure.

These tests results show that roughly 49% of modules attained high-achiever status, experiencing less than 2% degradation through 192 or more hours of PID test exposure. More than half of these high-achieving modules, nearly 28% of the test samples, experienced less than 1% degradation over the test period. By comparison, less than 9% of modules achieved greater than 5% power loss. RETC notes that these results represent an across-the-board improvement on a year-over-year basis.

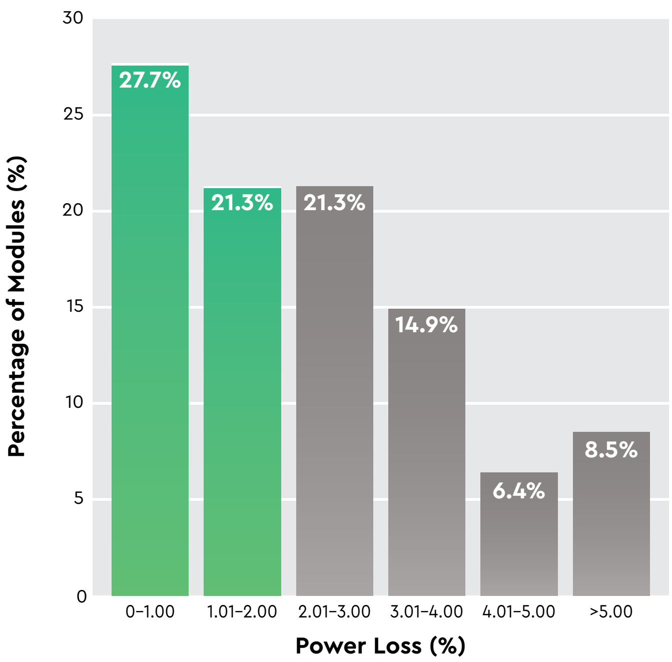
2,000-HOUR DAMP HEAT (DH2000)



HIGH RELIABILITY IN DAMP HEAT TEST

RETC proudly recognizes, in alphabetical order, those manufacturers whose modules degraded less than 2% after being subjected to 2,000-hour DH exposure: Astronergy, JA Solar, LONGi Solar, Qcells, Runergy, Trina Solar, Yingli Solar.

192-HOUR POTENTIAL INDUCED DEGRADATION (PID)



HIGH RELIABILITY IN PID RESISTANCE

RETC proudly recognizes those manufacturers, in alphabetical order, whose modules degraded less than 2% after being subjected to 192-hour PID test exposure: Astronergy, JA Solar, JinkoSolar, Qcells, Runergy, Trina Solar.

SDML TEST RESULTS

For its 2023 edition of the *PV Module Index Report*, RETC has compiled performance distribution data for modules exposed to SDML testing followed by TC50 and HF30 environmental exposure. To showcase high performance in manufacturing, we recognize module companies that achieved less than 2% degradation in power.

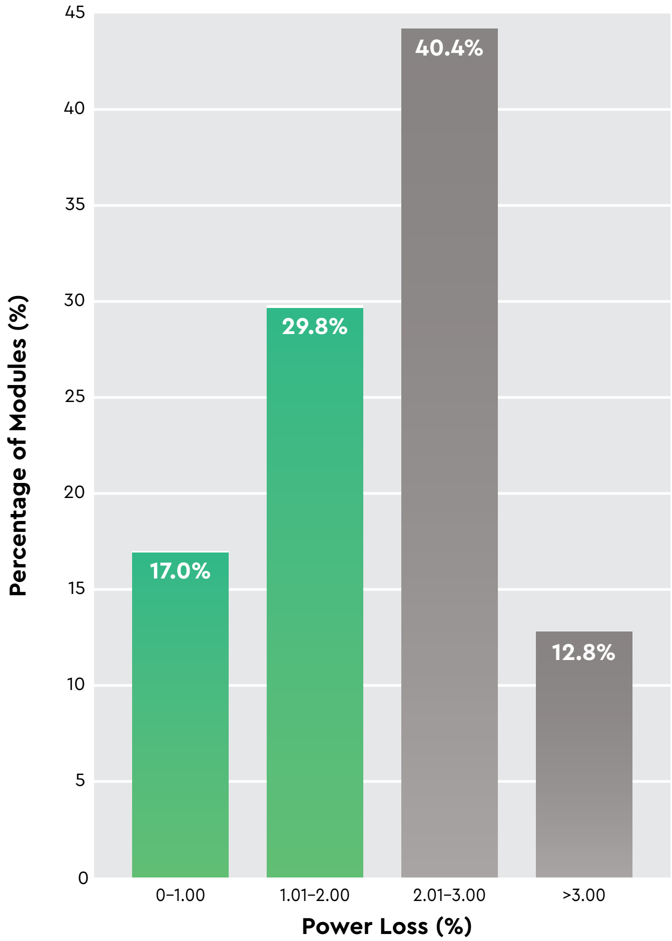
As shown in these test results, nearly 47% of the modules that RETC subjected to simulated wind and environmental stresses achieved less than 2% degradation in power. Roughly 17% of the total test samples experienced less than 1% degradation in power after the SDML sequence. RETC notes that the results in this category represent a modest improvement on a year-over-year basis.

