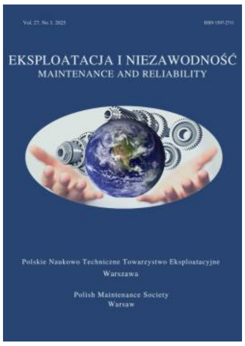

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Study on Reliability of Field-Aged Photovoltaic Connectors

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Highlights

- Testing 75 connectors life ranging from 2 to 10 years from varied climatic regions.
- Weaknesses in insulation resistance of connector especially in cold arid and desert region.
- Connector failure observed after contact resistance increased 200 % from its initial value
- SEM analysis reveals evidence of material degradation in connector casings.
- Need for Region-Specific Material Selection and Enhanced Workmanship.

Abstract

The paper presents the reliability study of field-aged photovoltaic connectors of different makes, collected from utility and rooftop solar plants across India, exposed to diverse climatic conditions with operational life of two to ten years. Tests conforming to IEC 62852 are conducted on both field-aged and control samples including Scanned Electron Microscopy (SEM) to elucidate aging mechanisms, failure modes, potential hazards, and changes in electrical and mechanical performance due to environmental and operational stresses. On-site field survey and testing reveal poor workmanship and maintenance of connectors. Laboratory testing reveals that samples with less than six years of operational life have a low contact resistance and remain relatively stable or have a marginal linear increase after undergoing thermal and damp heat testing. However, samples with operational life of six years or more sampled from regions with extreme climatic regions have shown a high contact resistance in a nonlinear pattern increasing to 300% in the thermal cycle and up to 600% in damp heat test, beyond the permissible limits of 150% from the initial value. In SEM analysis fretting was observed on connectors which had shown high contact resistance with marginal polymer deterioration

Keywords

contact resistance, damp heat testing, degradation, photovoltaic connector, reliability, scanning electron microscopy, thermal cycling

1. Introduction

Photovoltaic connectors are essential components of the Balance of Systems (BoS) in a PV plant but are frequently overlooked because they cost a minuscule (0.5%) of the plant's initial expenditure. As of December 2021, 3.5 billion photovoltaic connections were estimated worldwide as reported by PV Evolution Laboratories (PVEL) which would have considerably increased in last three years. Extensive research and efforts have been conducted on the reliability of PV modules and inverter, but this cannot be stated for photovoltaic connectors. The industry also holds the belief that 1% of the strings should be replaced annually in terms of quantified connector replacement. But according to current guarantees and standards, the operator extends it to a lifetime of 25 years, which appears excessive [1]. For a solar photovoltaic system to operate

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at its peak efficiency, PV connector performance and condition are critical. Reduced system efficiency, rapid panel degradation, and possible safety risks are just a few of the problems that can result from degraded connectors. To guarantee a solar plant's long-term efficiency and dependability; routine maintenance, inspections, and prompt connector replacement are essential [2]. Three main factors can cause connectors to fail: stress, corrosion, and wear. Stress is the steady change in material shape with aging, while corrosion is the degradation of the contact interface caused by the entry of moisture and dust. Fretting is the relative movement of the contact interface caused by wear in a connection [3]. In solar bankability report by European union [4], it has been brought out that a significant portion of reported fire incidents in SPV plants which ranges from 12% to 29% are caused by PV connector failure. According to the report [5] it is possible to prevent fires in operational assets having faulty connectors, however, it is only possible through proper testing, inspection, certification, and design. A report from the International Energy Alliance (IEA) on PV module failures [6] claims that incorrectly crimped or fitted connectors are the root cause of PV connector failure, which can result in power loss over the entire string or even cause electric arcs and fires. According to the findings, there is an estimated 5 mΩ contact resistance between connectors. This resistance grows over time and can cause temperature increase as well as changes in dimension as a result of expansion and contraction. It ultimately causes a shift in the connector's morphology and stiffness, which brings it to the fast rundown condition. One study [7] found that an increase in a connector's contact resistance might result in an annual potential power loss of 140 Watthours per string. The similar studies that have been carried out on this subject are appended below as Table 1.

Table 1. Summary of similar studies carried out on PV connectors.

Paper	Key Results	Limitations
[8]	This study has been based upon damp heat testing at temperature of 85°C with 85% relative humidity with respect to the degradation and reliability of photovoltaic connectors, connector pins didn't show any corrosive effects because of dust, however, it caused the contact resistance of connectors to slightly rise throughout the first 100–250 testing hours.	• PV connector longevity concerns have not received enough attention. • Accelerated lifetime testing's limitations in forecasting actual connector lifetimes. • Insufficient knowledge or assurances regarding the lifespan of related DC wiring.
[9]	In another study during the first 1000 damp heat cycles, the contact resistance of connections tested under accelerated fretting conditions increased linearly. It's failure was brought about abruptly by a rapid increase in the contact resistance. A critical transition amplitude exists above where gross slip at the connector interface occurs which leads to connector failure.	• The study's laboratory circumstances were unable to reproduce all real-life outdoor environmental loads, and the fretting tests employed might not adequately represent the wide and complicated range of environmental pressures that PV connections encounter in real-world field situations. • The study solely focussed on fretting only.
[10]	In task 3, of its comprehensive study on the reliability of PV systems, Scandia National Laboratories conducted research on the development of diagnostics and preventive techniques for arc faults by analysing catastrophic arcing failures in solder joints and PV connectors.	• The study was unable to cover all climatic variables, such as harsh desert or coastal climates, which would have limited the results applicability to other regions. • The study faced limitations due to the limited short- and medium-term available data. • There were also some assumptions made in the reliability models regarding the degradation and/or failure modes that do not necessarily take all the operating realities leading to possible lifespan over- or underestimates of some components. The outputs were only derived from accelerated stress testing.
[11]	In the first stage of the research, 75 new connectors were subjected to AST to determine their reliability. An approximately 9% difference of the contact resistance between the various manufacturers was noted during the analysis. 450 hours of damp heat were then followed by exposure to grime for corrosion studies on connector pins; the further studies indicated a slight increase in the resistance during the first 100 hours and no changes in resistance thereafter.	• The research only focused on the grime effects and other potential mechanisms or conditions leading to the failure were not included in the research; grime effects on connector performance are not adequately measured during the expedited test due to time constraints. • Significant differences in connector resistance existed between different manufacturers, which might have affected the results.
[12]	A separate study after undergoing hundreds of hours of damp heat cycles and corrosion testing, revealed the dependability based on the arc fault risk of the connector, highlighting the new connector's resistance to corrosion. It also showed that a connector design geometry affects the likelihood of an arc fault, and a degradation model was created to frame a data-driven strategy for connector maintenance.	• The study mostly relied on laboratory testing and modelling, and it investigated a small number of connector types and materials. • This study is mainly focused on specific arc fault types and may not have considered several other fault scenarios or interactions that can be present and that may aggravate the deterioration and failure rates of several PV systems. • The degradation models were built on assumptions of material wear and environmental factors.

