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The Ultimate Safety Guide for Solar PV Connectors

An In-Depth Primer with Best Practices for Solar Professionals and Asset Owners

Executive Summary

Solar connectors are easily overlooked when PV systems operate as expected. But when they fail, they can cause fires that jeopardize safety and property. These incidents are more likely to occur as installed solar capacity grows and more connectors are deployed to the field, particularly in markets without a skilled solar workforce and in projects installed by new or temporary crews.

This white paper explains how connectors operate, why failures occur and how to prevent them. Solar PV asset owners, operators, and operations and maintenance providers can protect their projects by following the practical, evidence-based best practices detailed here.

Introduction

PV connectors are integral to every solar project: they are the links through which DC solar power is transmitted from PV modules through cables into inverters. For a system to produce AC power safely and reliably, connectors must:

1. Provide low-resistance connections that minimize resistive losses as electricity flows through the array.
2. Withstand 25+ years of environmental exposure with minimal corrosion, degradation or current leakage.

However, the industry lacks a universal standard for PV connector design. While the design details of these electromechanical devices vary, they usually have a male part, which is an internal plug that encloses a contact, and a female part, which is a socket with an extended contact. Tightly locking these two parts creates an electrical circuit.

Hot connectors, or connectors that have high operating temperatures, are the most important indicator of latent failure. Any other warning signs are usually hidden from view because field-made connectors cannot be internally inspected after installation without destroying them.

Connectors and Fires

Connectors are a leading cause of fires instigated by PV systems in many global solar markets. These rare events pose severe threats to safety, property and even the public image of solar power. While many are confidential, there are documented cases of PV system fires and connector failures:

- In January 2022, SunPower initiated a >$30MM USD PV connector replacement initiative due to a cracking issue in third-party products it supplied.[1]
- In the U.K., 27% of 58 fires instigated by PV systems from 2010 to 2017 were caused by connectors.[2]
- In Germany, connectors were blamed for 24% of 180 fires caused by PV systems from 1995 to 2012.[3]
- Japan's Consumer Safety Investigation Commission recommended rooftop PV system inspections in a report citing 127 fires from 2008 to 2017.[4]

Burnt and melted connectors at an operating project.

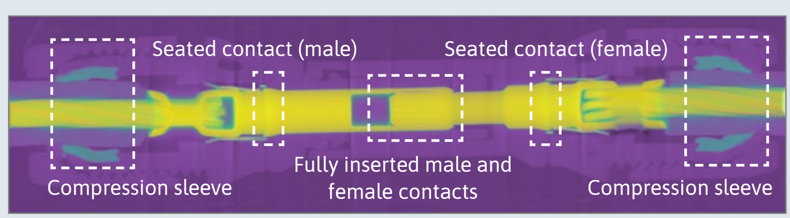
A Growing Concern

As of December 2021, there were approximately 375M PV connections in the U.S. and an estimated 3.5B PV connections worldwide. Each of these individual connectors represents a potential point of failure, but only a tiny fraction of them are regularly monitored. **Fires in operating assets with faulty connectors are preventable, but only with the right inspection and testing techniques.**

Inside a PV Connector

The inside of a PV connector is rarely seen. Many PV connectors are field-made, which means their two parts are pushed together in the field during installation. Once locked, opening a field-made connector permanently destroys it.

PVEL's field testing team obtained the image shown to the right using an advanced lab testing technique called X-ray Computed Tomography, which yields a 3D image of the inside of the connector.



In order to operate properly, the male and female contacts of connectors must be correctly matched, fully inserted and correctly crimped as shown above.

Modern Connectors and Field Failures

Push-fit connectors accelerated the growth of the solar industry in the early 2000s by simplifying PV system installation. The design allowed construction workers to make electrical connections in the field instead of licensed electricians.

Unintended Consequences

As technology improved, the slow pace of development for connector standards and regulations led to confusion in the market and failures in the field.