THERMAL CYCLE TEST RESULTS

For the 2023 edition of the *PV Module Index Report*, RETC has compiled performance distribution data for modules exposed to a 600-hour TC test (TC600). Compared to minimum certification requirements, the extended TC600 test duration better characterizes module durability and robustness. IEC and UL certification standards require only a 200-hour TC test (TC200).

To showcase high performance in manufacturing, RETC has highlighted data for modules that experienced less than 2% power loss after TC600 exposure. As shown in these data, roughly 80% of modules subjected to TC600 testing in 2022 experienced less than 2% power loss. RETC notes that the percentage of high-achieving modules in the TC category held steady on a year-over-year basis.

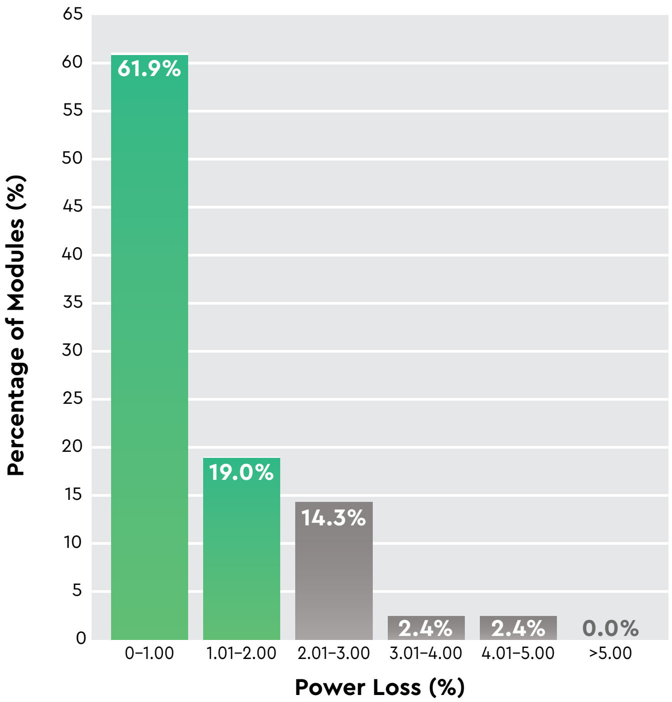
STATIC AND DYNAMIC MECHANICAL LOAD (SDML | TC50 | HF30)



HIGH RELIABILITY IN SDML TEST

RETC proudly recognizes, in alphabetical order, those manufacturers whose modules degraded less than 2% after being subjected to static and dynamic loads followed by 50 thermal cycles and 30 humidity-freeze cycles: Astronergy, JA Solar, JinkoSolar, LONGi Solar, Runergy, Trina Solar, Yingli Solar.

600-CYCLE THERMAL CYCLE (TC600)



HIGH RELIABILITY IN THERMAL CYCLE TEST

RETC proudly recognizes, in alphabetical order, those manufacturers whose modules degraded less than 2% after being subjected to 600-hour TC exposure: Astronergy, JA Solar, JinkoSolar, LONGi Solar, Qcells, Runergy, Saint Gobain, Trina Solar, Yingli Solar.