Paper	Key Results	Limitations
[13]	In a different study also done at National Renewable Energy Laboratory (NREL), accelerated stress testing of 37 connectors was performed so that the understanding of the influences that mechanical perturbation has on these joints could be improved. These samples were stressed through electrical contacts specifically designed for BoS components as well as environmental stresses. It is found from the study that most of the mechanical perturbation effects are experienced at the metal pins of the male and female connectors. In both the field aged and the accelerated aged samples, corrosion, inelastic deformation and oxidation were found to be the most important degenerating factors. In both pin's, the hottest spot was discovered to be the failure spot.	• The sample size was limited to 37 samples. • Long-term field data was absent, and most of the study relied on laboratory testing, and the time for the tests was insufficient to capture the characteristic wear and degradation in a given actual scenario.
[14]	In this study, with application of the mechanical perturbation on the sub-assemblies of BoS components, the operational temperature increased and a shift in the failure mode was observed. Mechanical perturbation led to a change in the most common failure mode, from fuses to the connections made with the metal pins, and the current at failure shrank from 35 A to 15 A. Failure analysis on failed BoS components utilized X-ray computed tomography, optical and electron microscopy and chemical composition analysis, among others.	• A more sophisticated combined-accelerated stress testing chamber was still being developed, and the study made use of a prototype fixture. • As part of this investigation, the in-situ data collecting techniques were still being developed. • As part of this investigation, the failure analysis techniques, such as different spectroscopy and microscopy methodologies, were still being improved.
[15]	In this study total of 117 connectors from 5 brands were put under various tests. The connectors exposed to a combined accelerated stress testing (C-AST), which consisted of UV exposure, humidity, and temperature cycling, connectors were found to have failed quite significantly with time. It has also been revealed that connectors deterioration was severely affected by installation issues, high temperatures and humidity. As per the findings, there was an increase in contact resistance with time, but it was more pronounced in the connectors with higher initial contact resistance. The fact that various designers and brands connectors appeared to respond distinctly to the accelerated stress conditions, it theorizes that not all the connectors perform as satisfactorily in harsher conditions. In order to reduce early PV system failures, the results emphasized the necessity of better material specifications, installation guidelines, and field testing.	• Limited brand diversity and sample size • Varying controlled laboratory conditions may be different than the real time conditions. • Only samples from warm climates were primarily considered.

The present study novelty is that it highlights a more diverse testing with field aged samples aged 2 to 10 years which are collected from varied climatic regions that provides a real time data and brings out the behaviour of connector in varied environments. Moreover, a current market scenario is highlighted that gives a practical picture of the brands used with pricing which brings out the requirement of more stringent regulations and standards. The study explains correlation between contact resistance, field age and environmental conditions, which may be helpful in planning localized region-specific maintenance strategies for further failure reduction.

2. Methodology

Sampling

In this study, 75 connectors from different manufacturers are sampled from 11 different regions of India having varied seven climatic zones with operation life of 2 to 10 years and being exposed to different kinds of environment conditions. These connector samples comprised 15 new control samples, 55 field-aged samples, and 5 burnt samples as shown in Figure 1 and details depicted in Table 2.

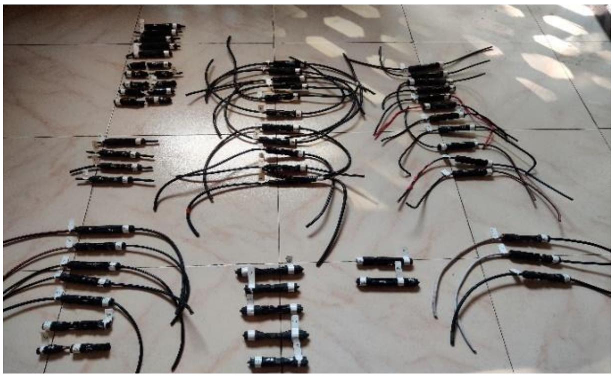


Figure 1. Samples of marked PV connectors gathered from various parts of the country

It was ascertained during scrutiny of the technical data sheet of connectors collected that some of these connectors outer casings are manufactured using different types of polymer material. The samples are collected randomly from plants based on field inspection, involving visual inspection and thermal imaging. Moreover, a detailed market survey was also carried out regarding the brands available and the pricing of the male and female pair of connectors.