As a result, many solar installation professionals have received incorrect training that specifies:

1. Uncertified, generic tools can be used for installation.
2. MC4-compatible connector parts produced by any two different manufacturers can be paired.

These are myths that cause field failures.

The Signs of Connector Failure

The obvious signs of failure are: loose or disconnected connectors; high temperatures; melted, discolored or cracked casings; arc faults and ground faults; fires. But these field observations are only the symptoms of deeper challenges:

- Uneven, insufficient or improper surface contact on metal contacts.
- High resistance due to soiling, corrosion or foreign particles.
- Moisture or water ingress that creates alternate electrically conductive paths, typically resulting from a broken seal and/or separated connectors.
- Material degradation due to environmental factors.

The conditions described above arise when fundamental mistakes are made at the time of connector manufacturing, procurement or installation, or due to a natural catastrophe or force majeure event.

A mismatched MC4 and MC4-compatible connector in the field at a site with extensive connector failures.

A Brief History of the Modern PV Connector Market

2000

Before 2000, National Electrical Code (NEC) required licensed electricians to make all connections over 50 V.

In 2000, Radox and Multi-Contact (MC) developed the first push-fit connectors that anyone can install.

2008

In 2008, NEC banned the opening of connectors under load.

Now push-fit connectors were required to contain positive locking mechanisms controlled by certified, product-specific tools.

The MC4 connector, now owned by Stäubli, began to dominate the market.

But Amphenol soon disrupted the industry with its MC4-compatible connector.

2018

By 2018, the solar market was flooded with MC4-compatible connectors from different suppliers. Marketing materials implied that any “MC4-compatible” products could be linked.

Many PV module manufacturers have stopped specifying connectors on datasheets, instead stating “MC4-compatible.”

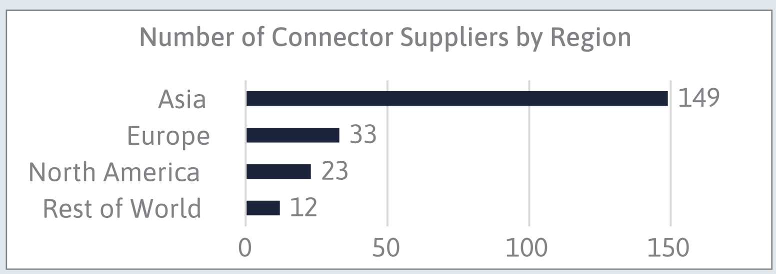
2020

In 2020, NEC was revised to explicitly state that the two parts of connector pairs must be tested together and certified for intermatability.

The connector market has continued to diversify globally.

Universal design standards have not yet been established.

MC4, produced by Stäubli, has an estimated ~30% global market share today. But Stäubli's MC4 design is proprietary, and it is just one of 200+ PV connector manufacturers worldwide.



Why Failures Happen: The Most Common Root Causes are Simple Mistakes

Improper installation
Contacts that are not inserted fully into housing is a common issue.

Improper installation tools
Uncertified tools may not meet product specifications and/or damage components.

Lack of training
Proper torquing technique and the use of end caps are often overlooked.

Mismatched connectors
Design differences may prevent complete, watertight locking.

Counterfeit connectors
Untested, uncertified products may be unsafe and degrade quickly.

Faulty materials
Some polymeric materials degrade rapidly after contact with oil or sunscreen.

What Happens When Connectors Fail?

Some connector failures are worse than others. Catastrophic incidents that jeopardize safety and property are more likely to occur when faulty connectors continue operating in the field over time.

