HELIOVOLTA

THE PV CONNECTOR STATE OF THE FIELD REPORT

An updated guide for 2025 with findings from 5 GWs of field inspections

TABLE OF CONTENTS

INTRODUCTION

Connectors are one of the cheapest, most frequently installed PV system components. They are also a leading cause of safety incidents and financial losses in solar assets.

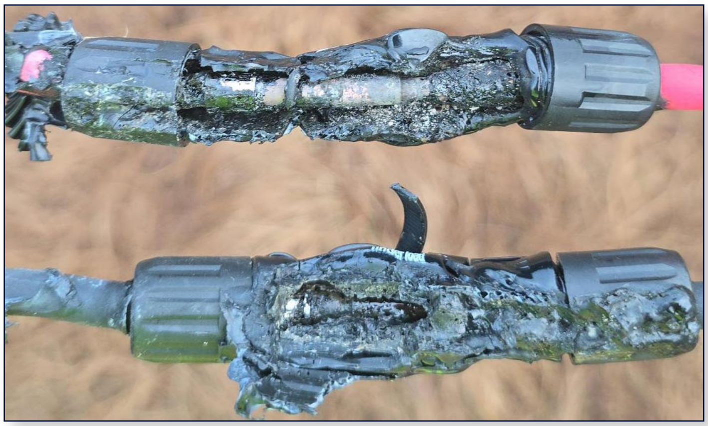
The risks of improperly specified, made, installed, or maintained PV connectors have been well-known since at least 2018[1] and likely earlier. HelioVolta published its first white paper on connector risks with PVEL in February 2022. **But issues remain common.**

Connector issues were found in 83% of projects inspected by HelioVolta from 2021 to 2024[2]:

- 45% of projects had major connector issues that required urgent corrective action.
- 4.3% of projects had critical safety issues that required partial or total de-energization.

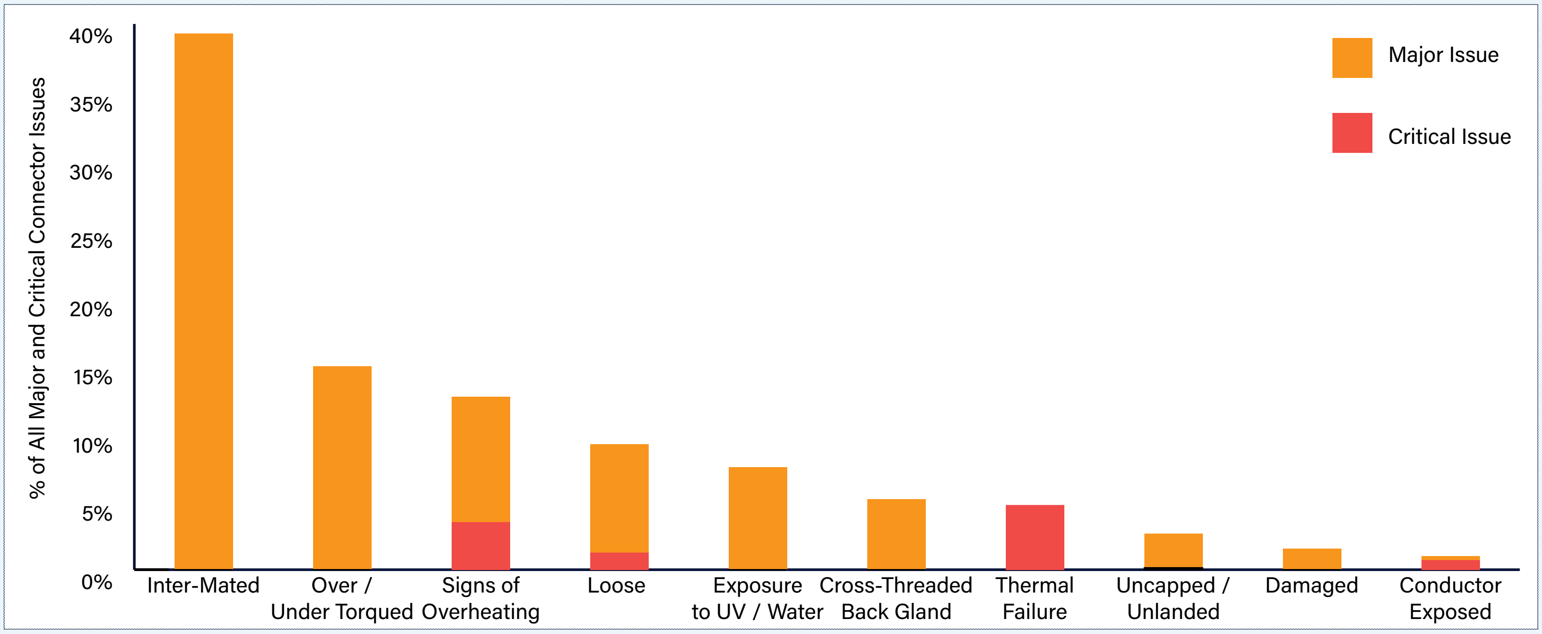
Most connector issues were readily avoidable: inter-mating (i.e., crossmating, mismatch), exposure to the elements, and under or over-torquing make up over 60% of all connector issues.

