MAKE DATA MATTER.

FIRST EDITION

2019 PV INVERTER SCORECARD

PVEL
PV EVOLUTION LABS

Authors

Tara Doyle
Chief Commercial Officer
tara.doyle@pvel.com

Ryan Desharnais
Chief Technology Officer
ryan.desharnais@pvel.com

Michael Mills-Price
Head of Inverter and Energy Storage Business
michael.millsprice@pvel.com

Contributors

Arseniy Voropayev, Calibration Engineer
Adam Gushansky, Project Manager
Tori Clifford, Head of Marketing

About PV Evolution Labs

PV Evolution Labs (PVEL) is the leading reliability and performance testing lab for downstream solar project developers, financiers, and asset owners and operators around the world. With nearly ten years of experience and accumulated data, PVEL conducts testing that demonstrates solar technology bankability. Its trusted, independent reports replace assumptions about solar equipment performance with data-driven, quantifiable metrics that enable efficient solar project development and financing.

The PVEL network connects all major PV and storage manufacturers with 300+ global downstream partners representing 30+ gigawatts of buying power. PVEL's mission is to support the worldwide PV downstream buyer community by generating data that accelerates adoption of solar technology. Learn more online at pvel.com.

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MAKE DATA MATTER.

FOREWORD: A NOTE FROM OUR CEO

Inverter performance is the most important driver of solar project profitability. When inverters fail, the entire system produces less energy – or none at all. Maintenance costs compound financial losses. **Yet very few PV equipment buyers require independent testing that assesses inverter reliability and performance.**

Our collective requirements for inverter procurement lag far behind those for PV modules and they are inconsistently enforced. Instead, as in the early days of unsophisticated PV module procurement, buyers rely on certifications, brand names, datasheets and warranties to evaluate inverter bankability. Field observations of inverter failure prove that this process does not identify problem products.

The challenge is that project stakeholders lack the institutional knowledge and data required for in-depth technical due diligence. Inverters are complex, multi-functional power electronics driven by sophisticated software. They optimize system-level power output, interface with the local utility grid, monitor and communicate energy production data, and even ensure PV systems shut down in unsafe conditions.

PV Evolution Labs (PVEL) began inverter performance and reliability testing back in 2014. Over the past five years we developed rigorous evaluations for inverter diligence, then tested the products available in the commercial market and those installed in field sites around the world. **PVEL is the only independent lab in the world that offers an inverter test Program designed by and for downstream buyers.** Our PV Inverter Scorecard compiles these results. It is the first objective, comprehensive inverter benchmarking report that is publicly available to PV buyers.

PVEL has compiled this Scorecard to close the industry's knowledge gap in inverter reliability and performance. PV inverter buyers can use this report to both better understand the products they source and to develop robust procurement strategies that ensure inverters meet quality and financial performance expectations.

Data-driven inverter sourcing is critical to understanding the economic performance of solar projects – especially as systems age. The results in this Scorecard demonstrate that PV equipment buyers need objective performance and reliability data to mitigate the technology risks inherent to inverters. PVEL is pleased to share this important data with the global PV industry.

JENYA MEYDBRAY
CEO
PV Evolution Labs (PVEL)

INVERTER TECHNOLOGY OVERVIEW

Over the past two decades, inverters have advanced from cumbersome and heavy pieces of equipment with limited functionality to highly advanced power electronic devices. Modern inverters balance demands for significant power density and operational efficiency while performing under an ever-evolving set of grid and safety mandates. **Within an operating PV plant, inverters are solely responsible for more operational functions than any other PV system component.**

What do inverters do?

PV inverters ensure the entire ecosystem of a PV system operates continuously. Their functions span management of the direct current (DC) side of the system where the PV modules operate, to interacting with the alternating current (AC) side where the electrical grid operates, while reporting all of this information continuously.

Complex functions involving efficiency, safety, availability and communications are all required to perform consistently and reliably for decades, despite harsh environments with unpredictable and sometimes non-ideal behavior on both the AC and DC sides. The following is an overview of the inverter's five main functions.

Inverters at a Glance: Five Main Functions

- Convert DC to AC
- Maximize Power Output
- Interface with the Utility Grid
- Reporting
- Ensure Safe PV System Operation

1 **Convert Direct Current ("DC") to Alternating Current ("AC")**
Solar PV inverters are primarily responsible for converting the DC energy from the interconnected PV modules into AC energy. This conversion process makes solar electricity accessible; AC is the standard used by most commercial, industrial and residential appliances and facilities. AC is also the basis for existing utility grid design and infrastructure.

2 **Maximize Power Output**
Power is the product of current and voltage (Current × Voltage = Power) as indicated in the blue curves in Figures 1 and 2 on the right. A typical PV module's maximum power voltage (V_{mp}) is approximately 35-50 volts. With 15 modules serially connected in a PV string, this net summation results in a string voltage of 525-750 V_{mp}. The inverter scans this continuously to identify which voltage point corresponds to the maximum power at which to operate the string of PV modules.

Inverters are responsible for continuously tracking the maximum power point (MPP) of the solar array throughout changing environmental conditions. Any non-ideal system conditions, such as non-uniform shading from leaves or bird droppings, mismatched modules or degraded modules, can result in multiple local peaks in this curve. Many inverters identify the wrong peak and settle there, which results in overall reduced energy yield for the PV system.

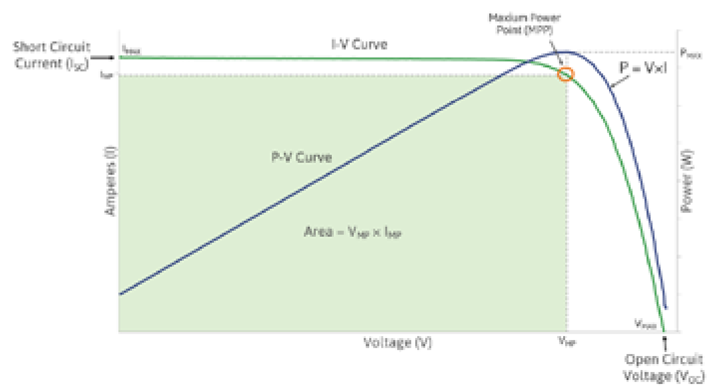


Figure 1: Maximum Power Point Tracking (MPPT)

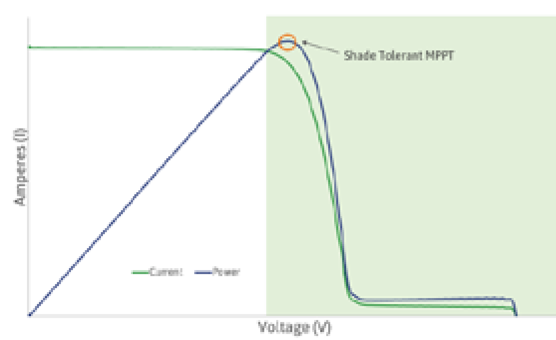


Figure 2: Shaded Module IV Curve

3 Interface with the Utility Grid

Inverters are responsible for interconnecting with the utility grid. In many markets, this task is complicated by the aging electrical grid infrastructure and the increasing adoption and penetration of solar PV. According to Rhodes, the average age of power lines and transformers in the U.S. is 28 years. Power generation plants are decades old, except for solar and wind whose average age is less than 10 years.[1] The situation is similar in most countries.

Increasingly, inverters are tasked with advanced grid-interfacing requirements, including operating through system-wide and local power disruptions to reduce the risk of wider electrical infrastructure problems and outages. Under these conditions, the inverters inject both real and reactive power into the grid, stabilizing system level voltage and frequency, while reducing system losses by supporting the local loads.

Regional behaviors can cause the grid frequency of the electrical power system or the voltage provided by the utility to operate in unstable conditions. These events strain the grid and increase the risk of brown-outs or black-outs. Examples include:

- Local industrial loads switching on and off
- Weather events leading to high use of air conditioning or heating demand
- Grid fault events whereby power needs to be re-routed to loads

The ability of inverters to stabilize the grid by modulating a PV system's power output is both an opportunity and a risk. On the opportunity side, the inverters are closer to the local loads, reducing line losses when compared to central generation stations. They also have the capability of providing reactive power in addition to real power, playing a vital role in helping maintain the distributed line voltages of the area electrical power system. The risks come from foregoing the harvest of real power, which is the existing driver of compensation for asset owners.

No other generating technology is so widely distributed and capable of mitigating local events.

The stabilizing role that inverters play during these frequent, non-ideal conditions is defined by evolving local grid-code regulations. However, not all inverters are capable of operating as expected, required or advertised. As PV power penetration into an electrical grid increases, these adaptive grid response capabilities become more important.

4 Reporting

Inverters are responsible for aggregating, compiling and transmitting power output data. This often includes a range of raw data, error codes and other diagnostics. Whether it is a small residential system or a multi-megawatt utility-scale project, many inverters have hard wired ethernet, Bluetooth and/or WiFi connection capabilities for communications. For inverters with distributed module-level electronics or external rapid shut-down devices, additional communication is required. These communications can be wireless or through the power line.

Communications are notoriously unreliable. When communications falter, the most common solution is an expensive technician site visit to simply power cycle or reset the wireless communication device.