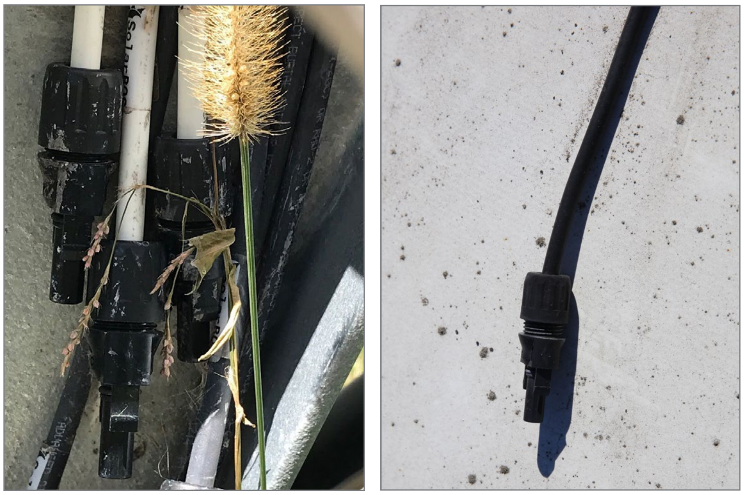
Compromised Connectors Can Be Time Bombs

Connectors that are left unplugged and uncapped during construction are often exposed to moisture and foreign particulates, such as dirt or other organic matter. Without connector caps, the metal pins of the connectors will be exposed to moisture and begin to corrode.

Then, once the connector is closed, the corrosion continues to propagate, increasing connector resistance until the connection eventually fails. **These connectors can become time bombs waiting to ignite to the field.**

Poor Sealing Causes Nuisance Tripping

When connectors are not properly sealed against the environment, current can leak to ground. Inverters have sensitive circuits to detect the isolation of the system from ground during start up. In PVEL and HelioVolta's experience, inverter nuisance tripping during periods of high humidity (e.g. from morning dew) is frequently traced back to the combined ground leakage current from many poorly sealed connectors.



The connectors above are examples of potential time bombs: they were left unplugged without end caps at a utility-scale plant (left) and a commercial rooftop system (right).

Connectors and Personal Safety

The safety of personnel and consumers cannot be overlooked in any discussion of connector failure. Silent, non-detected or non-flagged ground faults can be lethal for technicians and other personnel, as well as the customers of solar-powered businesses and homeowners with PV systems.

The Spectrum of Connector Failures

Initial symptoms of failure may go unnoticed, such as minor reductions in energy yield caused by resistive losses. The chart below describes the spectrum of failure modes and range of potential impacts for asset owners.

Failure risk and severity increases over time

	Field Observations of Failure	Performance Impacts	Commercial Impacts
Power Loss	• Visible signs of failure may or may not be apparent • Disconnected, loose or connectors	• 0.3% to 1% power loss • Resistive losses may go unnoticed	• Up to a few thousand dollars per year in financial losses
Ground/ Arc Faults	• Compromised enclosures • Melted connectors • Sparks • Frequent inverter tripping	• Periodic downtime and/or inactive strings are possible • Major underperformance and power losses can occur	• Up to a few thousand dollars per day in financial losses • Safety risks to personnel • Equipment damage
Fires	• Extremely hot connectors that ignite system components • Explosions • Destroyed equipment	• System failure • Total power loss • Repairs may require extended system downtime	• Severe safety risks to staff and general public, for which asset owners may be legally liable • Total or near-total financial losses possible due to property and equipment damage • Business closures for repairs and restoration

Analysis assumes the following initial conditions: 5 MW commercial project; \$0.15 PPA rate; 1400 kWp/kWh production; 425W modules; 588 strings; 10 A module current; 42.5V module voltage; 1000 V string voltage. Connectors with resistance of 150mΩ affect 10% of the project. 1% of field made connectors are open, rendering six strings inactive.

Diagnosing Connector Failure

There are many ways to make mistakes when creating a PV connector, but few ways to validate their quality after installation.

Assessing connector quality in the field is challenging. While these devices can safely be unplugged when they are not under load, they cannot be disassembled without compromising their integrity: assembly is irreversible. Visual inspection of the connector's exterior can reveal some errors but it does not validate the quality of the internal connection.