This white paper explores why connector issues continue to occur frequently, the costs of remediation, and how to prevent them.



TOP 10 MAJOR AND CRITICAL CONNECTOR ISSUES IN THE FIELD

The chart below is based on the dataset for the 2024 SolarGrade PV Health Report, which summarizes findings from hundreds of HelioVolta's inspections. Issues defined as "critical" trigger partial or total system de-energization, while "major" issues require urgent corrective action.



REMEDIATION COSTS

Connectors are cheap to buy, but expensive to fix. When connectors fail, costly corrective actions are mandatory to avoid safety events caused by electrical shorts, overheating, and fires. **The cost analyses below are based on real projects, but use anonymized system details.**

1 MW_{DC} ROOFTOP
TOTAL COST: $558,450

58% OF ANNUAL REVENUES LOST

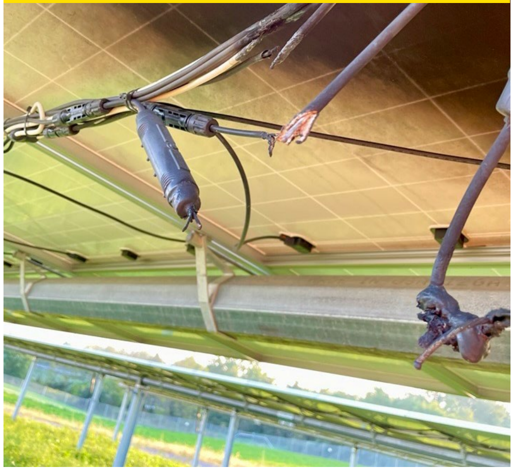
EVENT	IMPACT
A fire caused by an overheated, arcing connector severely damaged PV system equipment and roof of a retail store. The root cause was systemic bad crimps during installation on all home runs.	▪ 1-day store closure ▪ 3-month de-energization for inspection and remediation of affected 1 MW_{DC} site ▪ 1-month portfolio de-energization to complete inspections and rework of EPC's 9 other sites

COST BREAKDOWN	
Lost revenues from store closure	$25,000
Losses from store de-energization	$19,200
Losses from portfolio de-energization	$57,600
Cost of roof repair for affected store	$150,000
Cost of repair and remediation of damaged PV system	$140,000
Remediation work - rest of portfolio	$106,650
Indirect costs: legal fees, insurance premiums, and third-party inspections	$60,000

Additional background and specifications: total portfolio size of 100 MW_{DC}, 10% of the affected store's PV system was replaced at \$1.40/W_{DC} installed, portfolio's annual O&M budget is \$80,000, PPA rate is \$0.06/kWh, electrician labor rate is \$60/hour, the portfolio's annual revenues are \$960,000.

100 MW_{DC} PLANT
TOTAL COST: $1,913,500

19% OF ANNUAL REVENUES LOST



EVENT	IMPACT
A fire occurred due to failed connectors at DC string harness after 24 months of operation. The thermal event followed intermittent systemic failures that began 6 months after operations began.	▪ If the fire had gone unnoticed, a major forest fire could have occurred ▪ Entire site de-energized immediately to prevent additional fires ▪ Block-by-block re-energization over 3 months as remediation work to replace 100% of DC connectors is completed

COST BREAKDOWN	
Losses from 3-month partial system de-energization	$1,237,500
PV system repair and remediation	$676,000
Indirect costs: legal fees, insurance premiums, and third-party inspections	$260,000

Additional background and specifications: PPA rate of \$0.045/kWh, project's annual revenues are \$9,900,000, project's annual O&M budget is \$800,000, 100% of DC string harnesses were replaced at \$0.02/W_{DC} installed.

