Benchmarking inverter performance and reliability with a new PVEL Scorecard

Inverters performance | Inverters are the leading source of corrective maintenance activity in PV power plants, yet independent testing to inform procurement decisions remains the exception rather than the norm. Michael Mills-Price and Jenya Meydbray of PVEL describe how a new inverter testing regime is seeking to set quality benchmarks for this increasingly critical part of the PV system

Inverters are the number one driver of PV project profitability. Every time a solar inverter underperforms or shuts down unexpectedly, the entire PV system produces less energy – or none at all. Maintenance costs are compounded by the financial consequences of energy shortfall.

Modern inverters contain hundreds of complex, software-driven components that monitor and control the most vital operations of a PV system. Like all electronics, these components degrade over time. But what is a reasonable lifetime expectation – and how do PV inverter buyers generate reliable predictions? Only about 25% of the world's total installed PV capacity has operated for more than five years, so the industry lacks long-term real-world data. While most inverters today are warranted for 10 years, results from the field show that many products do not last that long.

PVEL's inverter testing aims to provide investors with better intelligence on inverter performance and reliability

As systems age and inverters degrade, the industry is beginning to recognise the importance of inverter selection to a project's long-term economic performance. Low-performing inverters that generate unexpected, ongoing maintenance expenses can ultimately become costly for asset owners. Due to the underlying complexity of inverter design and construction as well as their broad functionality, inverters are also more vulnerable to reliability issues than any other PV system component. Developing accurate inverter lifetime and cost of ownership predictions should not be an afterthought.

PV Evolution Labs (PVEL) is one of very few independent labs that performs extended reliability and performance testing on PV inverters. We found that one-third of the products we tested through our PV Inverter Product Qualification Program (PQP) failed key safety and performance tests – even though all of the tested products were certified by IEC and/or UL. In response to these findings and to growing demand for inverter data, PVEL published its first PV Inverter Scorecard in May 2019.

This first Scorecard was developed with two main goals: first, to educate PV asset owners, project developers and investors about the complexity and inherent risks associated with inverters and, second, to introduce the PV buyer and asset owner community to inverter reliability and performance testing that provides critical insights for inverter diligence. It is also the first inverter benchmarking report based on independent test data that is available to the public. This article highlights key insights from PVEL's Scorecard to explain why and how PV equipment buyers can use objective reliability and performance data to mitigate the financial consequences of technology risks inherent to inverters.

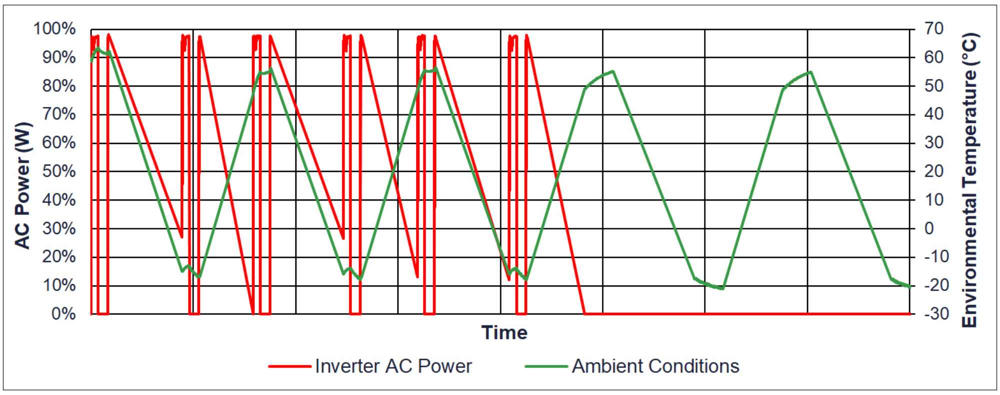

Figure 1. The figure shows an inverter that failed to operate after only 30% of the powered thermal cycling test sequence was complete. It was unable to return to operation