Table 2. Different types of connectors installed in various regions and plant sites.

S No	Manufacturer and Country of Origin	Place	Region	Field Temperature conditions (°C)	Operational Life (Years)	Plant Type (Rooftop/Ground Mounted	Material of Connector
1	‘A' (China)[16]	Leh (Leh & Ladakh)	High Altitude Arid (Extremely Cold)	-30°C to 25°C	2 to 8	Ground Mounted (100 kWp)	PC
2	‘B' (Switzerland) [17]	Deogarh (Jharkhand)	Sub-tropical humid	10°C to 42°C	2 to 10	Ground Mounted (5 MWp)	PC
3	‘B'(Switzerland)	Pune (Maharashtra)	Tropical wet and dry	5°C to 38°C	2 to 8	Ground Mounted (2 MWp)	PC
4	‘C'(India)[18]				2 to 6	Rooftop (50 kWp)	PPO
5	‘C' (India)	Dehradun (Uttarakhand)	Sub-tropical humid	2°C to 35°C	2 to 6	Ground Mounted (20 MWp)	PPO
6	‘D'(Japan) [19]	Tirunelveli (Tamil Nadu)	Hot Semi-Arid and humid	20°C to 35°C	2 to 8	Solar Park Ground Mounted (100 MWp)	Not specified
7	‘B' (Switzerland)				2 to 6	Solar Park Ground Mounted (100 MWp)	PC
8	‘A'(China)	Delhi	Hot and Semi-Arid	5°C to 45°C	2 to 6	Rooftop (100 kWp)	PC
9	Unknown	Cochin (Kerala)	Hot and humid	20°C to 40°C	2	Ground Mounted (2 MWp)	Not known
10	‘E'(China) [20]	Jaipur (Rajasthan)	Hot and Semi-arid	5°C to 45°C	2 to 6	Ground Mounted (2.5MWp)	PC
11	‘F'(China) [21]	Imphal (Manipur)	Humid Sub-tropical	5°C to 35°C	4	Ground-mounted (1MWp)	Not specified
12	‘G'(USA) [22]	Chennai (Tamil Nadu)	Hot and humid	20°C to 35°C	4	Ground-mounted (1 MWp)	PPO
13	‘B'(Switzerland)	Jaisalmer (Rajasthan)	Semi-arid and hot (Desert)	5°C to 50°C	10	Ground-mounted (5 MWp)	PC
14	‘C'(India)				10	Ground-mounted (5 MWp)	PPO
15	‘D'(Japan)				10	Ground-mounted (5 MWp)	Not specified
16	‘H' (USA)[23]				10	Ground-mounted (5 MWp)	PPE
17	‘J’(Germany) [24]				10	Ground-mounted (5 MWp)	Not specified

Diagnostic methods for detection of connector failures

International standards for connectors i.e., IEC 62852 [25], UL 6703 [26], and IS 16781 [27] use several functional metric tests as a group to include metrics of mechanical, electrical, service life, thermal, climatic and degree of protection with an emphasis on safety regulations. While there are systematic and sophisticated testing available in laboratories to identify the reason of failures, field test methods only provide visual examination, infrared imaging

and contact resistance measurement to determine the likely failures of connectors. The summary of testing plan in this study is given as per Table 3.

Visual Inspection. Visual inspection is carried out to check problems with connectors, such as separation or loose connections, improperly fitted or loose back nuts, incorrect polarity of string connectors, improperly bent connector wires, heat deformation signs, and indication of cross-mating at different sampling sites. The NREL visual inspection checklist and IEC 61215:2016 is followed while conducting the visual examination [28]. To see if the female and male parts of the connector are stuck together due to the presence of dust or another visual defect, a push-pull test is also run on it.

Infrared imaging. Without hindering the operation of the solar power plant, thermal imaging makes it possible to analyse the PV plant's components [29], [30]. To determine these components or connectors heat signatures, a hand-held long-wave infrared camera is utilized. The direct method used to identify faults is based on the observation that anomalous temperature variations relative to typical operating conditions are caused by any defect or loss in power plant components [31]. During the audit of the modules and BoS, thermal imaging is also used to find hotspots on PV connectors.