A CONNECTOR PRIMER

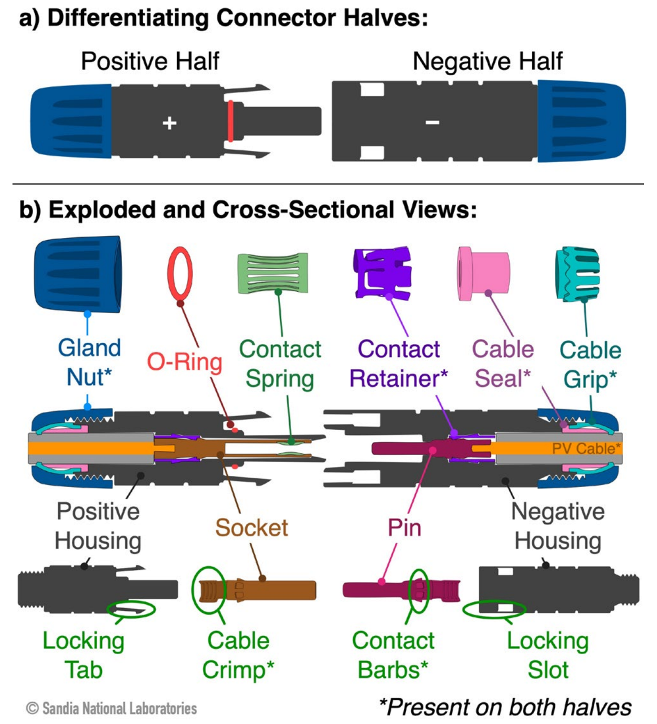
Inside the housing of every connector lies complex electrical and mechanical components.

Many of the internal components have several common names; for example, male and female vs. positive and negative; pins vs. contacts; tabs vs. hooks vs. barbs vs. flanges, and so on.

Inconsistent terminology increases the risk of miscommunications during installation, maintenance, and remediation. Quality standards are easily misinterpreted when teams assign different names to the same components.

A working group led by Sandia National Laboratories is calling for solar practitioners to adopt consistent terminology to reduce miscommunications (see diagram on right).[3]

CONNECTOR COMPONENTS



CODE REQUIREMENTS

The 2023 National Electrical Code[4] stipulates that:

- Connectors must be installed using specialized tools specified by the manufacturer.
- Positive and negative connector parts—the two sides of every connection—must be tested and certified together under UL 6703.
- Connectors must be polarized, lockable, outdoor-rated, rated to the PV system's voltage and current, and protected against overcurrent.

While projects built to older versions of the NEC may not adhere to these requirements, **inter-mated and improperly installed connectors are more susceptible to accelerated degradation and failure.**

WHAT IS MC4-COMPATIBLE?

Per the NEC: "Where mating connectors are not of the identical type and brand, they shall be listed and identified for intermatability, as described in the manufacturer's instructions."[4]

An "MC4-compatible connector" is not compatible with a Stäubli MC4, even if the parts fit mechanically. Internal connections and metal tolerances and materials must align to operate safely.

Stäubli has never specified compatibility with another brand's products in its instructions in HelioVolta's experience to date. Per Stäubli's Original MC4 instruction manual, parts are "to be used with suitable mated connectors from the MC4 product family and suitable lead."[5]

CONNECTOR TYPES

Both factory- and field-made PV connectors contain a positive and negative part and transmit electricity, but they have different manufacturing processes.

FACTORY-MADE CONNECTORS

Factory-made connectors are manufactured and terminated in controlled environments, then shipped fully assembled with cables attached. **They can be manufactured by hand or by machine on automated production lines**:

- Factories offer controlled environments, systematic quality controls, and specialized equipment that ensures consistency.
- Variable uniformity is more common in connectors from handmade production lines than automated lines.