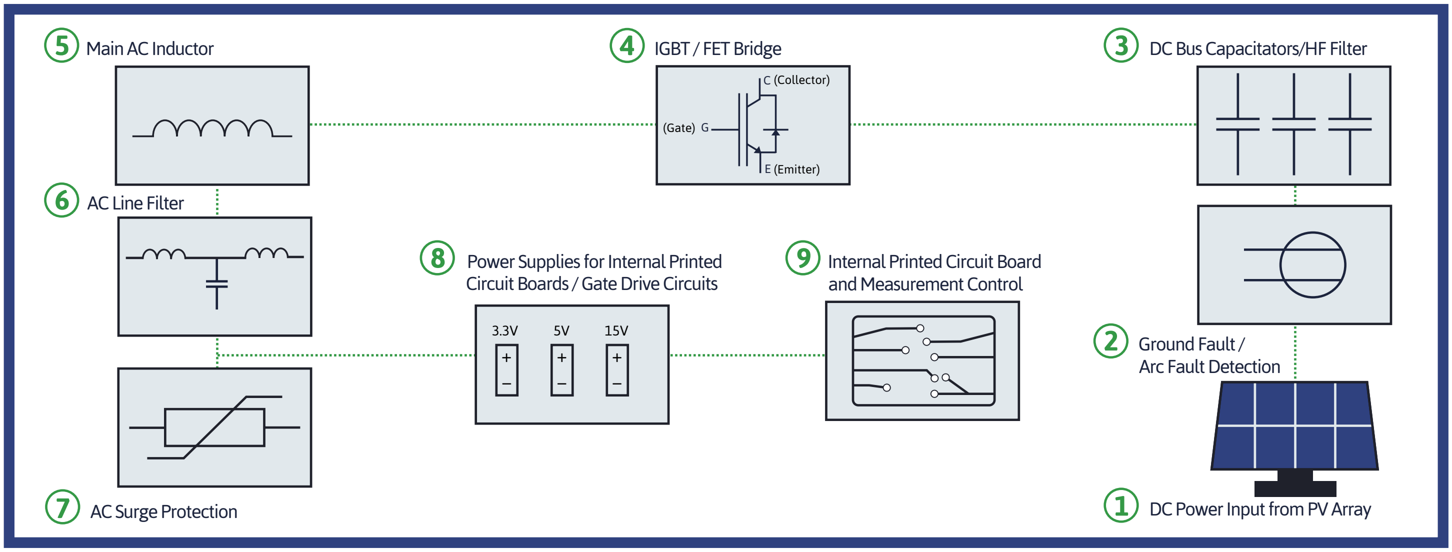
5 Ensure Safe PV System Operation

System aging and material degradation (i.e. insulation around system wiring, module backsheets) can expose electrical conductors to the environment which, in turn, can cause electrical arcs. Electrical arcs have a characteristic signature or fingerprint in the frequency domain that inverters are programmed to identify.

The inverter is required to shut down the system when electrical arcs are observed. However, as PVEL's testing demonstrates, not all inverters can do this effectively.

[1] Rhodes, Joshua D. "The old, dirty, creaky US electric grid would cost $5 trillion to replace. Where should infrastructure spending go?" https://theconversation.com/the-old-dirty-creaky-us-electric-grid-would-cost-5-trillion-to-replace-where-should-infrastructure-spending-go-68290

ELECTRICAL DIAGRAM



1 DC Power Input from PV Array

DC power from the PV array travels through wiring to the inverter. The array's DC power output varies in response to environmental conditions, so the inverter constantly monitors the current and voltage of each input.

2 Ground Fault / Arc Fault Detection (GFCI/AFCI)

The inverter is responsible for monitoring the array input power, voltage and current, looking for potential safety impacts such as ground fault current and arc fault current. If detected, the inverter should safely shut down the PV system. If the GFCI/AFCI subsystem degrades or doesn't perform properly, the inverter may not identify these conditions correctly, creating safety hazards.

3 DC Bus Capacitors / High Frequency (HF) Filter

DC bus capacitors smooth the variable input power generated by the PV array by maintaining a constant voltage across their terminals. The HF filter removes the switching noise from the DC bus side of the inverter during operation. The switching noise is generated by the inverter creating AC current from the DC input. These components operate over specific temperature ranges and may degrade when exposed to moisture and adverse environmental conditions. They are also prone to deteriorating when exposed to voltages and currents they are not designed to withstand.

4 Insulated-Gate Bipolar Transistor (IGBT) / Field-Effect Transistors (FET) Bridge

These components switch the DC current to AC current using a technique called "pulse width modulation" (PWM). These switches operate at very high speeds allowing the DC input power to be "inverted" into AC output power. IGBTs are typically used in string inverters and FETs are used in module-level power electronics due to the power processing needs of the system. Overvoltage, overcurrent and excessive temperature – as well as the mechanical failure of nearby diodes, circuit boards and capacitors – can cause these components to operate less efficiently or fail entirely.

5 Main AC Inductor

AC inductors are usually insulated metal wires, or coils, around a central core. As the electric current passes through the inductor, the coil creates a magnetic field that stores and releases energy, resisting changes in current. The inverter uses the energy stored in this magnetic field to apply resistance that keeps the voltage and current in sync. This process rectifies the square waves switched by the IGBTs into an AC sine wave. Inductors are unlikely to fail as they are generally made of iron and copper, however their behavior and ability to smooth the switched power will fluctuate based on a number of environmental and electrical factors. These components are susceptible to saturation, overheating, and vibration-related damage over time.

6 AC Line Filter

The AC line filter removes high frequency content caused by the IGBT switching as well as any noise that is able to propagate through the inductor, resulting in a cleaner sine wave. This reduces harmonic distortion from impacting the local interconnected loads and grid. AC filters are composed of inductors, capacitors and resistive components and can be susceptible to damage from electrical and environmental conditions.

7 AC Surge Protection

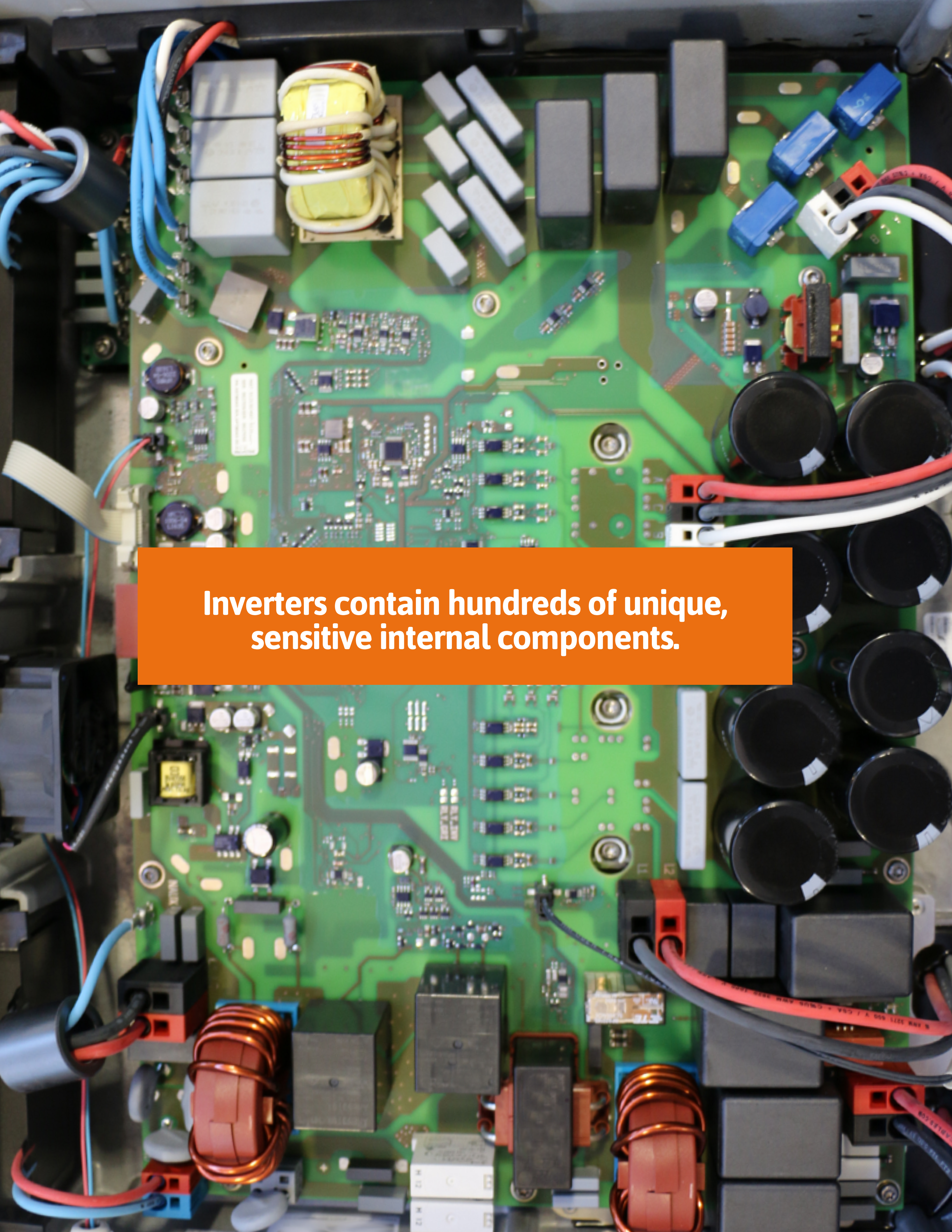
The AC surge protector is designed to limit damage to the inverter from voltage spikes present on the electrical grid due to switching events, lightning or other high voltage conditions. These devices are similar in operation to surge suppressors found in power supplies in your home, and are necessary to reduce chances of a surge damaging the inverter.

8 Power Supplies for Internal Printed Circuit Boards (PCBs) / Gate Driver Circuits

These internal power supplies ensure that the inverter's communications and measurement systems have the necessary voltage to operate internally. Internal circuits for measurement and control of inverters require, as an example, 3.3V, 5V and 15V power. These devices maintain the internal needs of the system including the micro-controller and measurement circuits. If these power supplies fail, the inverter will stop functioning.

9 Internal Printed Circuit Board Measurement and Control

This is effectively the "brain" of the inverter. It is responsible for managing all measurements, switching events, and control operations. The firmware that governs the behaviors of the inverter are stored in the Central Processing Unit (CPU) and other micro-controllers. This includes externally facing controls, internal monitoring and data processing. These systems are susceptible to mis-programming, electrical stresses, environmental conditions, vibration and shock.



Inverters contain hundreds of unique, sensitive internal components.

UNDERSTANDING INVERTER RELIABILITY

Inverters are more likely to fail than any other component of a PV system.

According to research from the Electric Power Research Institute (EPRI), inverters are the #1 cause of corrective maintenance tickets in PV power plants. The data is based on tens of thousands of maintenance logs generated from large-scale, ground-mount PV plants in the U.S. that have been operational for as many as 10 years. **As the solar PV industry matures and asset owners focus more on total system lifetime cost – and not just initial costs – inverter reliability becomes increasingly important.**

There are problems with warranties.

Many PV buyers rely on warranties to protect them financially in the event of inverter failure. This strategy can, and has, backfired for many reasons including but not limited to the manufacturer exiting the solar market and the lack of suitable and cost-effective replacements.

When suitable inverter replacements are not available, the PV system may require rewiring or rework to prevent electrical mismatch and to ensure compliance with new products.