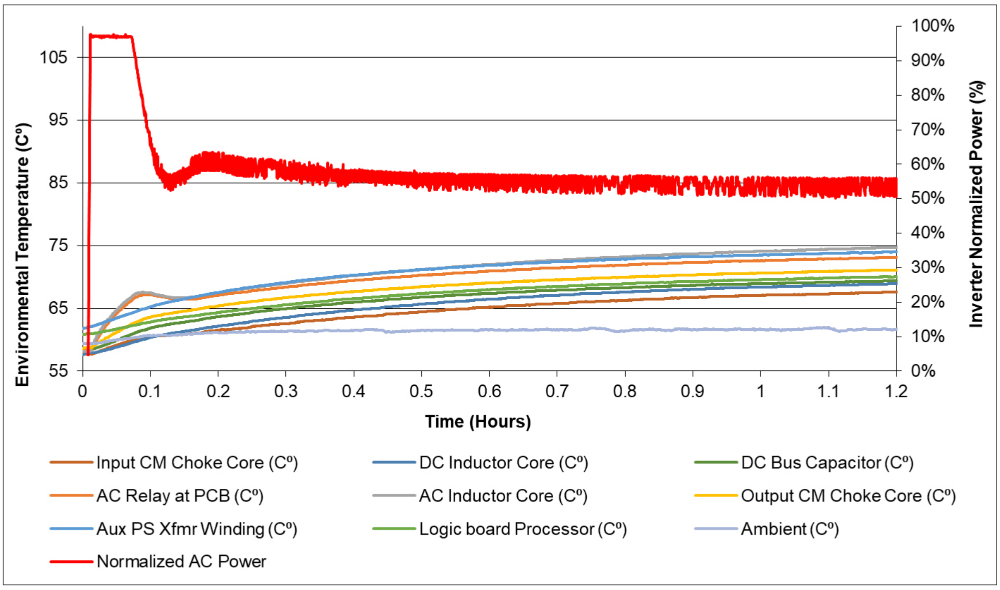

Figure 2. The figure shows an inverter that de-rated to avoid significant temperature increases of internal components during the high temperature test – even though the ambient temperatures sustained were within its operational window

Inverter procurement today

Although inverters are the leading source of corrective maintenance tickets in PV power plants and the top cause of energy outages [1], very few PV project developers, financial institutions and asset owners to date require independent testing that assesses inverter reliability and performance. Historically, due diligence expectations and testing requirements for inverters have been much less rigorous than those for PV modules.

The challenge is that many project stakeholders lack the institutional knowledge and data required for in-depth technical due diligence of inverters. Instead, buyers and investors rely on certifications, brand names, datasheets and warranties to evaluate inverter bankability. PVEL's PV Inverter Scorecard proves that these data sources are not sufficient for strategic inverter procurement where long-term financial returns are at stake. This is especially true for cost-sensitive projects that cannot weather the financial impact of higher than expected operations and maintenance expenses.

About the PV Inverter Scorecard

The 2019 Scorecard is based on independent testing of 35 inverter models produced by 12 different manufacturers. Tested products include string inverters (both three-phase and single-phase), microinverters and power optimisers. Each inverter evaluated for the Scorecard underwent testing through PVEL's Product Qualification Program (PQP) for inverters. Results from 14 tests are presented in the Scorecard. Highlighted results from seven of these tests are discussed below.

All inverters were tested in the same way, leveraging consistently calibrated equipment and in consistent laboratory environments. Inverters submitted for testing through PVEL's PQP are witnessed in production – from the opening of raw materials packages through every step of the process, including final packaging with tamper-proof tape. This ensures that hand-picked samples are not sent for testing. The inverters that ranked as Top Performers for each test are listed by name and model in the Scorecard, which is available as a free download at www.pvel.com/inverter-scorecard, and summarised in the box towards the end of this article.