FIELD-MADE CONNECTORS

Field-made connectors are assembled at the project site. Contractors cut cables to the required length, strip the insulation, crimp the contact pins, click the connector housing together, and torque the gland nuts as specified with proper tools.

Field-made connectors typically link different types of equipment, such as module strings to home run cables to inverters, often via combiner boxes.

The photos above show the process of making a connector in the field. First, the cable is cut to the appropriate length. Then insulation is stripped, and the stripping is measured. Next, the connector housing is clicked together (not shown). The depth of the pin can be measured to ensure contacts are seated correctly as a quality control step. Finally, the back gland is torqued using specified tools and measured to ensure the correct torque was applied.

COMPARING THE RISK OF SYSTEM CONFIGURATIONS

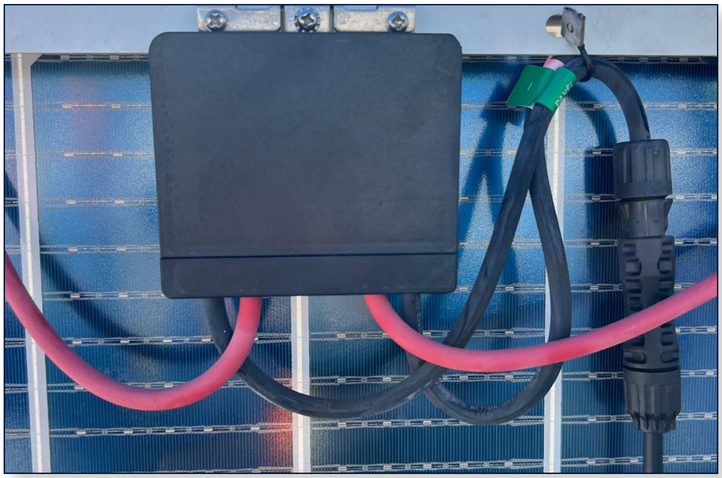
CONNECTOR-BASED RISK ANALYSIS

The number and type of connectors in a PV system can increase the risk of safety events by nearly 20x. The key factors are the number and type of connectors and the number of modules in the system. To illustrate the complexities faced by developers, consider the following system configuration considerations for a recent 1 MW_{DC} rooftop project in the U.S.:

- While UL 3741 certified products would avoid use of rapid shutdown devices, there was limited availability of certified products.
- MLPEs could be installed in 2:1 or 1:1 pairings with modules, but the 1:1 configuration often requires jumpers to prevent cross-mating.
- Domestic content PV modules were preferred, but only large-format modules intended for trackers were available. Jumpers were required for module-to-module connections.

HelioVolta compared the connector-based risk of fifteen potential system configurations under these constraints (see following page). To quantify risk, HelioVolta assigned multiplier factors to various types of connector: factory-made connectors received the lowest value of one, and field-made jumpers received the highest value of ten.

Connector quantities were multiplied by their associated multipliers and summed together to create a risk score for each configuration. The model uses a 1 MW project with 600W modules and 690W modules in different configurations, but it can be scaled to any system size and module capacity.



THE IMPACT OF MLPE

Module-level power electronics (MLPE) such as optimizers, microinverters, and rapid shutdown devices (RSDs) add connectors to PV systems.

As of 2017, MLPE are required in most U.S. rooftop PV systems to fulfill rapid shutdown regulations.

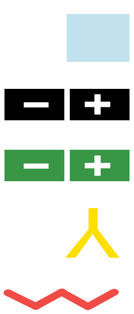
When factory-made connectors of MLPE and modules are not compatible, contractors have two code-compliant choices:

- Cut off and replace the factory-made connectors with matching field-made connectors, potentially voiding the PV module and/or MLPE warranty.
- Use jumpers, which are cables with connectors at both ends, to bridge incompatible connectors and avoid inter-mating.