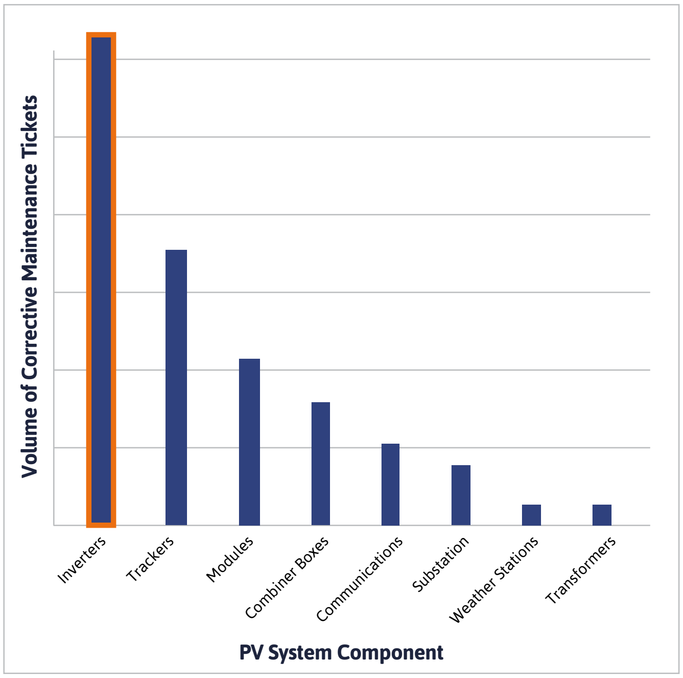


Figure 3: Source of Corrective Maintenance Tickets
Courtesy of the Electric Power Research Institute

Why is inverter failure so common?

1. **They're multi-functional.**

   Inverters are responsible for more tasks within a solar plant than any other system component. Manufacturers are under continuous pressure to increase inverter digitalization and to expand existing grid-interactive functionality. Inverters are expected to operate over a wider set of environmental and electrical conditions for longer durations, which further stress internal components.

2. **They're made of hundreds of components.**

   Inverters contain hundreds of internal components, operational subsystems and circuits. Failure or mis-operation can occur when any one component stops functioning. Like many upstream solar manufacturing companies, PV inverter manufacturers must also respond to cost pressure to remain competitive. As is often the case with material supply, cheaper components may not adhere to the highest quality standards or provide sufficient design margin to meet the operational life of the inverter.

3. **They're operated by software.**

   All commercially available inverters require complex software/firmware to operate. The firmware is central to aggregating the internal and external measurements, performing complex analytics functions, and ultimately making decisions about how to operate. It is becoming more common for manufacturers to leverage software/firmware revisions to "fix" an operational or systemic field issue. These remote firmware updates can be problematic if independent testing is not conducted prior to deployment.

> "When inverter manufacturers push out firmware updates without notifying asset owners, it absolutely causes problems – especially for projects with energy storage. The only way to prevent major performance losses is to diligently scrutinize system performance, then act immediately when issues are identified.
>
> **AMANDA BYBEE** CEO, Amicus O&M Cooperative

Inverter cost of ownership does not reflect supplier estimates.

"In view of the high costs associated with inverter failures, understanding the root cause of component failures, methods to access or ensure reliability and forecast lifetime of the power conversion electronics and their components through testing and quality standards becomes vital." [2]

A recent study assessed the true cost of inverter ownership. The chart in Figure 4 (right) compares the actual cumulative cost of inverter ownership with cost estimates provided by manufacturers for four years using data from 400 failure reports. Two of the four inverter types studied generated much higher costs than anticipated.

[2]*Peter Hacke, et. al.: "A status review of photovoltaic power conversion equipment reliability, safety and quality assurance protocols". Elsevier Ltd.*

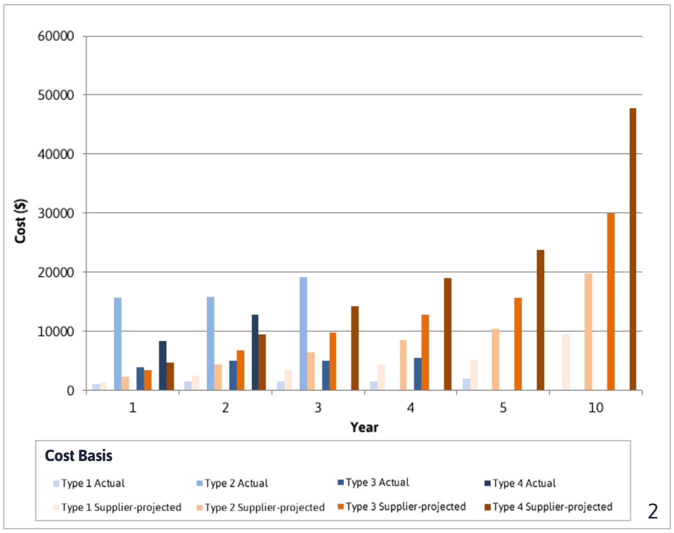


Figure 4: Inverter Cost of Ownership (Cumulative)

> "In the first five years of solar project operation, inverters are among the top determinants of economic success. When an inverter does not perform as expected, it almost always results in underperformance and economic losses.
>
> **JOE SONG** Vice President of Project Operations, Sol Systems

COMMON TYPES OF INVERTER FAILURE

Type	Description	Impacts
Out-of-Box	Inverter is "dead on arrival" and will not operate	**Power:** May lose days of production due to delayed commissioning **Economic:** Financial losses due to installation delays **Solution:** Inverter replacement or rework required
Interconnection	Inverter is not interfacing with utility grid; cannot measure AC/DC	**Power:** Reduced power output **O&M:** Requires technician visit (truck roll) **Solution:** Inverter replacement likely
Communication Failure	Inverter is not reporting energy production; display malfunctioning	**Economic:** Potential financial losses for third-party asset owners and off-takers, billing delays **O&M:** Requires technician visit (truck roll) **Solution:** Complete inverter or inverter component replacement likely
Inverter Underperformance	Inverter is not operating at peak power window	**Power:** Reduced power output **Economic:** Financial losses for asset owners and off-takers **O&M:** Requires technician visit (truck roll) **Solution:** Inverter replacement likely
AFCI/GFCI Nuisance Tripping	Inverter mistakenly detects arc or ground fault interrupt	**Power:** Total production loss after every instance of interruption **Economic:** Financial losses for asset owners and off-takers **O&M:** Requires technician visit (truck roll) to restart inverter **Solution:** Power cycling the unit
Component Failure or Wear-out	Internal component stops operating, sometimes due to "infant mortality" or normal wear and tear	**Power:** Partial or total production loss **Economic:** Financial losses for asset owners and off-takers **O&M:** Requires technician visit (truck roll) **Solution:** Inverter or inverter component replacement required
Catastrophic Failure or Failure to React to Arc or Ground Fault	Fire, explosion, sustained arcing	**Power:** Total production loss **Economic:** Major financial losses for asset owners and off-takers; significant safety liabilities **O&M:** Requires technician visit (truck roll) to diagnose inverter as well as other affected system components **Solution:** Inverter replacement required; other system components may also require replacement

> As developers and financiers are demanding more insight from independent engineers regarding the expected reliability and life of new PV inverters, the foremost option available to provide that insight is third party lab testing. **Independent, third party lab test results can produce real data in support of otherwise weakly substantiated product claims and expectations.**
>
> **DOUGLAS BLODGETT** Director - Electrical Systems, DNV GL, Renewables Advisory

INVERTER TESTING

Most inverter manufacturers have developed their own in-house reliability testing methods. They vary greatly across manufacturers and are rarely transparent to buyers. Some local markets have established their own test standards for inverters, but they are inconsistently applied. **Due to the lack of sufficient standards or empirical test data, it is common for inverter buyers to rely on brand names, datasheets and warranties rather than independent test data when making inverter purchasing decisions.**

The Limitations of Certification Testing

While there are standards for short-duration inverter certification tests, these tests do not address inverter long-term reliability or performance. Certifications only ensure that solar inverter products meet baseline standards:

- UL 1741 and IEC 62109.1: validates the safe operation of the inverter
- IEEE 1547 and IEC 62109.2: assesses safety and interoperability with utility grid

In general, all short-duration certification tests:

- **Are designed to identify safety issues with the product**
- **Are conducted on hand-selected samples provided by the inverter manufacturer**
- **Are only required for existing products after design changes – not when software is updated or key components are changed**
- **Do not provide data about component de-rating or product durability**
- **Involve in-lab evaluation only**

Standards Development

PVEL is proud to participate in several industry working groups led by IEEE, IEC and NREL that aim to develop urgently needed inverter test standards for extended reliability and real-world performance.

However, standards development for accelerated testing is a challenging, years-long process for any product, and particularly for inverters which are complex.

Extended Reliability and Performance Tests

The only way to truly determine whether or not an inverter will perform reliably for its expected lifetime is to deploy the product in the field, monitor its performance and simply wait until its useful life is complete. Unfortunately, that is not feasible or desirable for commercial PV products. As well, models constantly change as do operational requirements, which is evident from grid code updates and local jurisdictional requirements.

Accelerated laboratory testing and controlled field testing are the best alternatives to long-term field exposure for evaluating product reliability and performance. Unlike certification tests, extended reliability tests help buyers predict product reliability up through and after the warranty period expires. Test durations extend far beyond certification testing to focus on the wear-out mechanisms of inverters that occur after the product has operated in the field for an extended period of time.

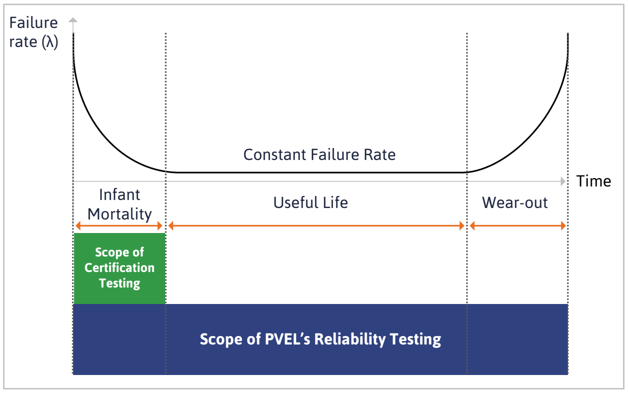


Figure 5: A "bathtub curve" failure rate

PVEL's testing replicates inverter failures observed in the field by stressing the product physically and electrically. The results help PV inverter buyers model lifetime product performance and compare different products.

SCORECARD METHODOLOGY

The data presented in the following pages are results from PVEL's Inverter Product Qualification Program (PQP), which was first introduced in 2014. PVEL remains the only independent lab to offer an extended reliability and performance test Program informed by the needs of the global downstream community.