Test results: thermal performance

Temperature directly impacts an inverter's electrical performance and long-term reliability; therefore, all inverter manufacturers provide product-specific maximum and minimum ambient temperatures for operation. The individual electrical components within inverters also have maximum and minimum temperatures at which they operate. Temperature conditions can vary widely in the field and inverter components

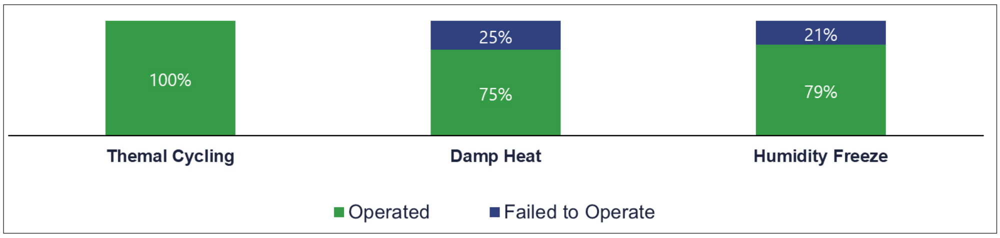

Figure 3. The share of inverters that failed to operate following each passive chamber test. Many of the inverters that were still operational following testing operated in a reduced capacity

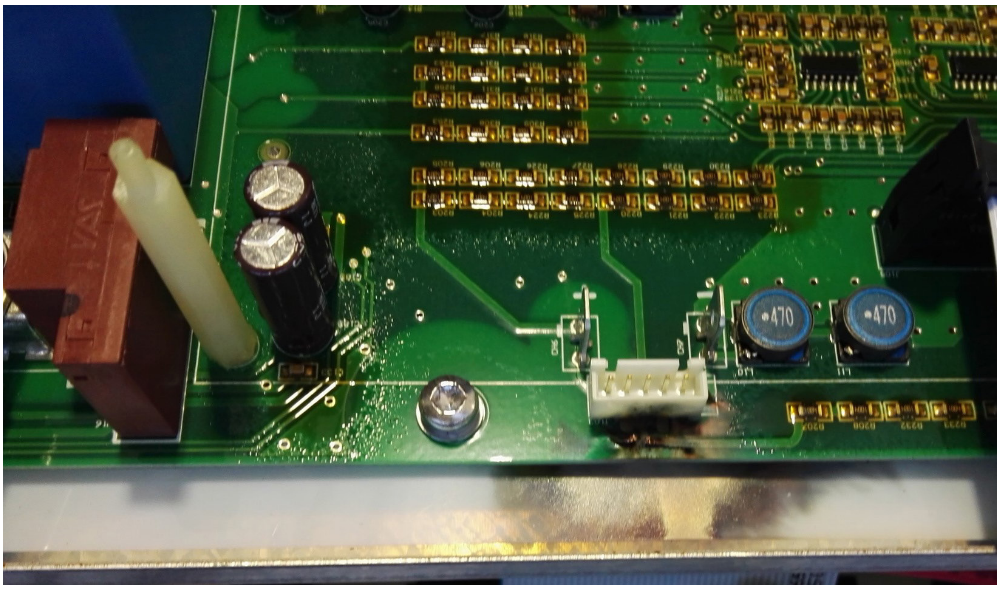

Figure 4. Delamination and internal corrosion in an inverter following passive chamber testing

may be susceptible to thermal drift, a phenomenon which results in individual components performing differently than expected. Inverters are designed with built-in safety mechanisms that prevent these internal components from reaching their maximum allowable temperatures – but these safety mechanisms should only be triggered when absolutely necessary because of their impact on energy yield.

Manufacturers design inverters with these safety mechanisms because degradation rates accelerate when components exceed their temperature limits during operation. Operating beyond allowable limits reduces the lifetime of the component and ultimately the inverter itself. To avoid this, inverters de-rate, or reduce power output, when the temperature limits of an internal component or subsystem are exceeded. While this de-rating process is important for inverter reliability, it should only occur when the inverter is exposed to conditions outside of its operational window. When inverters de-rate, they convert less energy than expected from the PV array. This results in reduced energy yield and financial losses for the asset owner.