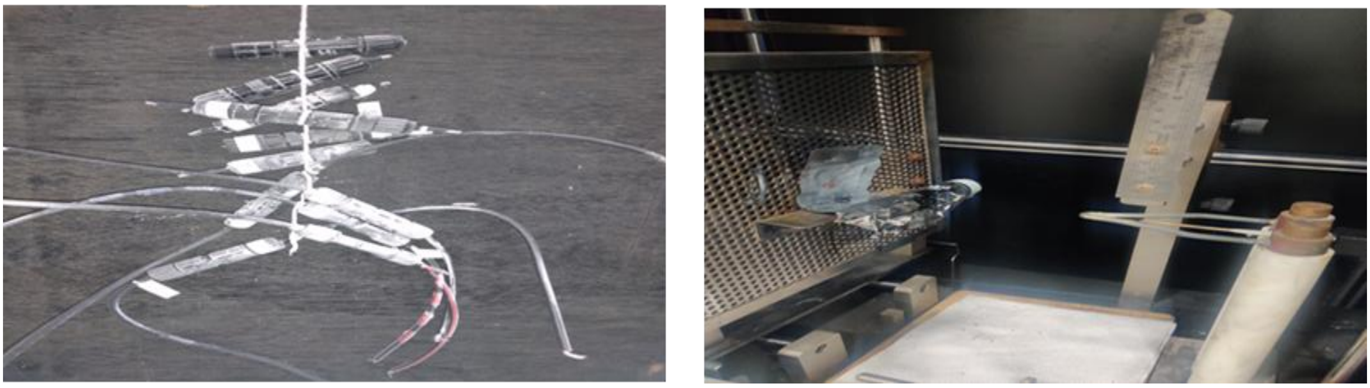
General Testing. In laboratories, routine non-destructive and destructive testing is done by following IEC 62852- 2014 [25] and IEC 60512 [32]. A total of 27 connector samples comprised of both control and field-aged samples are subjected to non-destructive testing for electrical performance including contact resistance, dielectric voltage withstand test, and insulation resistance as depicted in Figure 2(a), (b) and (c). Contact resistance is the most important electrical test for a connector which measures resistive heating and variation in resistance from thermal effects to evaluate their efficacy in reliability, safety, and performance. The insulation resistance test evaluates connector body integrity and the dielectric voltage withstand test is conducted to evaluate the ability of the connector's insulation to withstand high voltages without breakdown. A test for environmental exposure is conducted, which involves an Ingress Protection (IP) which is depicted in Figure 2(d) and (e). The IP test helps determine the connector's ability to withstand environmental factors such as dust, dirt, moisture, and water exposure. Finally, a destructive testing method of glow wire is conducted on samples to assess the fire resistance of connectors surface material by exposing them to a hot wire or glowing element by simulating a high-temperature ignition source up to 650°C as shown in Figure 2(f). The test evaluates the material response to the heat source and its ability to prevent fire propagation or ignition.

(a)

(b)

(c)

(d)



(e) (f)

Figure 2. (a) Conducting of Contact Resistance test on connector (b) Performing Dielectric Voltage withstand test on connector (c) Conduct of IR test on connector (d) Conduct of waterproof test as part of IP test on connector (e) Conduct of dustproof test as part of IP test on connector (f) Apparatus showing conduct of Glow wire test on connector.

Thermal Cycling. The thermal cycling test, as per IEC 62852 and IEC 60512 evaluates the connectors performance under cyclic temperature changes. A separate set of 16 connector samples comprising of control and field-aged connectors is subjected to a thermal cycling test for 200 cycles (each cycle comprising of 5 hours) as per laid out norms where the connector is subjected to repeated cycles of temperatures of -40 to 85 °C as shown in Figure 3(a) and (b). After every 100 cycles, the contact resistance of connectors is measured and finally, the dielectric strength test and IP test are conducted followed by the contact resistance test. Finally, the glow wire test is conducted on the samples. The connector is then examined for signs of damage or degradation, such as corrosion or changes in material properties after this test

(a) (b)

Figure 3. (a) Conduct of Thermal cycling for connectors in the chamber (b) Graph showing the thermal cycling test being conducted at temperatures of -40 to 85 °C.

Damp Heat Testing. Damp heat cycle tests as part of 'Climatic test group E' based on IEC 62852 and IEC 60512 are conducted on 14 control and field-aged connectors for 7 cycles for a total of 1416 hours, though the standard norms specify only 1000 hours as shown in Figure 4 (a). However, more stress was put on to the connectors for establishing a pattern of failure. In each cycle, the connector is exposed to a continuous temperature of 85°C and 85% humidity environment, and again after each cycle, the contact resistance test is repeated followed by tests as mentioned in thermal cycling after the termination of damp heat testing as depicted in graph shown in Figure 4(b). After this test, the connector is examined for any signs of damage or degradation, such as corrosion or changes in material properties.

Figure 4. (a) Conduct of Damp heat testing for connectors in the chamber (b) Graph showing the damp heat test being conducted at a fixed temperature of 85°C and RH at 85%.

Advanced microscopic testing. A total combination of 20 samples which amalgamated control samples, fresh field aged samples, samples that have undergone all aforesaid tests mentioned above and burnt samples are subjected to advanced forensic microscopic analysis which examines material morphological traits to find evidence of melting, arcing, corrosion, and other failure pointers (such as mismatch indications and the quality and total amount of the metal alloys in connector pin). PVEL and other studies [33], [34] have recommended Scanning Electron Microscopy (SEM) techniques for such advanced analysis. To detect metal corrosion and arcing products, SEM uses an electron beam to scan the connector and create a two-dimensional image. It is mostly utilized for micro and failure analysis, and it can also detect morphology and chemical composition.

Table 3. Summary of the testing plan.

Test ID	Type of Test	Arrangement	Testing Parameter(s)	Field/ Laboratory conditions	Requirements
V-1	Visual Inspection	12 Plants across different regions of India	• Dust accumulation • Loose fitting/connection • Broken parts • Improper installation • Clearances and creepage distances. • Durability/ Correctness of marking. • Cable clamp pull and torsion.	• Naked eye. • Push – pull test will be carried out in accordance with test 9a of IEC 60512. • Measurements	• Dimension shall comply with manufacturer's specification. • No visual crack or damage and dust intrusion. • Markings as per IEC 62852
IR-1	Thermal Imaging	12 Plants across different regions of India	Hot Spots	• Emissivity value is set as 0.85. • Angle of view has been set as 75° to 90° when taking image of connector.	Temperatures crossing 20°C over ambient temperature to be marked and further tested for contact resistance.
GT-1	General Testing (Electrical Performance)	• 4 control samples (unexposed) • 23 field-aged connectors in operation	Contact Resistance	• Test current of 1 A • Measuring options: At the end of termination	Deviation of the contact resistance shall be no more than 50% of reference value or <= 5mΩ.
			Dielectric Voltage Withstand test	• Application of r.m.s withstand test voltage of 4 kV for 1 minute. • The test voltage shall be applied between all live parts and accessible surface.	No breakdown or flashover should occur
			Insulation Resistance	Application voltage of 1.5 kV.	The value should be >= 400 MΩ
GT-2	General Testing (Environmental Performance)	• 4 control samples (unexposed) • 23 field-aged connectors inoperation	IP test	• Test probe 11 according to IEC 61032 with test force of 10 N. • IP code as specified by manufacturer	• No live part shall be accessible. • Mated connector