Inverter PQP Process

PVEL established our Inverter PQP with the same two goals that guide all of our testing programs:

1. To provide PV equipment buyers and power plant investors with independent, consistent reliability and performance data that supports effective supplier management.
2. To independently recognize manufacturers who outpace their competitors in product quality and reliability.

Scoring and Ranking

Thirty-five different inverter models produced by 12 different manufacturers were evaluated for the 2019 Scorecard. The products tested comprise string inverters (both three-phase and single-phase), microinverters and power optimizers.

To determine the Top Performers, PVEL identified specific metrics and scores for each test sequence as described in the following pages. The Top Performers are identified in each of the respective test sequences as either the top three scorers of the test population or the top percentile of the range of results, depending on the scoring evaluation criteria. Note that some inverter model types were not subjected to all tests, or some results may not have been available at the time of publication. Buyers should contact PVEL to obtain the full reports.

The Key Principles of the PVEL PQP

No hand-picked samples
Products submitted to PQP testing are witnessed in production - from the opening of raw materials packages through every step of the production process, including final packaging with tamper-proof tape.

Empirical data
The PQP replaces performance assumptions with empirical metrics that help PVEL's Downstream Partners optimize revenue and energy yield models. PVEL produces detailed PQP test reports that our Downstream Partners freely access.

Updated regularly
PVEL seeks and utilizes downstream buyer (i.e. EPC, developer, asset owner, financier, insurance firm) input to evolve our Inverter PQP on a regular basis. The PQP keeps pace with rapidly evolving technology and inverter product demands from field applications.

Standardized processes
All inverters are tested in the same way, using consistently calibrated equipment and in consistent laboratory environments. This enables a leveled comparison across all manufacturers.

PVEL's PQP Tests

New inverter functions, features and advancements are constantly released to keep pace with market and interconnection demands. The rapid pace of technology development requires a test program that stays current in order to properly assess and qualify new products. PVEL updates our PQP regularly to provide buyers with consistently relevant data to evaluate inverter products. Tests featured in the 2019 Scorecard are listed below.

Passive Chamber Testing	Thermal Performance Characterization	Performance Testing: Efficiency	Performance Testing: Operational Window	Field Testing
Damp Heat	Powered Thermal Cycling	MPPT Efficiency	AC Operational Window	Ground and Arc Fault
Thermal Cycling	High Temperature Operation	Conversion Efficiency	DC Operational Window	30-Day Runtime
Humidity Freeze	Low Temperature Operation	Energy Harvest	Transient Response	

TEST RESULTS

PASSIVE CHAMBER TESTING OVERVIEW

Background

Unpowered environmental chamber tests evaluate passive aging of the inverter from environmental stress. Product construction, bill of materials and design are all assessed. Inverters are equipped with a large number of circuit boards, silicon chips and integrated products which can each age or fail in the field. They can cause damage to specific functionality or they can cause the entire inverter to fail entirely. These components are all stressed when inverters are exposed to common environmental conditions such as sunlight (UV), rain, temperature swings, heat, humidity and snow.

There are various techniques to minimize component aging risks. For example, circuit boards typically utilize thin conformal coatings to protect against moisture. However, these coatings can degrade which reduces their ability to protect the printed circuit board. Moisture ingress is highly damaging to many internal electrical components and can pose a safety concern.

Testing Overview

This series of tests builds and expands on the PV module IEC 61215 test standard:

- **Damp Heat:** Temperature is held at 85° C and humidity is held at 85%
- **Thermal Cycling:** Temperature is cycled between -40 °C and 85 °C
- **Humidity Freeze:** Conditions are cycled between 85° C / 85% humidity and -40 °C

Since these tests are designed primarily to identify passive mechanical and electro-mechanical defects, inverters are not connected to a power source or electrical load inside the environmental chambers. To determine the impact of the environmental conditions on performance, each inverter is characterized in a series of electrical tests before and after entering the chamber and inspected visually for other failures. For all tests in this category, inverters were evaluated for Scorecard ranking according to these criteria: electrical performance before and after stress, and physical changes of the device under test.

Why the Tests Matter

Unpowered environmental chamber tests reproduce failure modes and they reveal reliability issues that are commonly observed in the field, such as:

- Coating delamination
- Corrosion
- Water condensation in wiring compartments
- Discoloration and melting of external displays and controls
- Electro-mechanical fatigue of solder joints and electrical connections

These failure modes can cause inverter failures, system underperformance and safety concerns.

Failure of individual inverter components can cause the entire inverter to fail or reduce product functionality. All inverters that are deployed to PV sites should pass these tests; however, that is not always the case.

Passive Chamber Testing Top Performers (in Alphabetical Order)

- Delta M8-TL-US
- SMA SB7.7-ISP-US-40

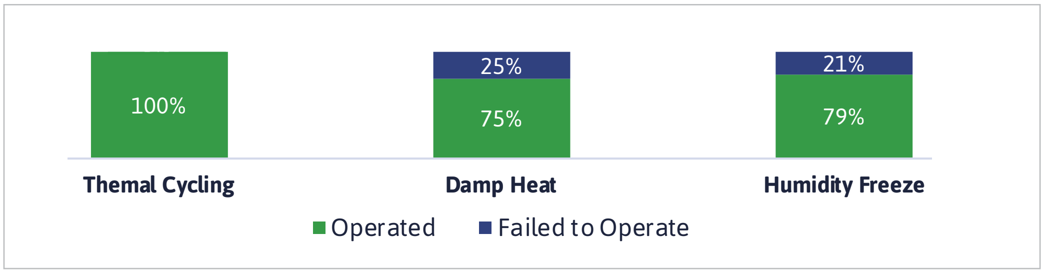


Figure 6

As shown in Figure 6 (left), PVEL found that 21-25% of all inverters subjected to these passive environmental tests failed to operate as intended following the exposure.

Image 1

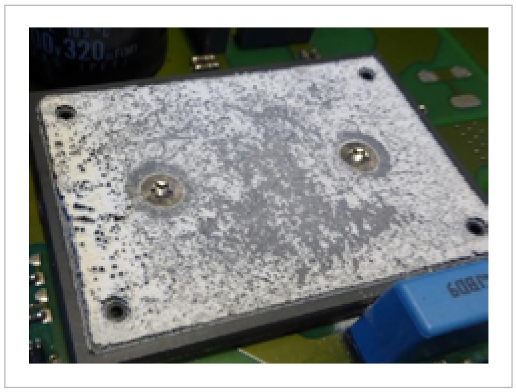


Image 2

A review of the equipment following exposure shows faulty moisture protection of the components (as shown in Image 1, far left), delamination and internal corrosion (Image 2, left) as the most common failures.

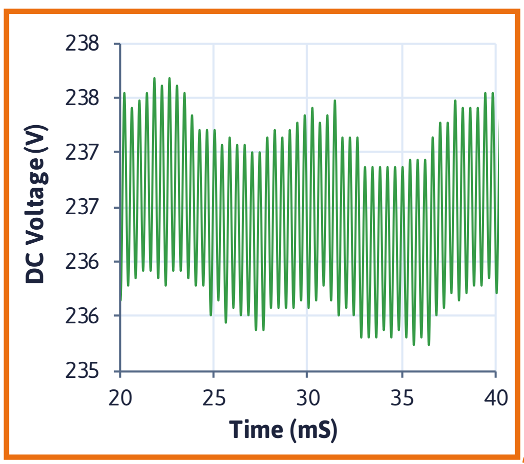


Figure 7

Figure 7 (above) and Figure 8 (right) show an example of an inverter that remained operational, but in a degraded state, following stress testing. These Figures depict a significant change in DC ripple, emphasizing the criticality of understanding not just whether or not an inverter operates following stress testing, but in what state it operates.

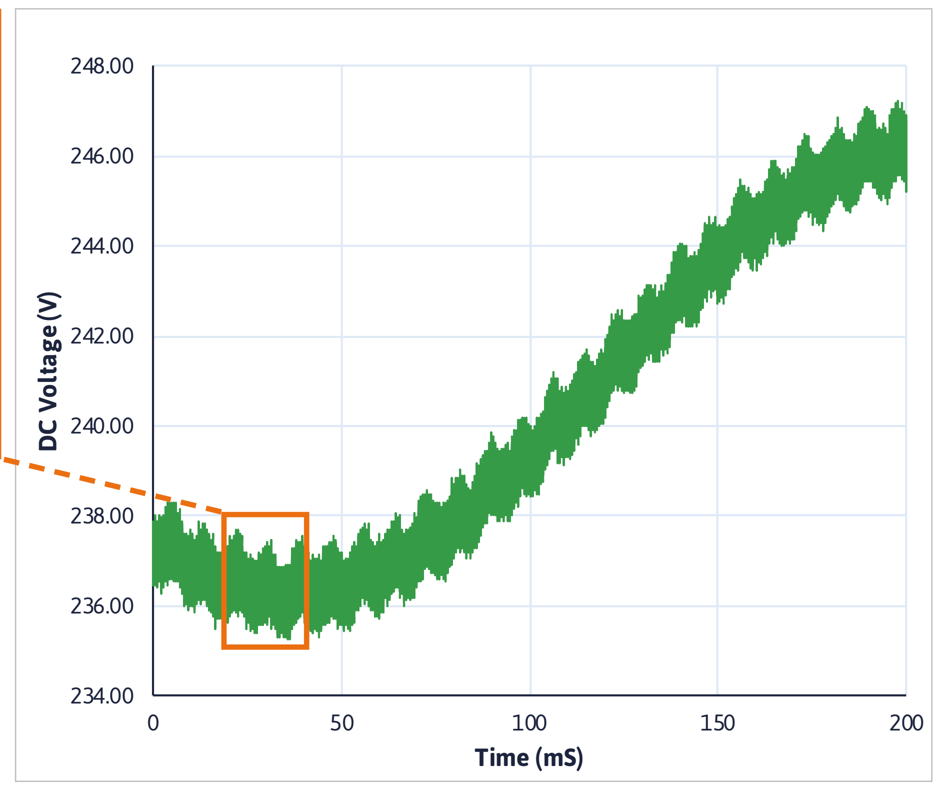


Figure 8

THERMAL PERFORMANCE OVERVIEW

Background

Thermal Performance Characterization evaluates inverter performance across the operational temperature windows provided by the manufacturer. Temperature conditions range widely in the field, from cold nights to hot, humid conditions during daytime operation. Each inverter contains hundreds of components that may be subject to thermal drift, which can cause individual components to operate beyond their temperature limits. Operation outside of temperature limits can cause degradation or complete failure. Since temperature directly impacts an inverter's electrical performance and long-term reliability, manufacturers provide product-specific maximum and minimum ambient temperatures for operation.