Thermal performance tests are used to measure and document the thermal de-rating of inverters. The tests are among the best methods of determining whether an inverter's performance accurately reflects the temperature specifications on its datasheet. To perform these tests, the inverter is placed in an environmental chamber and connected to a solar array simulator. Next, the following conditions are applied:

- **Powered thermal cycling.** Thermal cycling is performed across the full operational temperature range while the inverter is powered from minimum ambient temperature to maximum ambient temperature.
- **High temperature operation.** The maximum operational temperature is sustained while the inverter is powered.
- **Low temperature operation.** The minimum operational temperature is sustained while the inverter is powered.

As these tests are conducted, PVEL measures the temperatures of multiple individual components using thermocouple sensors. These temperatures are then compared to the component datasheets to verify design parameters and determine whether the inverters de-rated while operating within their specified temperature windows. Not all inverters tested were able to operate without de-rating – and some were not able to continue operating during the tests (See Figures 1 and 2).

As pricing pressure on inverter manufacturers intensifies, some producers may utilise smaller, less expensive and less robust components. For example, using a silicon chip with narrower temperature or voltage limits may reduce costs in the short term, but could ultimately cause problems for system owners as the cheaper components prove less reliable when exposed to various thermal conditions.

Test results: passive chamber testing

Inverters contain circuit boards, silicon chips and integrated products that can age and fail when exposed to sunlight, rain, temperature swings, humidity, snow and other common environmental conditions. Unpowered environmental chamber testing evaluates the impact of these environmental stresses on inverters and their components. PVEL's goal with these tests is to assess the product construction, Bill of Materials and product design of an inverter.

Passive chamber tests include thermal cycling, humidity freeze and damp heat. The test procedures align with and expand upon the IEC 61215 test standard, one of the most common certification requirements for determining the safe operation of PV modules. Importantly, PVEL's chamber tests reproduce failure modes and reliability issues commonly observed in the field, including coating delamination, corrosion, water condensation in wiring compartments, discoloration and melting of external displays and controls, and electro-mechanical fatigue of solder joints and electrical connections.

Passive chamber testing results (Figures 3 and 4) indicate:

- 25% of inverters failed to operate after damp heat;
- 21% of inverters failed to operate after humidity freeze;
- A significant population of inverters that operated following these tests were only able to operate in degraded,

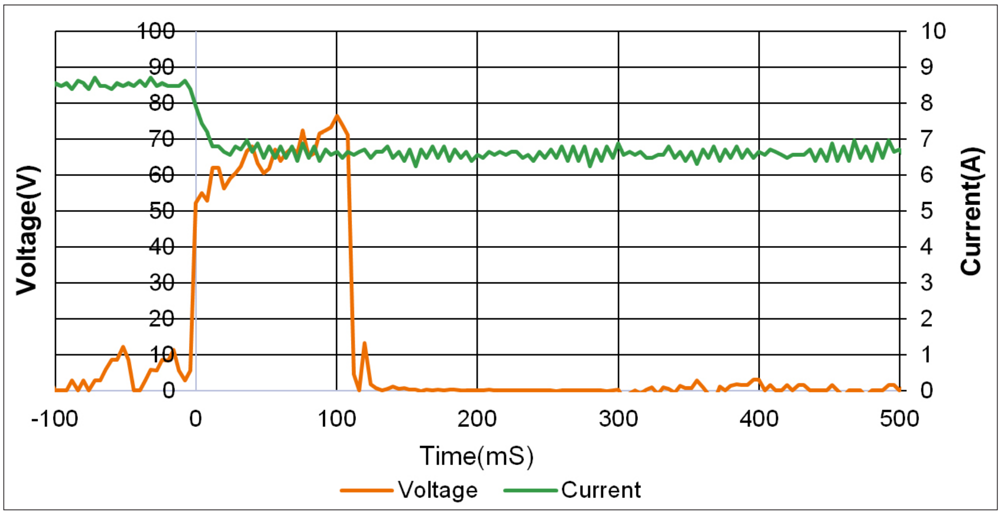

Figure 5. The figure shows a properly detected and interrupted arc fault. It highlights the ability of some inverters to effectively identify and respond to arc faults within the required time range, before the device or the array incurs any damage

less efficient states;