CONNECTOR-BASED RISK ANALYSIS (CONTINUED)

PV System Configurations	Factory Machine-Made Module Connectors	Factory Machine-Made MLPE Connectors	Field-made Connectors (home runs)	Factory Machine-Made Jumpers	Factory Handmade Jumpers	Field-Made Jumpers	Risk Score	Normalized Risk Score
A - UL 3741, 600W modules	1,667	-	93	-	-	-	2,593	**1**
B - 2:1, 600W modules		1,667	56				3,890	**1.5**
C - 1:1, 600W modules		3,334					5,557	**2**
D - 2:1, 600W modules with short leads, module-module jumpers		1,667		834			4,723	**2**
				-	834		8,062	**3**
					-	834	12,229	**5**
E - 1:1, 600W modules with short leads, module-MLPE jumpers		3,334		3,334		-	8,891	**3**
				-	3,334		22,227	**9**
						3,334	38,897	**15**
F - 2:1, 600W modules with short leads, module-MLPE jumpers		1,667		4,168		-	8,057	**3**
				-	4,168		24,727	**10**
					-	4,168	45,565	**18**
G - 2:1, 690W modules with short leads, module-MLPE Y connectors	1,440	4,320	48	4,320		-	10,560	**4**
				-	4,320		27,840	**11**
						4,320	49,440	**19**

LEGEND



Module-Level Power Electronics (MLPE)