Testing Overview

PVEL uses the IEC 62093 test standard as the foundation for its Thermal Performance Characterization tests. In all thermal performance tests included in the PQP, the inverter is placed in an environmental chamber while connected to a power supply and electrical load that together replicate an operational PV system in the field. Next, the following conditions are applied:

- **Powered Thermal Cycling:** Thermal cycling is performed across the full operational temperature range of the inverter from maximum to minimum operational temperatures.
- **High Temperature Operation:** The maximum operational temperature is sustained while the inverter is powered by a solar array simulator.
- **Low Temperature Operation:** The minimum operational temperature is sustained and the inverter is allowed to start operation after a thermal soak event in an environmental chamber. This process brings component temperatures to their minimum values.

PVEL affixes thermocouple sensors to measure the temperatures of individual internal components for the full duration of all three tests. Multiple components along the main power path of the inverter are monitored during these powered thermal tests. PVEL then compares the electrical characteristics and temperatures to the individual component datasheets for verification of design parameters. For all tests in this category, inverters were evaluated for the Scorecard according to these criteria: component temperature, current total harmonic distortion (ITHD) and conversion efficiency.

Why the Tests Matter

Each inverter component has a device rating, or maximum limit, for temperature, voltage, current and power. As an example, most inverters are designed such that the components never reach the maximum allowable temperature level. In other words, **inverters have built-in safety mechanisms that protect components from high temperatures**. However, through the PQP we have observed individual components operating well past the temperature limits. Not all inverter manufacturers have designs that effectively protect individual internal components.

Exceeding temperature limits reduces the lifetime of the component and ultimately the inverter itself. Performance is also reduced in the short term. For example, if a chip temperature starts to drift beyond its allowable maximum temperature, the inverter de-rates, or reduces, its output power to avoid over-stressing that component. **When an inverter intentionally de-rates to protect itself from accelerated aging, the total amount of energy available from the PV modules is not converted.** The inverter strays from the maximum power point and operates at reduced power, thereby reducing the energy harvest or yield of the system.

As intense pricing pressure on inverter manufacturers continues, some may utilize smaller, less expensive and less robust components. Using a silicon chip with lower temperature or voltage limits may reduce costs in the short term, but it may prove to be a problem for system owners because it can result in economic loss due to reduced yield.

If individual inverter components operate at elevated temperatures due to poor internal airflow or low design margins, the inverter may intentionally reduce output power in order to lower the component temperature. This leads to reduced energy harvest for the system owner and may shorten the inverter's expected lifetime.

Powered Thermal Cycling Top Performers (in Alphabetical Order)

- Delta M80U
- Schneider Context CL-60A
- SMA SB7.7-1SP-US-40

High Temperature Operation Top Performer (in Alphabetical Order)

- Delta M8-TL-US
- Fronius Symo 24.0-3
- Huawei SUN2000-11.4KTL-US

Low Temperature Operation Top Performers (in Alphabetical Order)

- Delta Solivia 3.8 TL
- Huawei SUN2000-11.4KTL-US

Powered Thermal Cycling operates an inverter at the extremes of its environmental and electrical capabilities. This compounded stress can lead to failures. Shown in Figure 9 (below) is an inverter that failed 30% through the test sequence with an inability to return to operation.

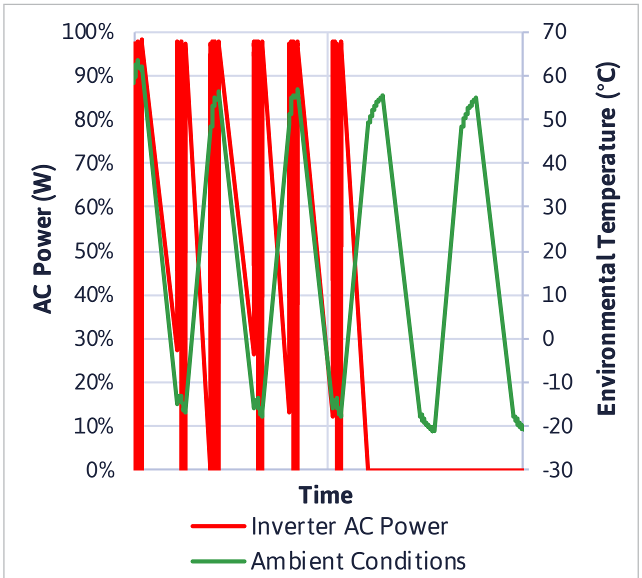


Figure 9

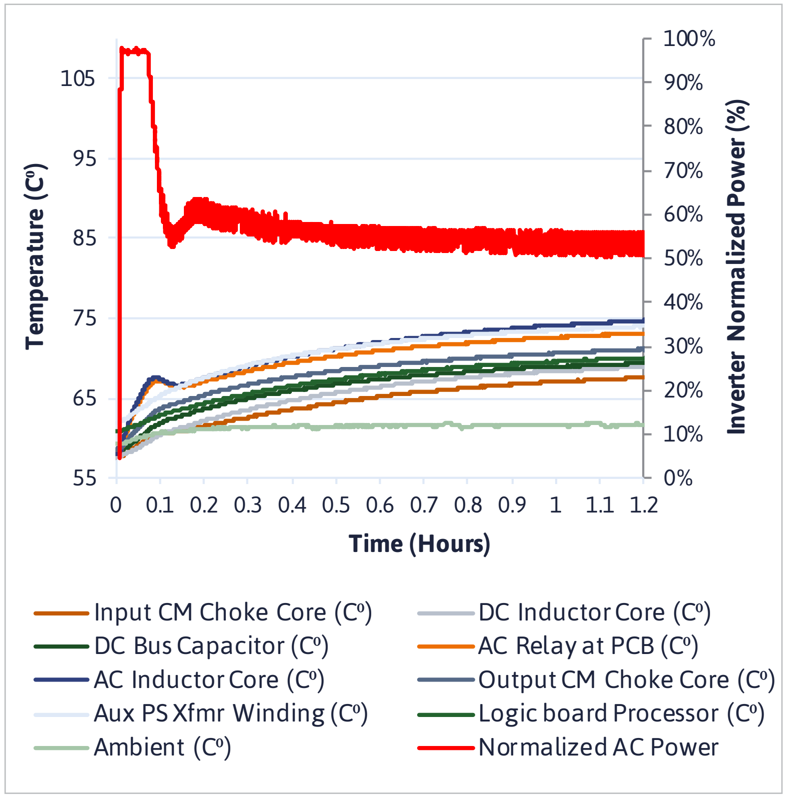


Figure 10

Thermal management goes hand in hand with design specifications for components. In Figure 10 (above right), the inverter de-rates to avoid significant temperature increases of its internal components during the High Temperature Operation test.

Conversely, the test results shown in Figure 11 (right) indicate that the inverter allowed some internal components to rise >75° above ambient during the Low Temperature Operation test .

This can lead to accelerated thermal cycling stress and electro-mechanical fatigue of internal inverter connections and interfaces.

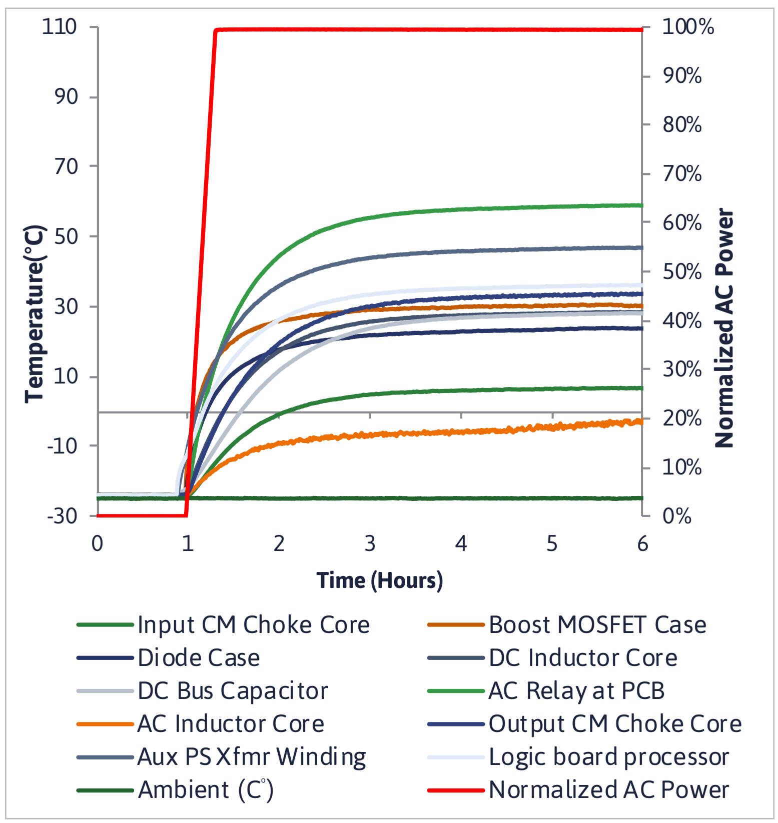
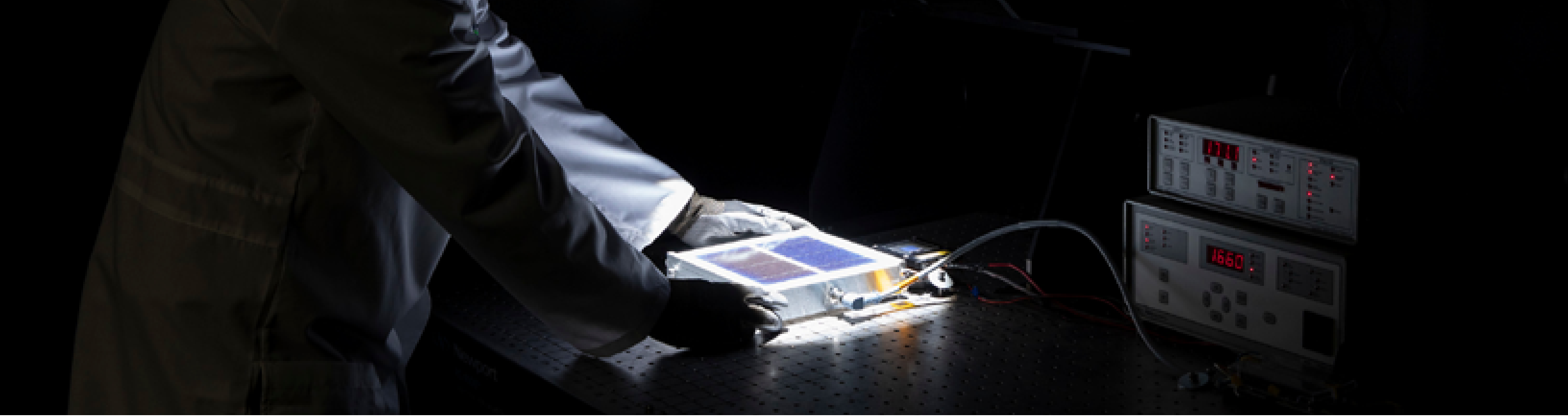


Figure 11



PERFORMANCE: EFFICIENCY OVERVIEW

Background

Performance tests help buyers analyze an inverter's performance under widely varying field conditions in a controlled laboratory environment. At a high level, they focus on the two most fundamental inverter functions: converting DC to AC energy and interconnecting PV systems to the utility grid.