- The most common failure modes were faulty moisture protection of a component, delamination and internal corrosion.

Successful performance in passive chamber tests indicates that products have robust construction and design that can withstand common field conditions. While all inverters that are deployed to PV sites should pass these tests, PVEL's data shows that this is not always the case.

Test results: ground and arc fault

Safe operation is fundamental to the economic success of a PV system, but electrical arcs can occur if electrical conductors are exposed to the environment. Exposure can occur as systems age; for example, when insulation around system wiring degrades, connectors age or come loose on module backsheets fail and start to crack. Properly detecting arcs is part of an inverter's core operation.

In PV systems, electrical arcs can manifest as fires– but only when the inverter fails to detect them and rapidly shut the system down. In extreme cases such as with fires, electrical arcs pose considerable safety risks. They can also result in significant, irreversible damage to the entire PV system. Inverters detect arcs by sensing their characteristic signature, or fingerprint, in the frequency domain. However, this fingerprint may be masked because it is dependent on the location of the arc in the PV array. PVEL's ground and arc fault testing exposes the inverters to arcs at several locations within the array and documents the response of the inverter.

PVEL's fault tests are conducted at our outdoor test site. The inverters are subjected to multiple ground and arc fault conditions on a grid-connected PV system. The inverter is monitored to track proper system shutdown. One third of the inverters evaluated for PVEL's Scorecard failed to detect at least one fault during testing – even though they passed certification testing (see Figure 5). This finding is alarming given the importance of fault detection to the safe operation of PV systems.

Independent test results in context

Every solar project's financial model depends on energy yield forecasts that predict safe, reliable power generation for decades. They also depend on reasonably accurate estimates of operations and maintenance costs. PVEL's testing shows that inverters are not always equipped to meet these expectations. Some do not even meet the minimum requirements specified by datasheets and certifications.

Many buyers and investors rely on warranties to protect them financially when inverters fail. This strategy can quickly backfire when an inverter manufacturer exits the market. Additionally, replacing inverter products may be nontrivial. Imagine searching for a new 600V central inverter today. If a suitable replacement is not available, the entire PV system may require rewiring to prevent electrical mismatch.

A 2017 study assessed the true cost of inverter ownership using data from 400 failure reports (see Figure 6) and found that two of the four inverter manufacturers assessed generated far higher operations and maintenance costs than predicted [2]. In some cases, annual maintenance expenses were underestimated by more than 500%.