			Glow wire test	• Glow wire test according to IEC 60695-2-11. • Test temperature: 650 °C.	No inflame
TC-1	Thermal Cycling	• 4 controls (unexposed) • 16 field aged connectors in operation	Visual examination	• Temperature cycle from 85ºC to -40 ºC. • 200 cycles	No damage likely to impair function.
			Contact Resistance	Test Current :1 A	Deviation of the contact resistance shall be no more than 50% of reference value or <= 5mΩ.
GT3	General Testing (Electrical Performance and Environmental Performance)	• 4 control samples (unexposed) • 16 field aged connectors in operation	Contact Resistance	Same as in GT1	Same as in GT1
			Dielectric Voltage Withstand test		
			IP test	Same as in GT2	Same as in GT2
			Glow wire test		
RH-1	Damp Heat	• 4 control connector samples • 10 field aged connectors in operation	Visual Examination	• Test temperature: 85ºC $\pm$ 2 ºC • Test humidity: 85% $\pm$ 5 %. • Test duration of 1416 hours for 7 cycles	No damage likely to impair function
			Contact Resistance		Deviation of the contact resistance shall be no more than 50% of reference value or <= 5mΩ.
GT4	General Testing (Electrical Performance and Environmental Performance	• 4 control connectors • 10 field aged connectors in operation	Contact Resistance	Same as in GT1	Same as in GT1
			Dielectric Voltage Withstand test		
			IP test	Same as in GT2	Same as in GT2
			Glow wire test		
SEM1	Scanned Electron Microscopy	• 3 control connector samples • 17 field-aged connectors in operation (including samples from previous testing procedures)	• Fretting • Corrosion • Surface deterioration	• High vacuum conditions – 8mbar • Temperature of laboratory 20 ºC. • Magnification - 25X to 170X • Accelerating voltage -15 kV • Field of View- 1mm to 100µm • Working distance – 10- 13 mm	Visible material deterioration or fretting or corrosion.

3. Results and Discussion

Visual inspection and Market survey

It was discovered that there is no industry standard for connector design being followed both on-site and during site visits to several plants spread throughout various parts of India. The technical data sheet specifies the size, form, and material variations of the connectors. On-site observations revealed that the PV DC connectors do not have the standard indications and markings that are necessary as outlined in IEC 62852. The connectors also differ in terms of their ingress protection (IP) rating (ranging from IP 65 to IP 67) and the insulation material (i.e., casing and back nut). All connectors are made of thermoplastics, primarily the material being used in the construction of connectors is polycarbonate (PC), polyphenylene oxide (PPO), and polyphenylene ether (PPE). It is appropriate to note that all of these thermoplastics have undergone extensive research, and their chemical and thermal characteristics are well established. It is up to the installer to determine which material works best for PV connectors in the most extreme environments (hot and cold climates). Hence, to determine the material specifications specific to each region a standard design is necessary.

Several counterfeit products are discovered to be available in the market after market analysis. The cost of connectors available in the market and online stores ranges from Rs 40 (0.47 US $) to Rs 150 (1.78 US $), which claim to be certified and have undergone regulatory testing. It is hard to imagine sacrificing quality for huge price difference between various manufacturers/brands for a pair of male and female connectors.

During the site visit, it was seen that there was stress in the connectors as a result of wires and connectors dangling from the module mounting structure in certain plants. A few of the connections between the string and SCB are not tightly sealed, making them vulnerable to the infiltration of dust and moisture. The majority of sites exhibit inadequate wire and connector discipline which causes mechanical stress in a connector at a later stage due to incorrect bending. This is more prevalent during the operation and maintenance phase due to bad workmanship rather than installation as depicted in Figure 5.

(a)

(b)

(c)

(d)