Connector Brand A

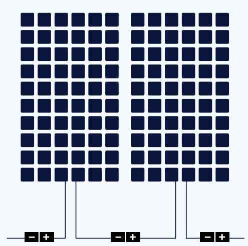
Connector Brand B

Y Connector

Jumpers
3 Possible Types:
Factory-handmade
Factory machine-made
Field-made

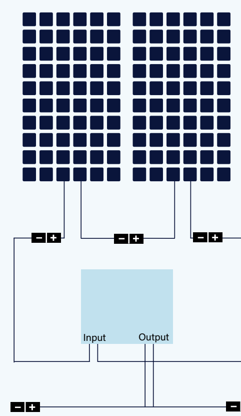
A Configuration

UL 3741; No MLPE



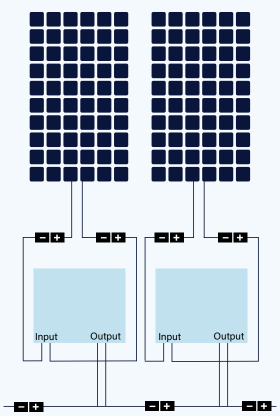
B Configuration

2 Modules: 1 MLPE



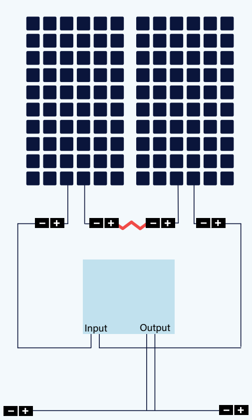
C Configuration

1 Module: 1 MLPE



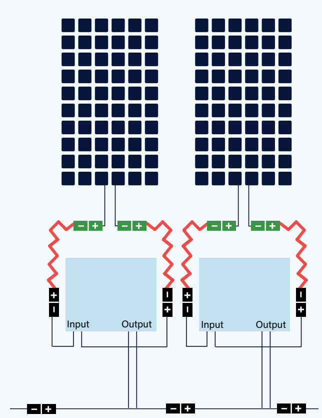
D Configuration

2 Modules, Short Leads: 1 MLPE
Same Factory-Made Connectors



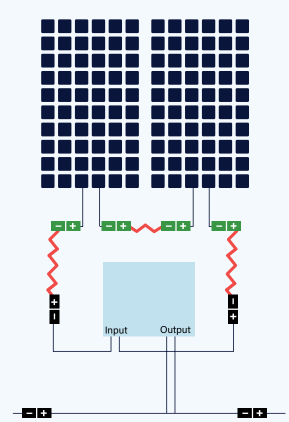
E Configuration

1 Module, Short Leads: 1 MLPE,
Different Factory-Made Connectors



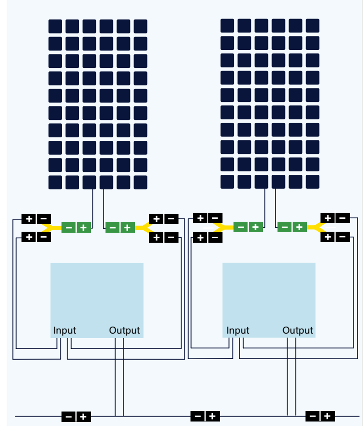
F Configuration

2 Modules, Short Leads: 1 MLPE
Different Factory-Made Connectors



G Configuration

1 690 W Module, Short Leads:
1 MLPE Using Two Inputs

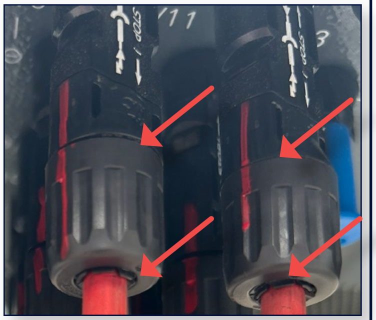


FIELD OBSERVATIONS OF COMMON SAFETY ISSUES

The table below details ten types of major and critical connector issues that are frequently observed by HelioVolta.

Inter-mated connectors pair positive and negative parts from different OEMs that fit together mechanically but are not electrically compatible, posing a high risk of thermal or electrical failures.

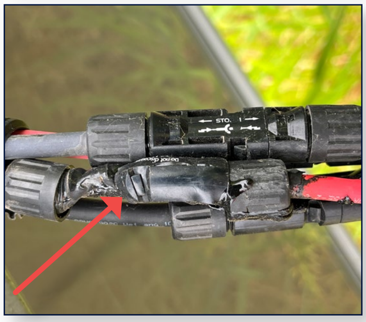
Overtorqued connectors are tightened beyond manufacturer specifications, which can cause internal component damage and compromise connector integrity and electrical performance.



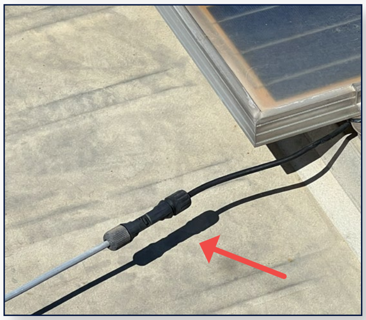
Loose connectors may physically disconnect over time. Improper seating can trigger arcing within the connector or create a higher resistance connection which can lead to a thermal event.

Undertorqued connectors are not tightened enough, compromising the connector's integrity and electrical performance.

Signs of overheating include high temperatures, deformed plastic, and "shining" surfaces. They can indicate imminent failure.



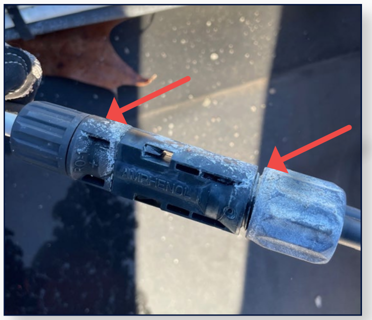
Exposure to sunlight and water can accelerate connector degradation, ultimately compromising the connector body and increasing the risk of faults.



Cross-threaded back glands prevent proper torquing and increase susceptibility to environmental conditions.

Uncapped/unlanded connectors are highly vulnerable to debris and moisture becoming trapped inside post-installation. This can undermine electrical performance until failure occurs.

Damaged and corroded connectors allow moisture and debris to readily enter the connector interior, which can cause faults.



Wire bending radius that is overly tight damages the connector's gland seal, increasing the risk of moisture ingress.

RISK MITIGATION TACTICS

EPC PHASE

1. **Minimize Connectors**
   Implement system designs that reduce the total number of required connectors in the system, especially field-made connectors.

2. **Procure Compatible Equipment**
   Specify PV module, MLPE, and inverter connectors during procurement to avoid the use of jumpers and prevent inter-mating.

3. **Conduct Factory Oversight**
   Third-party QA/QC inspections during manufacturing help identify and prevent production line issues.

4. **Provide Training**
   Establish strict installation quality standards, including the use of caps (see right) to prevent moisture and debris ingress. Training must focus on the use of specified, properly calibrated tools.

5. **Validate Quality**
   Conduct third-party inspections before project hand-off to verify that connectors are properly installed. Minimize use of field-made jumpers.

6. **Document Equipment Condition at Installation**
   Clearly photograph and note the location of all home run connections and a representative sample of factory-made connectors. These records are a valuable benchmark if issues arise in the future.