Both operations require inverters to accurately monitor DC current and voltage generated by the PV modules. In the field, these variables constantly change as PV modules are exposed to different irradiance levels, weather conditions and temperatures throughout the day. A leaf, bird dropping or fast-moving cloud can result in dynamic, non-ideal PV module output. The inverter's ability to monitor and respond to these conditions can either enhance or reduce the efficiency of the overall system.

Testing Overview

- **MPPT Efficiency:** The maximum power point of a string of PV modules is dynamic in the real world as irradiance, soiling, clouds, module temperature, degradation, and shading contribute to non-ideal operational conditions. MPPT algorithms have evolved over the years, and the most effective algorithms directly improve a system's financial performance. This test assesses the inverter's ability to track a PV system's maximum power point under a wide range of potential conditions. Inverters were evaluated for the Scorecard according to their response to tracking the MPP during low rates of change, high rates of change and static electrical conditions. These tests were performed in compliance with EN50530.
- **Conversion Efficiency:** Efficiency is often reported as a single number; however, conversion efficiency changes as environmental conditions change. Two inverters with identical datasheet efficiency numbers may actually have different conversion efficiency throughout a day in the field. This test determines the efficiency at which an inverter converts DC to AC under three different DC voltage conditions and across multiple power levels ranging from 10% to 100%. The output of the tests is a set of efficiency curves for each of the voltages at the respective power levels. Inverters were evaluated for the Scorecard according to their average weighted CEC efficiency.
- **Energy Harvest:** The ultimate metric for financial success is how efficiently the inverter converts available DC energy to AC output in the field. This test quantifies expected performance during morning start-up, full day operation, and evening shut-down conditions across varying daytime irradiance levels in a controlled laboratory environment. Inverters were evaluated for the Scorecard according to their performance across all (3) irradiance profiles.

Why the Tests Matter

These tests definitively demonstrate whether or not an inverter can actually perform as expected based on product datasheets when deployed in the field. Inverters are expected to operate under a broad spectrum of DC voltage levels, string configurations, ambient temperatures and irradiance levels. This complex range of conditions will impact efficiency and economic performance of the plant.

Project financial forecasts assume that inverters will operate, and efficiently convert DC to AC energy under a wide range of conditions. Some inverter products achieve this in the real world, but it should not be assumed for all.

MPPT Efficiency Top Performers (in Alphabetical Order)	Conversion Efficiency Top Performers (in Alphabetical Order)	Energy Harvest Top Performers (in Alphabetical Order)
• Delta M80U • Huawei SUN2000-30KTL-US • Schneider Context CL-60A	• Huawei SUN2000-30KTL-US • Huawei SUN2000-375W-USP0 • Schneider Context CL-60A	• Huawei SUN2000-28KTL • Huawei SUN2000-30KTL-US • Schneider Context CL-60A

As evidenced in the MPPT efficiency whisker plot shown in Figure 12 (right), there are a wide range of inverter responses under each of these conditions, including substantial outliers as tested in the PQP. Responses are captured showing >5% differential for low to moderate ramp conditions, > 16% for moderate to high ramp conditions and > 7% under static conditions. Top Performers in this test sequence had a 98-99% response rate for all three test conditions.

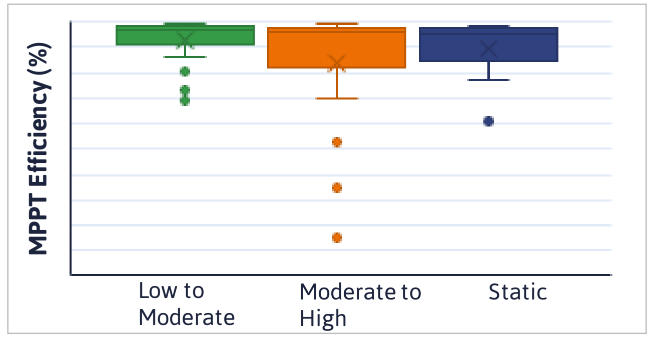


Figure 12

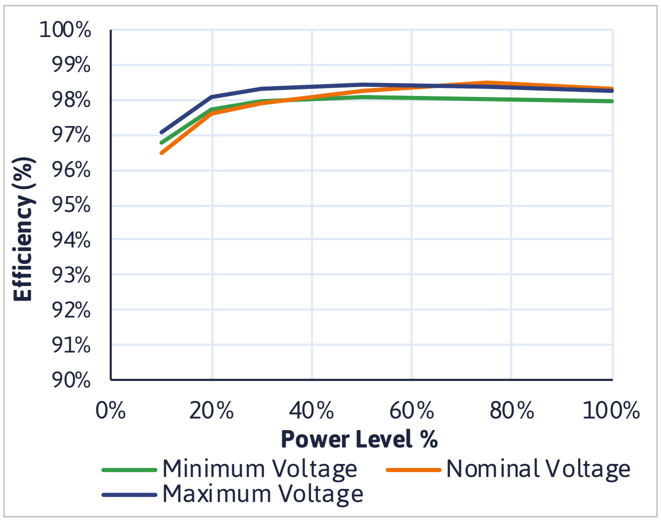


Figure 13

An example of a good response for conversion efficiency is shown in Figure 13 (above), with all conversion efficiencies for all three voltages above 98% for power outputs over 50% of nameplate.

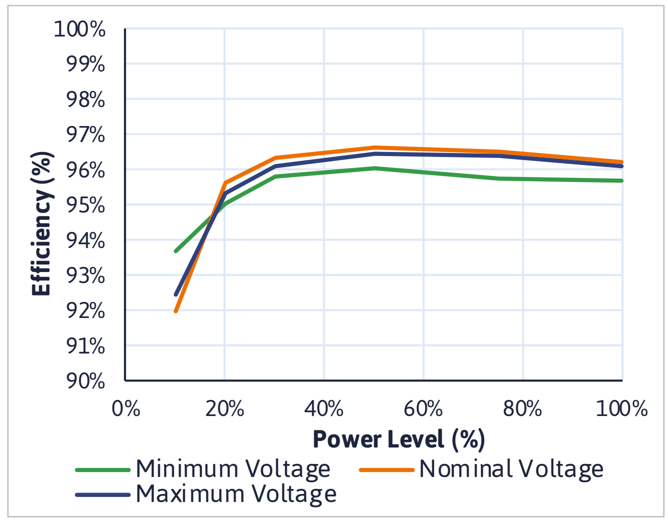


Figure 14

In the dataset highlighted in Figure 14 (above), we see the inverter's efficiency almost 2% lower for each of the DC voltages tested and across the 6 output power levels.

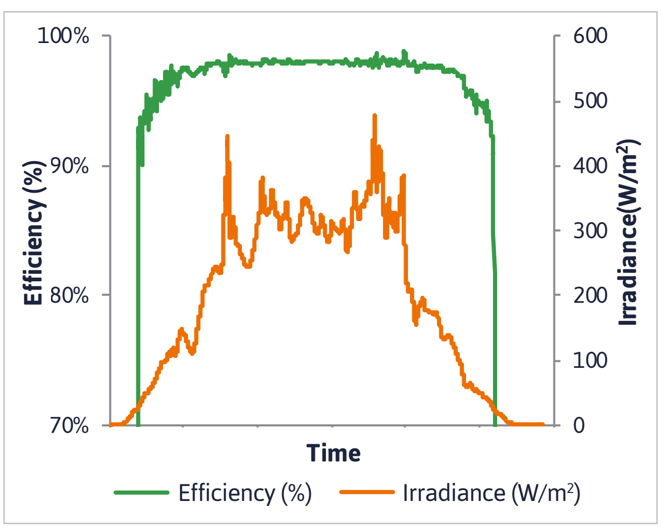


Figure 15

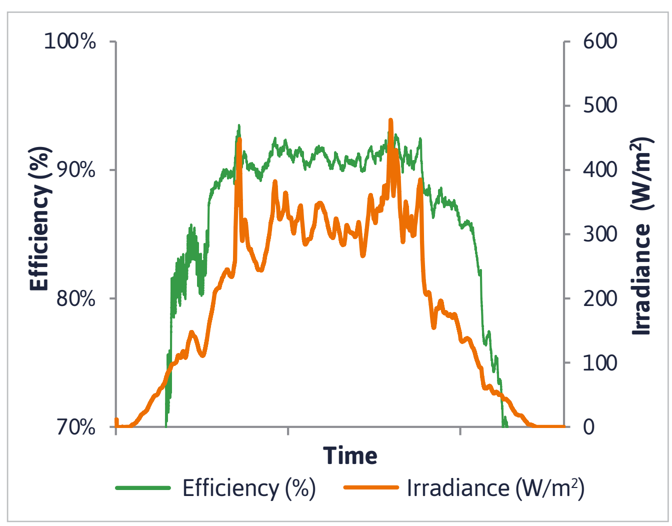


Figure 16

The Energy Harvest test, a combination of MPPT and Conversion Efficiency tests, evaluates total performance in converting DC to AC. Low performance is highlighted in Figure 16 (above right), while good performance is shown in Figure 15 (above left).

PERFORMANCE: OPERATIONAL ENVELOPE OVERVIEW

Background

PV systems are constructed around the world with different interconnection characteristics and requirements. The inverter is designed as a "one size fits all" device and is expected to operate as intended regardless of local electrical anomalies. The inverter's ability to continue to operate when fluctuations occur either on the AC output or DC input can have material impacts on total energy harvest over the lifetime of the system.

Inverters that have wide DC input ranges can support a more diverse set of possible stringing configurations, allowing flexibility for the designer or installer of the system. Similarly, those that can continue to operate when low or high voltage events occur on the electrical grid can greatly improve project returns over the system life.