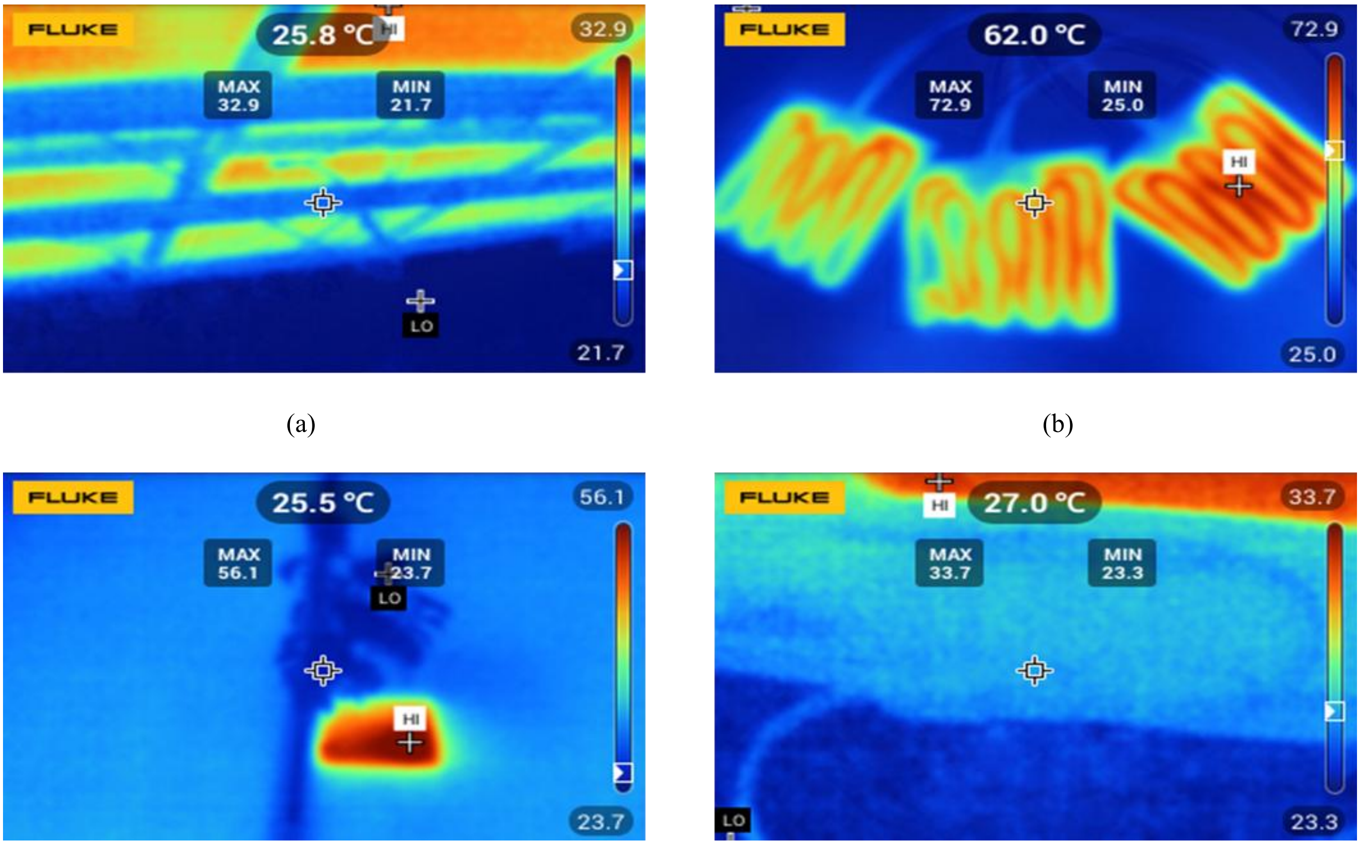
(e)

(f)

Figure 5. (a) Hanging connectors on the Module Mounting Structure at Deogarh (b) Bend and hanging connectors at Delhi rooftop plant site (c) Photovoltaic plug connectors loosely tightened in SCB at Pune plant site (d) Birds' nest with hanging connectors and on Module Mounting Structure at Pune plant site (e) Wires with connectors hanging at Dehradun plant site (f) Bundled-up connectors at Chennai plant site.

Thermal or Infrared Imaging (TI or IR)

Thermal imaging revealed that several PV connectors had temperature increase of more than 20°C over ambient temperature, which could cause further heating and system malfunction. These strings of PV plug connectors were quite dirty and had hotspots. The hotspots are also visible on the connectors which were bunched together in the Rajasthan site as shown in Figure 6 (b). Figure 6 (c) below illustrates that the solar cell in the module had also developed hotspots which had hotspots on connectors. If such connectors are not maintained in a routine manner, under severe circumstances they may burn, harming the module, or, in the worst case, result in a fire inside in the plant.



(a) (b)

(c) (d)

Figure 6. (a) Thermal imaging showing connectors hanging on the MMS at Pune site (b) Connectors bunched up together showing hotspots at Jaisalmer site(c) Hotspots on solar cell of the module which had connectors at Jaisalmer site (d) Connectors fitted with module mounting structure in a correct way.

General Testing Analysis

The initial tests are performed on 27 connectors in a laboratory, including contact resistance, dielectric voltage, insulation resistance, IP, and glow wire test. As the connectors had different lengths of 4 sq mm cables, the contact resistance of the whole sample was first measured and then the cable resistance was subtracted from the initial value to get the contact resistance of the connector.

Relationships between the field age of the connector and the contact resistance of the cable are shown in the scatter plots in the figure 7. The data points are presented in blue circles while a red trend line is drawn to show how the points are positively correlated. A field age correlation coefficient of 0.82 suggests that, as the field age of the connector increases, the contact resistance of the cable also increases significantly. This means that the older the connectors, the higher is the contact resistance. This is helpful in replacing and maintaining connectors with age for effective performance.