Failing Connectors are Hot

Compromised connectors have a higher resistance than properly made connectors. That resistance decreases energy yield and produces heat. As a result, high temperature is the primary warning sign of looming connector failure:

- If major issues are present at the time of installation, thermal identifiers may be present when the system is commissioned.
- When latent defects are present, thermal identifiers may not emerge until the system has operated for some time.

Thermal imaging on the ground can identify latent connector reliability issues before they become catastrophic failures. However, drone thermal imaging does not adequately identify hot connectors because they are typically positioned underneath modules that hide their heat signatures.

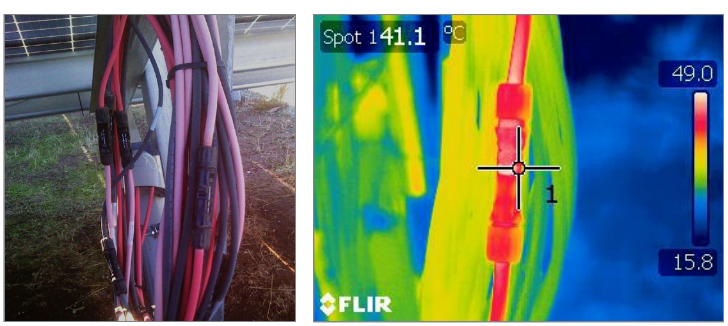
The sample of failed connectors above melted due to high temperature operation in the field. PVEL removed the devices from the field for testing and root cause failure analysis.

Identifying Failures with Thermal Imaging

There are no specific standards for on-site thermal imaging of PV connectors, but HelioVolta's data-driven approach has proven successful in the field. Their process establishes pass/fail criteria that includes two categories:

- **Absolute temperature failure**, which is defined according to manufacturer specifications, typically 85°C to 95°C. All connectors that display a temperature above this limit are considered failures.
- **Differential temperature failure**, which is project-specific. Some connectors that operate below the threshold for absolute temperature failure will measure at higher temperatures than others at the site. These connectors still present performance and safety risks.

The criteria for differential temperature failure is established using baseline average connectors temperatures at specific temperature and irradiance conditions. The threshold for failure is based on the deviation from that baseline average.

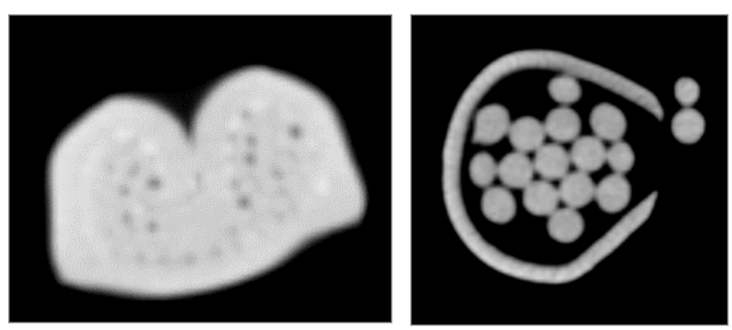


The images above show differential temperature failures. One of the connectors in the bundle (left) has an operating temperature that is 15°C higher than the others, as indicated by the thermal image (right).

Advanced Lab Testing for Root Cause Analysis

Determining the root cause of connector failure typically requires sophisticated destructive testing conducted in a laboratory setting. Neither thermal imaging nor visual inspection reveal the inner workings of connectors. PVEL recommends the following techniques for advanced analysis:

- **X-ray computed tomography (XCT)** to create a 3D image of the connector, including metal and plastic components.
- **Scanning electron microscopy (SEM) and energy-dispersive x-ray spectroscopy (EDX)** to identify metal corrosion and arcing biproducts.
- **Cross-sectioning** the connector at the position of the crimp to evaluate crimp quality.
- Subjecting connectors to **accelerated stress testing** in high temperature/humidity conditions and/or thermally cycling in a laboratory environment to accelerate failure of suspected bad connectors.



The above XCT cross-section images show the difference between a correct (left) and poor (right) connector crimp found by PVEL in an active PV installation.