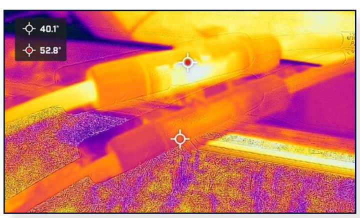
MITIGATING PROCUREMENT CHALLENGES

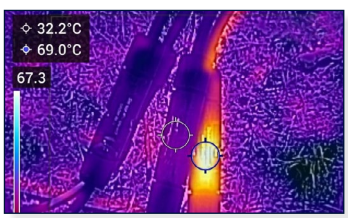
Engineering and procurement best practices do not eliminate connector risks: supply chain challenges often result in out-of-specification deliveries that make jumpers necessary. The table below describes how to reduce the specific risks posed by different jumper and connector types.

Jumper Configuration	Jumper Assembly QA/QC	Commissioning QA/QC	Annual Maintenance	Additional	Optional
No jumpers	N/A	Standard, sampling	Standard	N/A	N/A
Factory hand-made	3rd party QA/QC at factory ISO 2859	100% visual inspection by owner's engineer	20% visual and thermal	XCT ISO 2859 Sampling S-1	Additional 5-year EPC workmanship warranty
Factory machine-made	Prefer OEM as supplier Request quality certifications for batch for receiving		10% visual and thermal	N/A	
Factory machine-made inter-mated	Request quality certifications and tool calibrations for batch for receiving		10% visual and thermal	Optional XCT ISO 2859 Sampling S-1	
Field-made jumpers	Validate training of all persons making connectors in the field and QA/QC tooling used. Include connectors in Golden Row inspections.		100% visual and thermal	XCT ISO 2859 Sampling S-2	

O&M PHASE

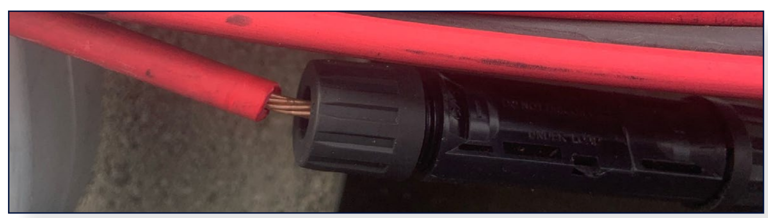
Connectors must be inspected for non-conformities during every preventative maintenance site visit. Like all electrical components, they are vulnerable to degradation due to environmental conditions, especially UV light and moisture—even when properly installed.





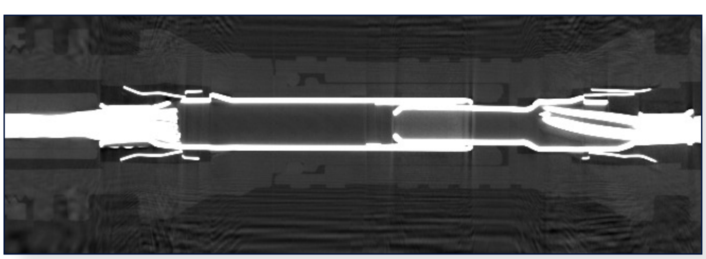
Thermal Scans

Use a hand-held thermal camera to scan for thermal anomalies on a statistically relevant sample of connectors, including home runs.



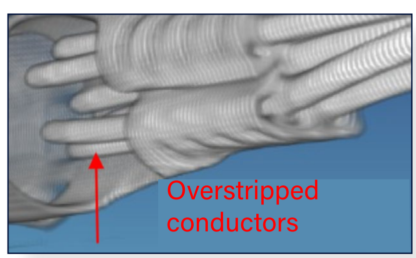
Visual Inspection

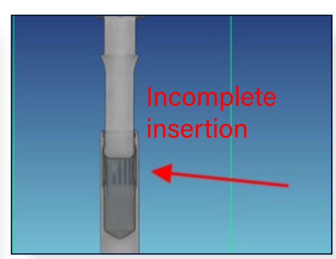
Look for signs of improper installation, degradation, and thermal deformation as they are leading indicators of failure.



X-Ray Imaging

Identify issues with conventional X-ray imaging, which depict internal crimps and contacts.





XCT Analysis

X-ray computed tomography (XCT) produces a 3-D computer model of the imaged volume of a sample that reveals internal failure points.