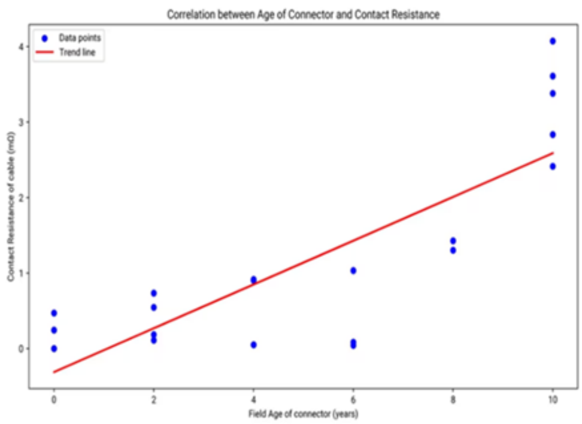


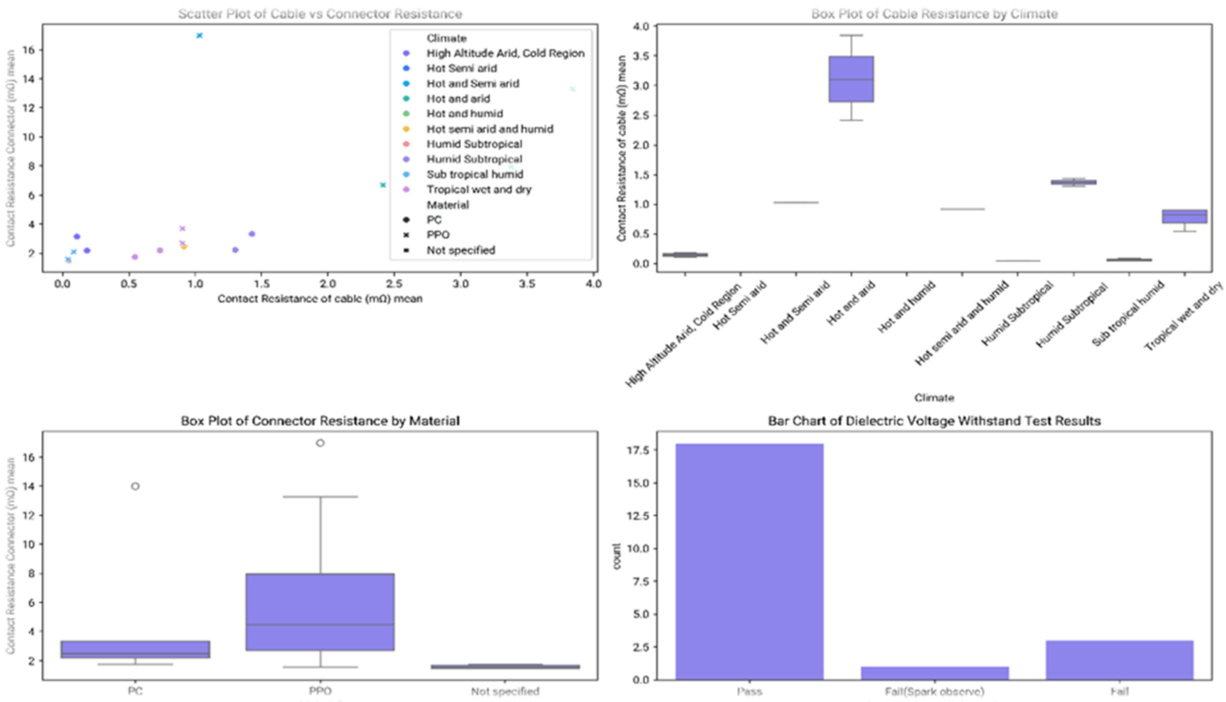
Figure 7. Depicts relationship of connector and contact resistance of cable.

Also, the scatter plot at Figure 8 (a) tends to show a direct relationship between contact resistance of the cable as well as of the connector. It was observed that if there was high cable resistance, then the connector being used was likely to have higher resistance. These observations led to the box plot at Figure 8(b) inferring that region with climates "Hot and Semi-

Arid" and "Hot and Humid," have high median values in terms of contact resistance of the cables. But "High Altitude Arid, (Cold Region)" appeared to deliver a wider range of resistance values. Resistance trends for the connector resistance were similarly exhibited except for the climatic regions of "Hot and Semi-Arid" and "Hot and Humid" which were recorded with higher resistance values.

The box plot shown in Figure 8(c) also shows that connectors made from PPO material have higher median contact resistance than those of connectors made from PC material. As shown in Figure 8(d), most of the samples pass the dielectric voltage withstand test, however, the samples which fail tend to show higher values of contact resistance. Most samples pass the IP test as depicted in Figure 8 (e), thus exhibiting effective ingress protection. However, samples which did not pass the IP test tend to have higher values of contact resistance. As seen in Figure 8(f), the majority of samples passed the glow wire test. Samples which fail this test have a tendency to have higher contact resistance values, which primarily suggests a relationship between poor thermal performance and higher contact resistance.

Climates which are "hot and semi-arid" and "hot and humid" have also attributed higher values of contact resistance on both cables and connectors. The strong positive and negative correlations within specific locations such as Cochin, Kerala Deogarh, and Jharkhand suggest that outside environmental indices in these locations might significantly affect relationship existent between contact resistance and the IP test. Connectors made of PPO material tends to have higher resistance when compared with PC. It is also observed that higher contact resistance exist on samples which have lower values of insulation resistance and this suggests relationship that exists between poor insulation and contact resistance. The connectors which pass the dielectric voltage withstand test have minimal contact resistance values, indicating an increasing pattern where the contact resistance increases progressively with time, as well as with varying test conditions. Though connectors that pass the dielectric voltage withstand test, there is a progressive increase in contact resistance over time, but the values remain lower compared to those that fail.