The study goes on to note: "In view of the high costs associated with inverter

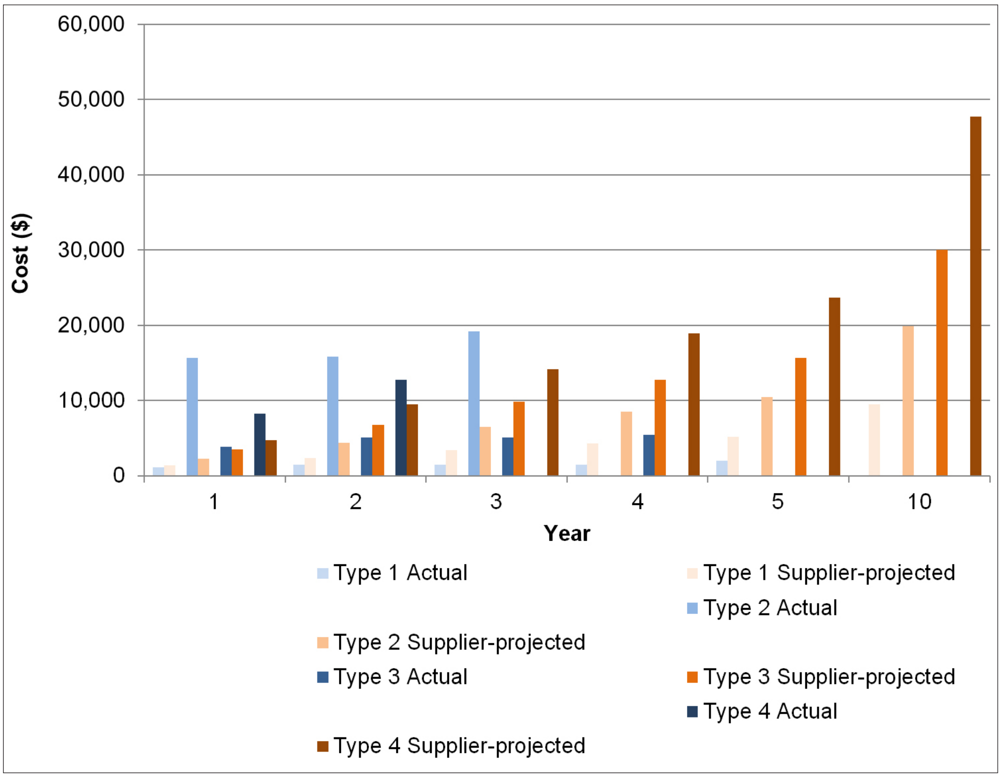

Figure 6. Comparison of the cumulative cost of inverter ownership to cost estimates provided by manufacturers. Actual costs are only provided for years where data is available [2]

PVEL's Top Performer inverters

The scorecard's 14 tests are broken down into five categories: passive chamber testing; thermal performance characterisation; performance testing – efficiency; performance testing – operational window; and field testing. Where appropriate, 'Top Performers' are identified for each test – specific inverter makes and models that have performed particularly well. The makers and inverter models awarded Top Performer status in the inaugural scorecard are detailed below:

Passive chamber
In the Passive Chamber tests, only two companies were awarded Top Performer status: Delta's single phase string inverter M8-TL-US and SMA Solar's SB7.7-ISP-US-40, another single phase string inverter.

Thermal performance characterisation
Three different companies' products were Top Performers in the powered thermal cycling category – Delta's single-phase string inverter M8-TL-US, Schneider's Conext CL-60A string inverter and SMA Solar's SB7.7-ISP-US-40. PVEL highlighted an example of an inverter that failed 30% through the test sequence with an inability to return to operation.

In the high temperature operation category, three different companies' products were Top Performers: Delta M8-TL-US, Fronius' Symo 24.0-3, a transformerless three-phase string inverter, and Huawei's SUN2000-11.4KTL-US string inverter.

There were two Top Performers in the low temperature operation test: the Delta Solivia 3.8 TL and the Huawei SUN2000-11.4KTL-US.

Performance testing: efficiency
In the performance efficiency test category, which analyses MPPT efficiency, conversion efficiency and energy harvest, PVEL noted the tests set out to demonstrate whether or not an inverter can actually perform as expected based on product datasheets when deployed in the field.

Three different companies' products were Top Performers in the MPPT efficiency test: Delta's M8-TL-US, Huawei's SUN2000-30KTL-US and Schneider's Conext CL-60A string inverter. PVEL noted that Top Performers in this test sequence had a 98-99% response rate for all three test conditions.

Top Performers in the conversion efficiency tests were Huawei's SUN2000-30KTL-US and SUN2000-375W-USP0, and Schneider's Context CL-60A.