Findings from Field Inspections by PVEL and Heliovolta

Inside a Root Cause Failure Analysis

Connectors regularly melted and caught in fire in a >150 MW project in California.

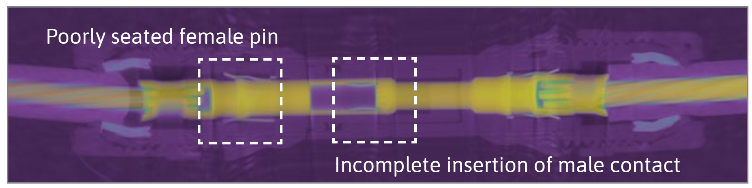
The owner contracted PVEL to conduct a root cause analysis that determined why the failures occurred and identified the EPC as the party at fault. PVEL evaluated 1,500 of the nearly 100,000 field-made connectors at the site with a combination of visual inspection, infrared thermography and XCT.

Installation error was identified as the overarching root cause of connector failure:

- Critical connector installation errors were extensive, including under- and overtorqued nuts, poor placement, improper crimping, and improperly seated contacts.
- 40% of the connectors evaluated with XCT had installation issues, and 20% had incomplete insertion of the contact, which suggests issues are widespread throughout the site.
- Persistent inverter nuisance tripping based on insulation resistance faults could be due to the widespread poor sealing of connectors due to under-torqued back nuts.

PVEL recommended further inspection and/or total replacement of all field-made connectors in the project due to significant installation errors.

A single overheated connector caused this catastrophic failure. Per PVEL's testing, installation error is likely the root cause.



These XCT images show two poorly installed connectors. The top image reveals incomplete insertion and the left image zooms in on a channel for water ingress due to an undertorqued nut.

Inspecting Rooftop PV Systems

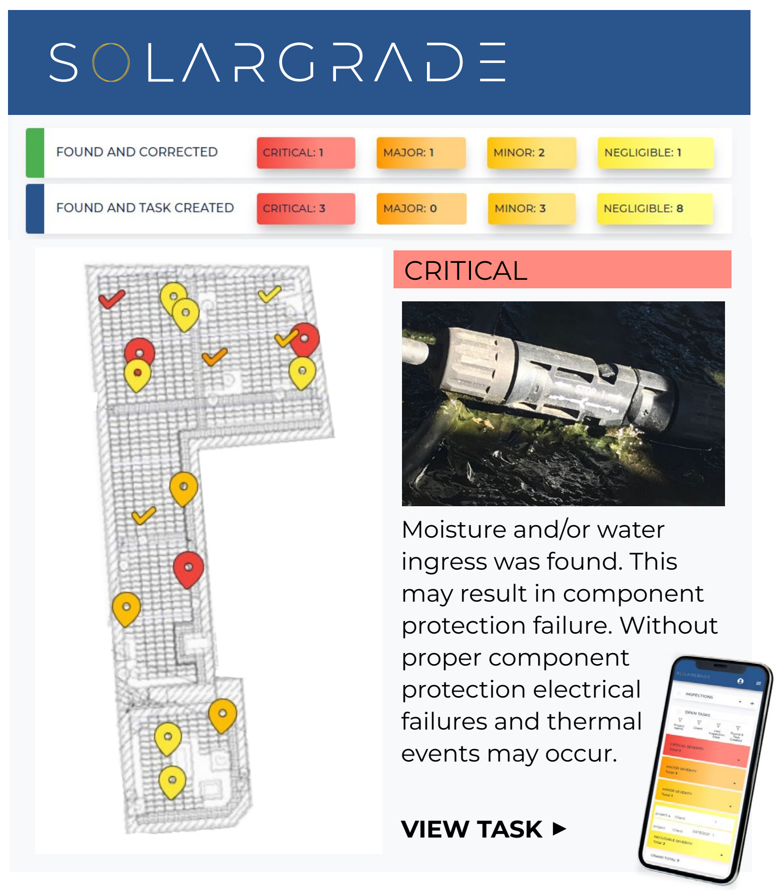
More than 70% of the commercial and industrial projects inspected by HelioVolta have serious connector issues.