A YEAR IN REVIEW

Throughout the 2023 edition of the *PV Module Index Report*, RETC has recognized 19 different manufacturers and showcased 77 instances of high achievement.

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

Note that this summary analysis of high achievement in manufacturing is based on available data. Manufacturers and products that are not recognized as overall highest achievers may still prove durable and provide excellent performance. RETC simply cannot make an overall determination regarding high achievement in manufacturing without module test data across all three categories.

RETC compiled the data and results presented in this white paper at its accredited testing facilities during a 12-month period, starting in Q2 2022 and extending to Q1 2023. We share these results in the *PV Module Index Report 2023* to showcase and recognize industry-leading PV module companies and technologies.

OVERALL RESULTS MATRIX

Model	Quality	Reliability	Performance
P1	✓	✓	✓
P2	✓	✓	✓
P3	✓	✓	✓
P4	✓	✓	✓
P5	✓	✓	✓
P6	✓	✓	✓
P7	✓	✓	✓
P8	✓	✓	✓
P9	-	-	✓
P10	-	-	✓
P11	-	-	✓
P12	-	-	✓
P13	-	-	✓
P14	-	-	✓
P15	-	-	✓
P16	-	-	✓
P17	-	-	✓
P18	-	OK	✓
P19	-	OK	✓
P20	-	✓	-
P21	OK	✓	OK
P22	OK	OK	OK
P23	-	OK	-
P24	-	-	OK
P25	-	-	OK
P26	-	-	OK
P27	-	-	OK
P28	-	-	OK
P29	-	OK	X
P30	-	OK	-
P31	-	OK	-
P32	X	OK	X
P33	-	-	X

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

OVERALL HIGHEST ACHIEVERS

RETC congratulates and proudly recognizes, in alphabetical order, eight manufacturers with products recognized for high achievement in manufacturing across three essential disciplines—quality, performance, and reliability—in the 2023 edition of the *PV Module Index Report:* Astronergy, JA Solar, JinkoSolar, LONGi Solar, Qcells , Runergy, Trina Solar, Yingli Solar.

2023 AWARDEES

In Alphabetical Order:

Aptos Solar • Astronergy • Auxin Solar • Dehui • JA Solar • JinkoSolar • LONGi Solar • Merlin Solar • Meyer Burger • Mission Solar Energy • Qcells • REC • Runergy • Saint-Gobain • SEG Solar • Silfab Solar • Solar Space • Trina Solar • Yingli Solar

OVERALL HIGHEST ACHIEVERS

Congratulations to our top eight performers of the year!
Astronergy • JA Solar • JinkoSolar • LONGi Solar • Qcells • Runergy • Trina Solar • Yingli Solar

HIGH ACHIEVEMENT IN QUALITY

HAIL DURABILITY TEST
JA Solar • JinkoSolar • Trina Solar

THRESHER TEST
Astronergy • JA Solar • LONGi Solar • Runergy

HIGH ACHIEVEMENT IN PERFORMANCE

LeTID RESISTANCE
Aptos Solar • Astronergy • JA Solar • JinkoSolar • Runergy • SEG Solar • Silfab Solar • Solar Space • Trina Solar • Yingli Solar

LID RESISTANCE
Dehui Solar • LONGi Solar • Merlin Solar

MODULE EFFICIENCY
Auxin Solar • JA Solar • LONGi Solar • Meyer Burger • Mission Solar • Qcells • REC Solar • Silfab Solar • Trina Solar • Yingli Solar

PAN FILE PERFORMANCE
Dehui Solar • JA Solar • LONGi Solar • Qcells • Runergy • Yingli Solar

PTC-TO-STC RATIO
Auxin Solar • JA Solar • Meyer Berger • REC Solar • Silfab Solar • Trina Solar

HIGH ACHIEVEMENT IN RELIABILITY

DAMP HEAT TEST
Astronergy • JA Solar • LONGi Solar • Qcells • Runergy • Trina Solar • Yingli Solar