Testing Overview

- **Operational Envelope:** These tests evaluate the inverter's ability to perform at full output power across the manufacturer-stated range of input and output voltages. The voltages are cycled through their operational ranges while multiple current, voltage and power measurements are captured. These test sequences capture when products de-rate when exposed to high or low voltage, on the AC or DC side. Inverters were evaluated for the Scorecard according to these criteria for the DC test: power output, continuous operation and low ITHD. For the AC test, the evaluation criteria were: continuous operation across stated MPPT range.
- **Transient Response:** The primary driver for performing transient response tests is to validate the bounds of inverter operation in response to changes in grid voltage and frequency. The inverter is evaluated to understand and document its trip-threshold, or the value and time at which it ceases operation. As grid codes continue to evolve to support more renewable energy penetration, wider AC voltage and frequency ranges are required of the distributed products. The inverter's transient response was evaluated for the Scorecard according to these criteria: response times and trigger points.

Why the Tests Matter

Operational performance tests give developers and asset owners insights into expected product performance in the design and construction phases, and after the products are fielded. The results of these tests can quickly help the developer improve stringing design, understand and identify products which are less prone to nuisance tripping, and improve financial and production models when designing projects.

All inverters are expected to operate continuously when the AC voltage and frequency are within local code limits and DC energy is available to the inverter. Testing has shown that inverters, although compliant with certification testing, may have narrower operational windows than stated, resulting in nuisance trip events, de-rated power output and ultimately loss of total energy production.

AC Operational Envelope
Top Performer (in Alphabetical Order)
- Delta M80U

DC Operational Envelope
Top Performers (in Alphabetical Order)
- Delta M80U
- Schneider Context CL 25000NA

Transient Response
Top Performer (in Alphabetical Order)
- Delta M8-TL-US
- Fronius Symo 24.0-3
- Huawei SUN2000-11.4KTL-US

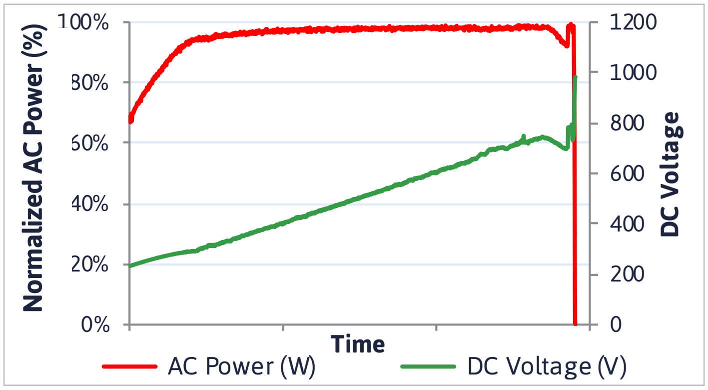


Figure 17

Figure 17 (above) shows an inverter with a very wide DC operational window, allowing power to be produced from ~200V through 850V.

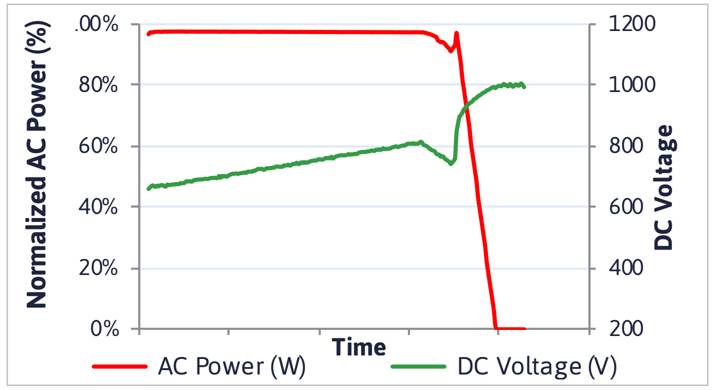


Figure 18

Figure 18 (above) shows a significantly reduced DC operational window, with the inverter only capable of operating from ~625V through 800V.

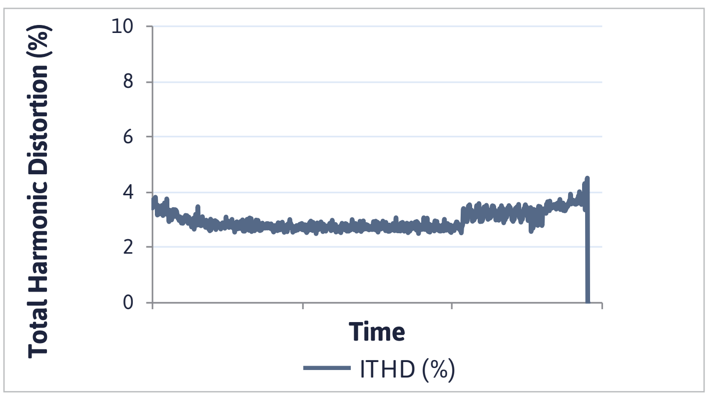


Figure 19

In Figure 19 (above), the curve shows the inverter maintaining total harmonic distortion (THD) at consistently low values throughout the DC operational envelope testing.

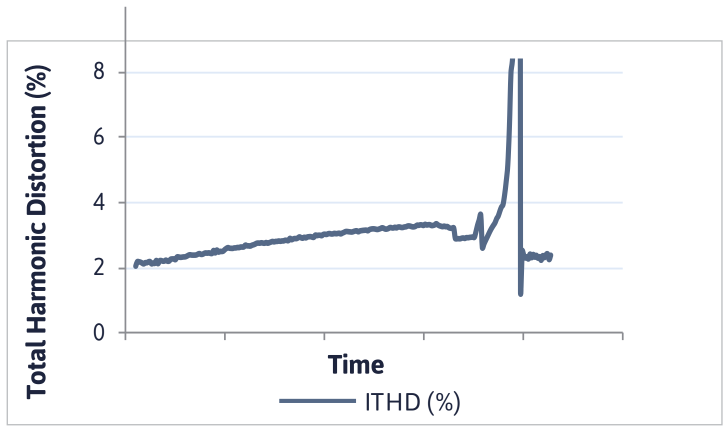


Figure 20

The curve in Figure 20 (above) highlights very high THD levels as the inverter transitions into a power limiting (derating) state.

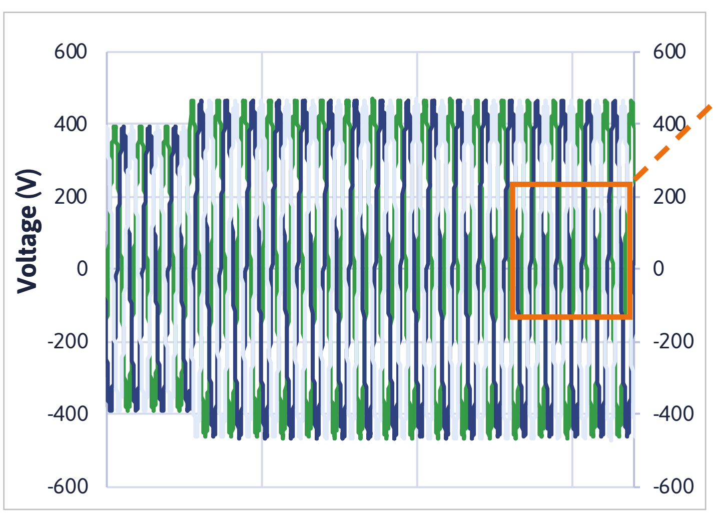


Figure 21

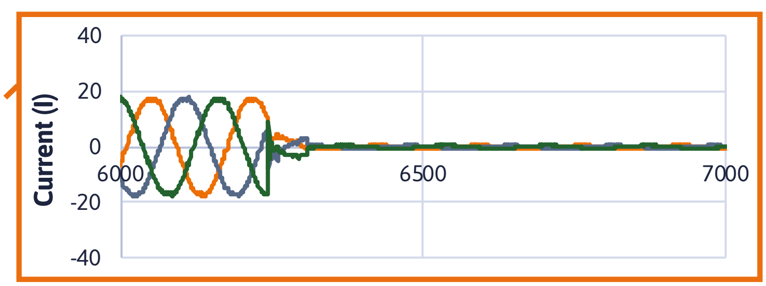


Figure 22

During transient response testing, the applied (grid) voltage is raised and lowered to determine inverter capabilities to detect and respond appropriately. Figure 21 (left) highlights the increase in grid voltage while Figure 22 (above), the detailed image, shows the cessation of current as the inverter shuts down.

FIELD TESTING OVERVIEW

Background

As the brain of the PV system, the inverter is responsible for the system's safe and continuous operation. While lab tests effectively quantify performance and reliability, certain characteristics should be evaluated in the field during real-time operation at system level. For this reason, the PQP includes both indoor and grid-connected outdoor tests.

Testing Overview

- **Ground and Arc Fault Tests:** Electrical arcs can occur if electrical conductors are exposed to the environment. For example, if the insulation around system wiring degrades, connectors age or come loose or module backsheets fail and start to crack, electrical conductors can be unprotected. Electrical arcs have a characteristic signature, or fingerprint, in the frequency domain. Inverters are responsible for detecting this and should shut down if an arc is suspected. However, an arc between the positive terminal and ground is very different than an arc, for example, between the 5th and 6th modules of a string. Some inverters are able to accurately detect all arcs, some are not. In this test the inverter is subjected to multiple arc or ground fault conditions at different locations on a grid-connected PV system. The inverter is monitored to track proper system shutdown and reporting. Inverters were evaluated for the Scorecard according to arc fault detection by location and detection time
- **30-Day Runtime:** Inverter availability is a key metric for forecasting energy yield of a PV system. Nuisance tripping or shutting down for erroneous reasons leads to unnecessary expense for system owners. This test determines whether or not an inverter can operate continuously for one month in the field in PVEL's grid-connected outdoor test laboratory. The inverter is connected to a PV system for 30 days and energy production is measured at 5-minute intervals. Inverters were evaluated for the Scorecard according to these criteria: uptime, faults and performance.

Why the Tests Matter

Safe and continuous operation of a PV inverter is fundamental to the economic success of a PV system. An inverter's ability to detect safety issues like arc faults is critical; however, an overly sensitive arc fault detection could result in frequent, unnecessary tripping. The field tests in the PQP determine if an inverter will operate safely and continuously in real-world conditions.

Safe and continuous operation is fundamental to the economic success of a PV system. System owners and operators can utilize the results from these tests in the PVEL Inverter PQP to avoid undesirable inverter behavior in their PV plants.