HelioVolta is usually contracted by the asset owner after a safety event occurs. Several trends have emerged:

- **Connectors can be difficult to locate and poor wire management is common.** Inspectors often crawl on their knees with hand-held thermal cameras.
- **Cross-mated connectors are frequently found on homerun cables.** This classic problem usually occurs because modules come with a connector type that the EPC does not have readily on-hand.
- **Poor installation practices are often to blame for failures.** Connectors may be exposed to the elements, resting on roof membranes, have a tight bend radius, or poorly torqued backnuts, among other issues.
- **Hot connectors are the most obvious indicator of underlying issues.** These connectors have higher operating temperatures than other connectors installed on-site, which indicates a higher electrical resistance.

Unfortunately, failure is only a matter of time for connectors that are time bombs. To prevent future safety issues, HelioVolta advises asset owners to:

- Ensure that connector quality assurance/control protocols are in place for construction and commissioning.
- Mandate proper field-made connector training for personnel.
- Include connector inspection requirements and pass/fail criteria in operations and maintenance contracts.



HelioVolta developed SolarGrade, a software application that helps PV system inspectors identify, document and analyze all types of problems in PV systems. The SolarGrade mobile app can be used to record issues and generate reports in real-time at project sites. It is available for Android and iOS devices.

Drilling Down on Connector Inspection Techniques

Different types of connector inspections can reveal different issues. The table below describes the types of connector failure modes that can be identified through visual inspection, thermal imaging and advanced lab testing.

Root Cause	Failure Mode	Visual Inspection - Connected*	Visual Inspection - Disconnected*	Thermal Imaging**	Advanced Lab Testing
Lack of Training or Improper Installation Practices	Dirty contacts or contamination by foreign particles	No	Yes	Somewhat likely	Yes
	Corroded by exposure to water during installation	No	Yes	Somewhat likely	Yes
	Contact not seated in housing	No	Yes	Very likely	Yes
	Cross-threaded	Yes	Yes	Not likely	Yes
	Incorrect choice of contact for wire gauge or strand count	No	No	Likely	Yes
	Incorrect choice of plastic housing for wire insulation outer dimension	No	No	Likely	Yes
	Connectors exposed to elements	Yes	Yes	Not likely	No
	Wire nicks during stripping	No	No	Somewhat likely	Yes
	Lost wires during stripping	No	No	Somewhat likely	Yes
	Wires too bent going into connector	Yes	Yes	Not likely	No
	Low point location (water dripping)	Yes	Yes	Not likely	No
	Not fully seated (plastic pins do not click)	Yes	Yes	Likely	Yes
	Too much tension	Yes	Yes	Likely	No
Counterfeit Products	Many failure modes are possible due to lack of certifications and testing	Maybe	Maybe	Somewhat likely	Maybe
Improper Tools	Improper torque	Maybe	Yes	Not likely	Yes
	Bad crimp	No	No	Likely	Yes
	Incorrect stripping length	No	No	Somewhat likely	Yes
Mismatched Parts	Disimilar contacts and couplers specifications	Yes	Yes	Somewhat likely	Yes
Faulty Materials/ Manufacturing Defects	Fast degradation of polymer materials	Maybe	Maybe	Somewhat likely	Maybe
	Propensity for fretting corrosion	No	No	Somewhat likely	Yes

**Non-destructive visual inspection can be conducted on connectors that remain connected; i.e., the male and female parts are locked together. It can also be conducted on connectors that have been disconnected, so long as they are opened safely and are not under load. Removing the back nut and opening the plastic housing of a connector to inspect its interior will compromise it.*