PID RESISTANCE
Astronergy • JA Solar • JinkoSolar • Qcells • Runergy • Trina Solar

STATIC AND DYNAMIC MECHANICAL LOAD TEST
Astronergy • JA Solar • JinkoSolar • LONGi Solar • Runergy • Trina Solar • Yingli Solar

THERMAL CYCLE TEST
Astronergy • JA Solar • JinkoSolar • LONGi Solar • Qcells • Runergy • Saint Gobain • Trina Solar • Yingli Solar

LOOKING FORWARD

Building a solar-powered future is essential to meeting global decarbonization goals and mitigating the destabilizing impacts of human-induced climate change.

Our current trajectory is increasing severe weather, natural catastrophes, extreme wildfires, ecosystem collapse, resource insecurity, and economic disruption. Reversing these decadeslong trends with renewables and mass electrification seems like a quixotic goal to some and an insurmountable one to others. Though difficult, it is not yet impossible.

In its latest call for urgent action, a United Nations panel of international scientists estimates that we can mitigate the worst climate change impacts with a two-thirds reduction in carbon pollution by 2035. While it will be challenging to win the race against time and global temperature rise, lessons learned from the Jet Propulsion Laboratory (JPL) suggest this is a race we can win. In 1975, JPL launched its Flat-Plate Solar Array (FSA) Project with the goal of bringing a space-age technology down to Earth. Today, much of what seemed like science fiction in the 1970s is now science fact.

GRID PARITY

Scientists at JPL launched America's first satellite, achieved the first unmanned moon landing, and were the first to fly by or orbit other planets in the solar system. They also estimated the solar module cost reductions required to support mass adoption in terrestrial applications and displace other power generation sources.

According to the authors of JPL's contractor report: "[In] 1975, the costs were still much too high for widespread use on Earth. It was necessary to reduce the manufacturing costs of solar cells by a factor of *approximately 100* [emphasis added] if they were to be a practical, widely used terrestrial power source."

Adjusted for inflation, PV module costs were $200/W in 1975. By 2012, PV module costs in the U.S. crossed under the $2/W threshold in all market segments. At the system level, costs for utility-scale and commercial solar projects have been less than $2/W since 2014 and 2016, respectively. In 2023, government reports estimate that more than half of new U.S. electricity generation capacity will come from solar.

Werner Slocum / NREL

LONG LIFESPAN

Extended test sequences conducted in a laboratory setting have dramatically improved in-field reliability. By systematically identifying failure mechanisms, accelerated stress testing sequences, and allowable failure levels, the JPL team was able to steadily improve c-Si PV module lifespans over the course of the FSA Project. This foundational work set the stage for today's high-reliability, long-life PV module designs.

In 1975, PV module warranties were nonexistent; though manufacturers designed PV modules with five-year service life in mind, many failed prematurely after only one or two years of field exposure. By 1985, most PV modules carried a 10-year warranty and many operated successfully in field applications for 20 years or more. Informed by the pioneering work on the FSA Project, today's PV modules have a useful life expectancy of 30 to 40 years and are warranted by manufacturers accordingly.

ENERGY SECURITY

The impetus for the FSA Project will resonate with anyone reading today's headlines with trepidation. According to JPL's contractor report, the U.S. government initiated the program to confront "the pressures of increasing demand for electric power, combined with the uncertainty of fuel sources and ever-increasing prices for petroleum." Some 50 years may have passed, but concerns about energy security in the face of global instability remain top of mind. Then as today, the strategic potential of widespread solar power adoption stood out as a promising path to a brighter future.

Together, we are making this promise a dream come true. As evidence, look no further than Texas, the largest carbon polluter in the United States. In May, pro-oil legislators nearly passed a series of bills that would have decimated the state's solar market. Mere weeks later, record-setting heat blanketed the state, forcing multiple thermal power plants offline exactly when grid operators most needed power-generation capacity. With the heat index exceeding 45°C (113°F), an unlikely hero emerged to keep life-saving air conditioners running—the state's solar power capacity, which has doubled since the end of 2021.

RETC

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