In the energy harvest tests, Top Performers were Huawei's SUN2000-28KTL and SUN2000-30KTL-US, also accompanied by Schneider's Context CL-60A.

Performance testing: operational
In the performance operational tests, which include operational envelope and transient response, PVEL noted that "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".

PVEL only scored Delta's M80U inverter in the AC operational envelope test and the same inverter in the DC operational envelope category with Schneider's Conext CL 25000NA inverter.

In the transient response test, Top Performer status was given to Delta's M8-TL-US, Fronius' Symo 24.0-3 and Huawei's SUN2000-11.4KTL-US inverter.

Field testing
In the field testing category, PVEL said that the PQP determined whether an inverter would operate safely and continuously in real-world conditions. The tests include a ground and arc fault tests and a 30-day runtime in operation.

The three Top Performers in the ground and arc fault tests were Delta's M8 TL-US and Solivia 3.8 TL inverters, as well as Fronius' Symo 24.0-3 inverter.

In the 30-day runtime tests, only two companies' products were given Top Performer accreditation: Huawei's Sun2000-11.4KTL-US and SMA Solar's SB7.7-1SP-US-40.

Summary
In summary, the three most-cited Top Performer companies were Delta with 10, Huawei with nine and Schneider with five.

On a product basis, the three most cited Top Performers were Delta's M8 TL-US inverter with four accreditations, Huawei's Sun2000-11.4KTL-US also with four and Fronius' Symo 24.0-3 with thre accreditations.

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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] The testing conducted through PVEL's PQP and the results presented in the Scorecard provide the data developers, banks and asset owners need to better predict the long-term reliability of inverters.

Next steps

As the solar industry matures and asset owners focus more on total system lifetime performance – and not just initial costs – inverter reliability is becoming increasingly vital. PV inverter service life expectations began at less than five years in the 1990s. Today the market expects a central inverter to last at least 20 years. Inverters were once expected to convert DC electricity to AC electricity – and not much else. Today they communicate with complex monitoring systems and diagnose system performance problems in real-time.

Despite this dramatic technical evolution, inverter procurement strategies have not evolved significantly over the past decade. This is a risky approach for PV asset owners and investors because independent testing proves that not all inverters live up to expectations. Instead there is a range of performance, functionality, efficiency and reliability across commercially available products.

When PVEL began testing PV modules in 2010, we observed tremendous variability in performance and reliability across manufacturers and tests. The product landscape was very similar to the market for inverters today. As the buyer community began to recognise the variability of PV modules and the advantages of independent testing in identifying the best products to buy – as opposed to brand, warranty terms and datasheets alone – module quality has improved. We hope to see inverter quality similarly improve over time. ■

To learn more about PVEL's inverter testing services or to access the full test reports behind PVEL's PV Inverter Scorecard, contact Michael Mills-Price at michael.millsprice@pvel.com

References

[1] Hacke, P. Lokanath, S. Williams, P., Vasan, A., Sochor, P., TamizhMani, G., Shinohara, H., Kurtz, S. 2017 "A status review of photovoltaic power conversion equipment reliability, safety, and quality assurance protocols", Renewable and Sustainable Energy Reviews, Vol. 82, No. 1, pp. 1098

[2] Hacke, P. Lokanath, S. Williams, P., Vasan, A., Sochor, P., TamizhMani, G., Shinohara, H., Kurtz, S. 2017 "A status review of photovoltaic power conversion equipment reliability, safety, and quality assurance protocols", Renewable and Sustainable Energy Reviews, Vol. 82, No. 1, pp. 1098

Authors

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Michael Mills-Price is head of PVEL's inverter and energy storage business. He has nearly 20 years of renewable energy industry experience and has authored over 30 technical innovations, patents and whitepapers to advance the state of the industry. He specialises in power electronic devices and the interface of renewable technologies to the broader electrical power grids. Michael joined PVEL team in 2014 to create a suite of performance and resiliency inverter testing strategies to benchmark commercially available products.