***Thermal imaging is presented by probability of detection because this technique can only identify issues that cause resistance rise to the point that the connector causes significant resistive losses and is close to failure. While thermal imaging does identify hot connectors, it typically does not reveal the specific issue or root cause of failure.*

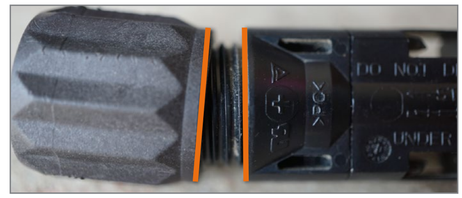
Insights from Non-Destructive Visual Inspection

During O&M inspection, thermal imaging is the primary tool for identifying PV connector issues. However, there are also visual cues that can identify the longer-term connector issues soon after commissioning, before they are apparent in a thermal scan. These cues are also helpful if irradiance conditions are below a minimum threshold for inspection.

Connectors may be unconnected, loose, or improperly connected. If the connector is not pushed in all the way, the connection is not perfect and can lead to increased resistance over time.

Signs of overheating ("shine effect" or thermal deformation). Materials in connectors change appearance when they degrade due to operation outside of specified temperatures.

Cross-threaded back nuts. When torquing back nuts, threads can bite in the wrong channels, or crossthread. This can compromise the connector's watertight seal.

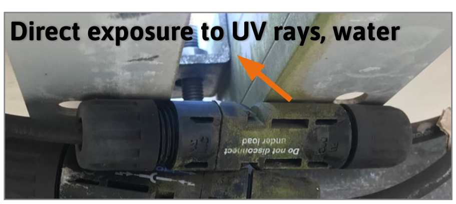


Over-torqued back nuts. Torquing specifications vary by manufacturer and must be followed. Over-torquing compromises the seal and integrity of the connector body.

Under-torqued back nuts.* This error is usually caused by skipping a step or using plastic installation wrenches. Some manufacturers specify the number of visible threads.

Inconsistent back nut visible threads. This can indicate a mistake because all connectors in a single array are usually made with the same tools and conditions. They should match.

Exposure to sunlight and water. Connectors should be protected from moisture and direct UV rays as they will degrade the material over time. This is often manufacturer-specified.



Insufficient bend radius or too much tension on the leads. These conditions can compromise the integrity of the seal at the back nut or even damage the internal crimp.

Crossmated connectors. The term "compatible" refers to the shape of the termination and does not guarantee safety. Parts from different brands are not usually tested/certified together.

Additional Notes

- Connectors should not be located at a low point in cabling. This allows water to seep along their cables and interact with the backing nut. If the back nut seal is compromised, moisture ingress may create an alternate path for electron flow.
- Exposure to mechanical interference can also damage connectors and lead to electrical problems. For example, connectors may be pinched due to tracker movements or affected by vibrations from heating and cooling systems.

*The Solar Industry's Most Common Torquing Myth

It is a common misconception that the plastic wrenches used for installation slip when there is sufficient torque on the back nut. This is false. Plastic wrenches may be used to initially make the connection, but then the nut must immediately be torqued properly with the manufacturer-approved torque wrench.

Torque on the back nut cannot be checked post-commissioning. It is imperative that asset owners are confident in their installation teams and the quality of the connectors in their projects.

Best Practices to Ensure Connector Reliability

Connector failure creates safety risks and causes underperformance in PV assets, but these negative outcomes are avoidable. Take action throughout the project lifecycle to prevent connector failure by following these five steps:

1. **Specify Connectors**

   Specify certified connectors by manufacturer and exact product type in both module supply agreements and EPC contracts. Mandate and validate product authenticity to avoid counterfeits.

2. **Install the Right Connectors**

   Do not allow cross-mated connectors unless they are tested and certified together as a single component. Obtain new connectors from module manufacturers if necessary.

3. **Install Connectors Properly**

   Use manufacturer-provided crimping tools. String modules immediately to prevent environmental exposure and use end caps when necessary. Document the status and location of all field-made connectors at the time of installation.