Ground and Arc Fault Tests
Top Performers (in Alphabetical Order)

- Delta M8 TL-US
- Delta Solivia 3.8 TL
- Fronius Symo 24.0-3

30 Day Runtime
Top Performers (in Alphabetical Order)

- Huawei Sun2000-11.4KTL-US
- SMA SB7.7-1SP-US-40

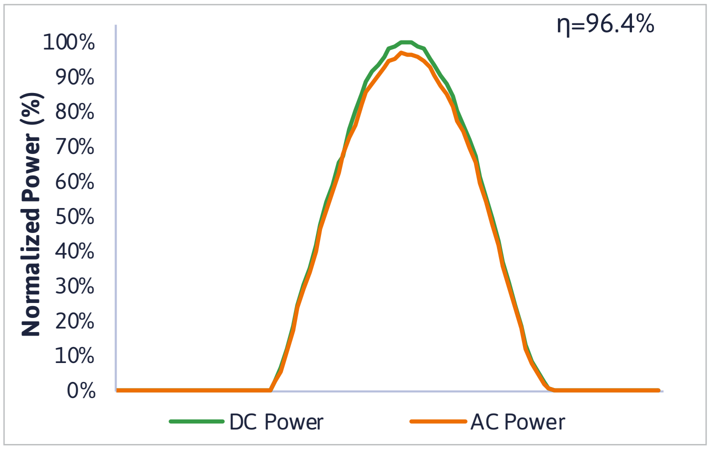


Figure 23

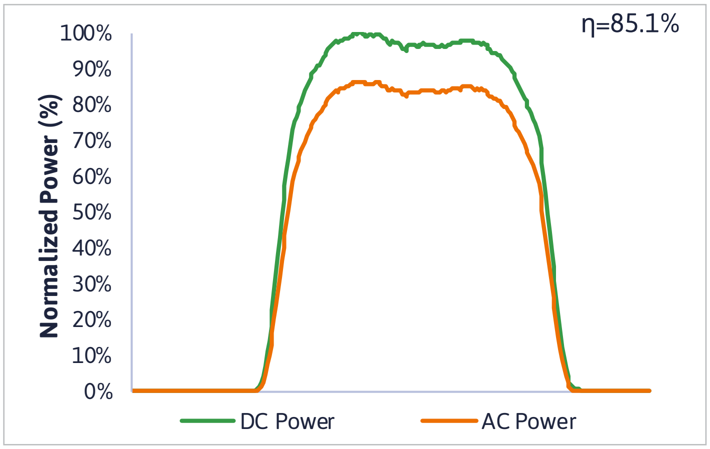


Figure 24

Each of the above plots compare the AC and DC production for 2 inverters installed in the field on a clear day – Inverter 1, shown in Figure 23 (above left) with fixed tilt modules and Inverter 2, shown in Figure 24 (above right) with modules installed on trackers. The strong performer in Figure 23 is showing 11.3% more relative energy yield than the poor performer in Figure 24.

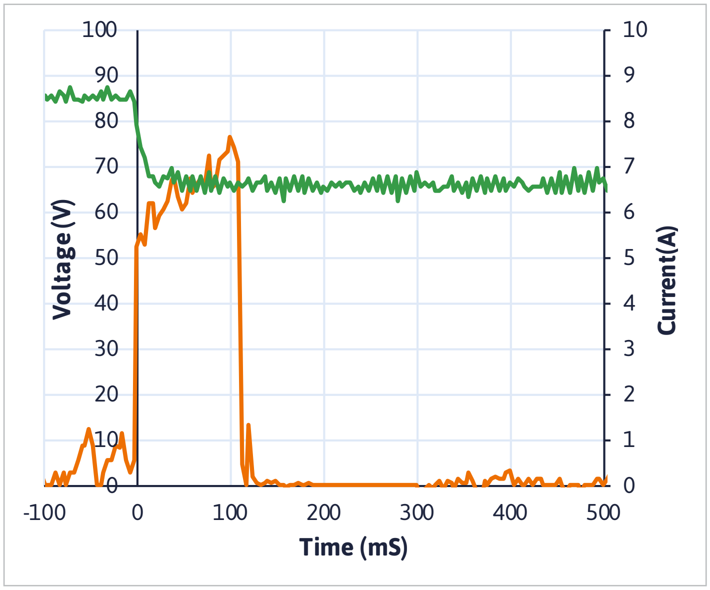


Figure 25

A properly detected arc event with a cessation of current is shown in Figure 25 (above), highlighting the inverter's capability to effectively identify and respond to arc fault events within the required timeframe.

Image 3 (right) shows significant internal inverter damage as a result of a bolted ground fault during testing. Inverters should be capable of detecting and interrupting ground faults without damage to the device.

Image 3

PROCUREMENT BEST PRACTICES

Asset owners expect solar power plants to generate energy safely and reliably for decades to meet project economic returns. PV inverter service life expectations started at less than 5 years in the 1990s and have grown to over 20 years as of today for central inverters. Expected functionality began with rudimentary tasks and is now much more complex due to evolving grid codes, safety standards, and PV plant operational needs. Conversion efficiency has jumped from 91% to over 98% today. Just seven years ago, a Xantrex 4kW inverter weighed 116 pounds. Today an inverter weighing 50% less can have triple the processing power.

How is a procurement manager to sift through this complex array of technical needs and available market offerings? **Inverters have evolved while standard inverter procurement practices have failed to keep pace.**

This year's PV Inverter Scorecard demonstrates that there is a range of performance, functionality, efficiency and reliability across commercially available products on the market today. A combination of controlled laboratory testing and real-world field evaluations are required to effectively evaluate the current landscape of inverter reliability and performance trends. In four steps, PVEL has outlined the various factors and considerations for risk mitigation when sourcing inverters.

Choosing the Right Inverter: Key Considerations

- Successful completion of powered thermal testing should always be required because it is the most similar to field conditions. PVEL uses these tests to evaluate product derating, component design margin and product engineering. The results validate that the manufacturer has used acceptable engineering design practices for key components.
- High and/or low temperature sites should use inverters that can maintain full power across the voltage window regardless of temperature. This isn't always the case; some inverters do not maintain full power in all climate conditions.
- If arc fault detection is required, select inverter products that perform this function well and minimize false or "nuisance" trip events. Validate arc fault detection in likely field conditions – not just in certification testing.
- If the installation is sensitive to energy harvest – as most installations are – pay special attention to MPPT and conversion efficiency because they can impact energy harvest (kWh/kWp) as much as 5% from product to product.
- When procuring equipment, be sure to purchase adequate spares for future replacement and/or ensure that a secondary source for future supply is available.

4 Steps for Risk Mitigation

1 Know Your Environment: Evaluate Project Conditions

All site conditions are harsh and demanding, but some have special considerations. Before you select a product, first:

- Determine expected maximum and minimum operating temperature conditions
- Verify expected AC and DC voltage requirements
- Consult local regulatory and interconnection requirements
- Set reliability and service life expectations

PVEL can provide consulting services to aid in selection criteria. This step will help you choose the right type of inverter product, whether it's a microinverter, string inverter or central inverter.

2 Select the Right Product: Consult PVEL Inverter PQP

Use PVEL Inverter PQP reports to evaluate inverters for the specific use case:

- Validate system performance under expected project conditions by analyzing data for MPPT, conversion efficiency and operational envelopes
- Confirm inverter will function as expected in site-specific real-world conditions by reviewing results from powered thermal and passive chamber testing as well as field data
- Determine optimum DC voltage and DC loading ratio for maximizing inverter lifetime performance by using data from operational envelope and power derating tests

PVEL PQP reports are provided to Downstream Partners on a complimentary basis and PVEL staff are available to help interpret the data and evaluate products for individual projects or use cases.

3 Verify Quality of Selected Product: Factory Acceptance and Statistical Batch Testing

Audit the production process to ensure consistent quality:

- Evaluate the equipment during and after assembly by testing on-site at the factory
- Randomly test inverters from the production run to confirm they meet specifications
- Validate firmware revision history and product compliance to ensure any firmware updates that occurred after lab testing do not cause problems

PVEL offers factory acceptance testing on-site at production facilities, provides statistical batch testing at its labs and can validate firmware revisions.

4 Monitor Performance: Field Testing

Track system-level energy yield to identify underperformance early:

- Analyze field production data to identify latent issues
- Conduct inverter field testing to diagnose and address problems
- Monitor and troubleshoot suspected inverter issues

PVEL provides a full suite of inverter field testing services, including installing additional third-party monitoring tools, providing on-site technical support and remote analysis of performance data.

CONCLUSIONS

Inverters are complex and multifaceted, and a lot is expected of them – by developers, asset owners, the PV system, the local markets, regulations and the grid. With so much complexity and so much at stake, there are many aspects that can go wrong both inside and outside the device. Diligence is not only paramount to ensuring the long-term reliability and performance of the inverter device, but also of the entire PV system.

Results in Context

As demonstrated in PVEL's PV Inverter Scorecard, not all inverters measure up to expectations. Predicted inverter field performance and cost of ownership can be overly optimistic compared to actual costs. Existing certification tests are focused on short term wear-out; they're not designed to consider long-term reliability and durability, nor do they evaluate inverters within the PV system as a whole.

Most PV inverter manufacturers offer standard ten-year warranties for their products, unlike PV modules, which are usually warranted for 25+ years. Every asset owner today is likely to contend with warranty mismatch in the future – even if their inverters are Top Performers.

Defining Quality

When PVEL began testing PV modules in 2010, we saw tremendous variability in performance across manufacturers and tests, much like we see for inverters now. Since then, PVEL has shone a spotlight on PV module reliability and performance for the buyer community, highlighting the importance of buyer diligence. Consequently we have seen PV module quality improve over time. We now have the opportunity to make a similar impact in the inverter market. In our first PV Inverter Scorecard, PVEL has highlighted manufacturers and models that have withstood rigorous testing while also illuminating the reasons diligence through testing is so critical to the safety and operation of the solar plant for the lifetime of the product and the system.

Guiding Industry

Our aim is to provide the critical testing diligence that is often missing in today's PV inverter procurement scope. We support buyers in understanding inverters' critical role in the lifetime of the PV plant with the hope of improving inverter quality over time like we did for modules. The PVEL team looks forward to improving market-wide PV inverter quality with you.

Our PV Inverter Scorecard is just the beginning. With nearly 10 years of accumulated test data and reports, PV Evolution Labs (PVEL) is the leading independent lab for the downstream solar PV industry.

Learn more:
PVEL.COM | info@pvel.com

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