LOOKING AHEAD: PRODUCT INNOVATION

In the face of persistent connector issues, both public and private sector engineers and technicians now recognize that the risks are so serious that product designs must evolve to safeguard against failure.

NEW CONNECTOR DESIGNS

Several manufacturers have developed new products to reduce installation complexity and degradation susceptibility. For example, crimpless solar connectors are designed to eliminate the need for specialized crimping tools by allowing a secure mechanical or spring-loaded electrical contact between the cable conductor and the connector itself.

Disclaimer: *Field data that proves the reliability of these products is limited. This content is provided for informational purposes only.*

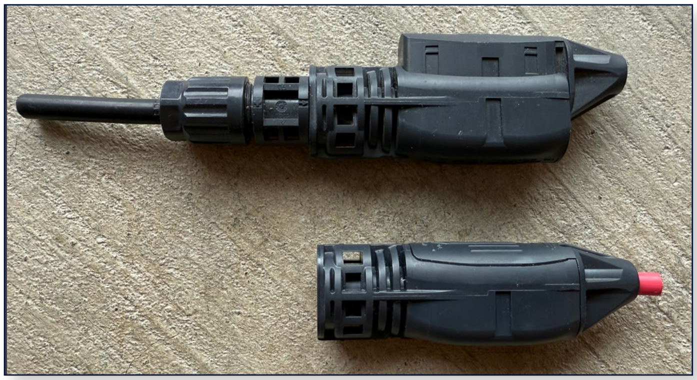
A UNIVERSAL CONNECTOR STANDARD

The National Renewable Energy Laboratory (NREL) is also working to develop a new International Electrotechnical Commission (IEC) standard for the design of a universal connector, which aims to reduce issues associated with inter-mated connectors in PV systems[6].

The standard's design specifications will include the criteria for a new universal plug and socket and will also align with previous standards such as IEC 62852 with slight modifications. While currently unreleased, the universal connector standard has potential to significantly reduce connector-related issues if it is widely adopted by manufacturers.

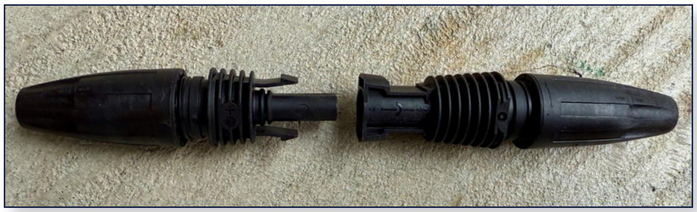
CRIMPLESS CONNECTORS

The "MC4-EVO ready" manufactured by Stäubli. Not available in the U.S.



The "SOLARLOK 2.0 DC Plug & Splice Connector" manufactured by TE Connectivity.

"RadCrimp® Solar Splice" manufactured by Amphenol.



"PV-Stick" manufactured by Weidmüller. Not available in the U.S.

CONCLUSION

Connectors are a small component with an outsize impact on solar PV system safety, reliability, and profitability. Despite years of industry warnings, evolving code requirements, and growing awareness, connector issues are common in projects new and old.

The data is clear: persistent installation errors driven by insufficient training and a lack of construction quality control are driving costly failures, most of which are preventable.

As PV systems become more complex, the need for robust connector practices becomes more urgent. Every compromised crimp is a potential fire, a loss of revenue, and a step backward for the energy transition.

But there is a path forward. Solar professionals can meaningfully reduce connector risk by:

- **Reducing system complexity.**
- **Specifying compatible equipment early.**
- **Enforcing strict QA/QC during construction.**
- **Regularly inspecting connectors during ongoing project operations.**
- **Remediating connectors without delay whenever necessary.**

Now is the time for the solar industry to raise the standard. The tools exist. The knowledge exists.

It's up to every stakeholder—developers, EPCs, O&M teams, and manufacturers—to put them to work.

TAKE THE NEXT STEP

HelioVolta provides independent inspection and technical advisory services for solar and storage projects in the U.S.

We help clients reduce connector risk by conducting independent construction oversight and QA/QC, operational health audits, and failure root cause analyses alongside a range of consulting services.

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SolarGrade is field operations software designed for solar and storage teams. It turns renewable site visits into field intelligence with a mobile app that helps teams work 30% faster in the field.

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