4. **Validate Connector Installation**

   Include third-party as-built inspection and verification requirements in EPC contracts. Ensure connectors are covered under EPC warranties.

5. **Regularly Inspect Connectors**

   Periodically inspect connectors throughout the project lifecycle using SolarGrade software and an acceptable quality level (AQL) sampling approach. Always conduct inspections after force majeure events because they can compromise the integrity of well-made connectors.

Next Steps

Connectors are not complicated when they are installed correctly and functioning properly – but when they fail, the ramifications can be enormous. While field inspections can prevent costly fire incidents, the root causes of connector failure are more fundamental and must be addressed.

Standardize Connector Design

The industry lacks a clear, consistent standard for connector design. MC4 has emerged as the de facto connector standard, but it is a proprietary design. Product marketing that promotes “MC4 compatibility” has resulted in widespread and dangerous assumptions about connector intermatability. The best way to prevent compatibility-related failures is to standardize connector design.

Improve Installer Training

Solar training programs do not always provide accurate guidance for connectors. In our experience, problematic practices that lead directly to connector failure are widespread and deeply ingrained. A concerted industry-wide effort to improve training programs is necessary, especially as the solar installation workforce grows. The best way to prevent installation-related failures is to require robust, accurate installer training.

Conduct More Research

The industry will benefit from new tools and more test methods that enable frequent, low-cost connector inspections on a regular basis. The humble PV connector should be prioritized by researchers precisely because it is easy to overlook in the field. With the right technology, connector inspections can become a standard operating procedure for solar PV systems instead of a reactive response to obvious signs of failure. We urge those interested in joining PVEL and HelioVolta’s research and development efforts to reach out.

Authors

Todd Karin, Ph.D. Technical Head of Power Electronics and Field Testing, PVEL

David Penalva Co-founder and CEO, HelioVolta, NABCEP Certified PV System Inspector

James Nagel, PE Co-founder and CTO, Heliovolta, NABCEP Certified PV System Inspector

Ready to inspect your assets?
Contact us to learn more.

HelioVolta is a solar and energy storage software and technical advisory services company.

We developed **SolarGrade**, a platform that provides fast, easy-to-use software to standardize solar and energy storage inspection procedures, enables team collaboration, and generates shareable professional reports.

Our mission is to ensure that solar and storage assets fulfill their promise as responsible and reliable energy sources beyond our generation.

To learn more about HelioVolta's software and services, contact our team at hello@solargrade.io.

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PV Evolution Labs (PVEL) is the leading independent lab for the downstream solar and energy storage market and a member of the Kiwa Group.

As a bankability testing pioneer, PVEL has accumulated more than a decade of measured reliability and performance data for PV and storage equipment. Our lab and field testing and technical services help mitigate risk, optimize financing and improve performance in solar and storage assets.

To learn more about PVEL's field testing services, contact PVEL's business development team at info@pvel.com.

References

1. “SunPower Announces Preliminary Fourth Quarter 2021 Results.” Press Release. SunPower Corp., January 20, 2022. https://newsroom.sunpower.com/2022-01-20-SunPower-Announces-Preliminary-Fourth-Quarter-2021-Results
2. Namikawa, Shohei. "Photovoltaics and Firefighters’ Operations: Best Practices in Selected Countries." International Energy Agency. Report IEA PVPS T12-09:2017. https://www.nrel.gov/docs/fy19osti/68415.pdf
3. Coonick, Chris. "Fire and Solar PV Systems – Investigations and Evidence." BRE National Solar Centre. Report P100874-1004 Issue 2.9. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/786882/Fires_and_solar_PV_systems-Investigations_Evidence_Issue_2.9.pdf
4. Bellini, Emiliano. “Japanese Government Warns against Fire Risk from Rooftop PV.” PV Magazine, January 30, 2019. https://www.pv-magazine.com/2019/01/30/japanese-government-warns-against-fire-risk-from-rooftop-pv/.