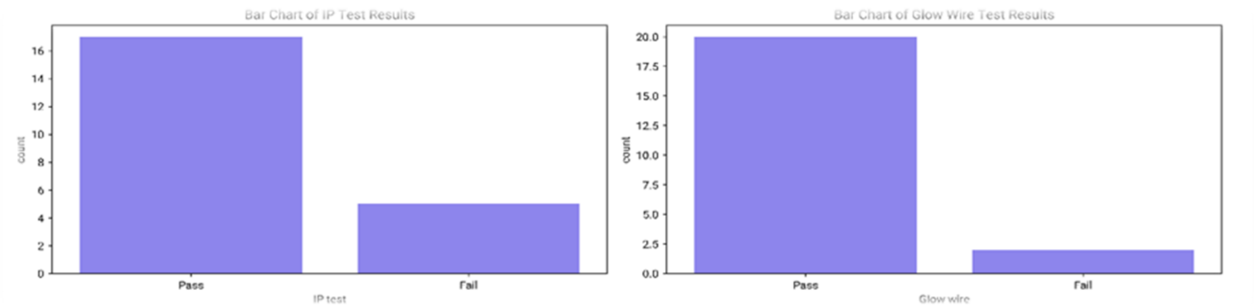


Figure 8. (a) Depicts correlation between contact resistance of the cable and the connector (b) Depicts correlation between contact resistance of the cable and climate regions (c) Depicts correlation between contact resistance of the connector and its material (d) Evaluates correlation between contact resistance of the connector and dielectric voltage withstand test (e) Evaluates correlation between contact resistance of the connector and IP test (f) Evaluates correlation between contact resistance of the connector and glow wire test.

Thermal Cycling

A total of 16 connectors were tested initially out of which one connector from Jharkhand (J10_B2) malfunctioned and a reading of 15 connectors is undertaken. Subsequently, one connector each from Leh (L8_A1), and Pune (P6_C6) also malfunctioned during first 100 cycle of testing procedure.

Correlation of contact resistance with time. As depicted in in Figure 9, almost all connectors showed high contact resistance values after 200 cycles of 1000 hours of thermal cycling test. The mean contact resistance at 0 hours is 3.94 mΩ, with a standard deviation of 3.82 mΩ. After 500 hours, the average contact resistance reaches 7.42 mΩ with 6.98 mΩ as its standard deviation. After 1000 hours, the average contact resistance increases to 12.29 mΩ with 9.02 mΩ as its standard deviation. The average contact resistance rises to 15.34 mΩ with 11.74 mΩ as its standard deviation after carrying out the dielectric voltage and IP test.

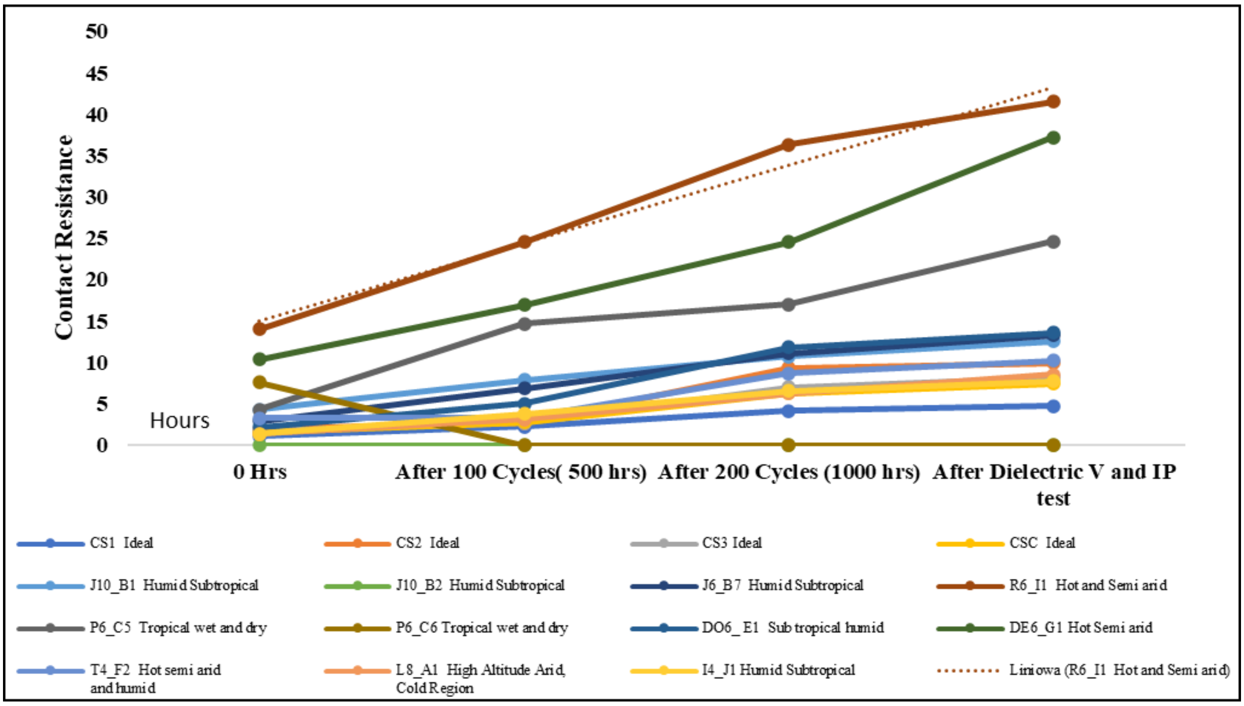


Figure 9. Values of contact resistance of 12 connectors depicted during Thermal Cycle testing of 1000 hours.

All connectors passed the dielectric voltage withstand test after undergoing a full cycle of testing except the connector from Rajasthan, Jaipur (R6_J1) with six years of operational life which failed in all subsequent tests of IP and glow wire. It has also been noticed that the connectors that had low contact resistance, in the beginning, showed a relatively stable contact resistance after 1000 hours of thermal cycle testing, however, the connectors that had already had high contact resistance initially, their values increased non-linearly throughout the testing and showed a sharp increase with highest being for the connector from Rajasthan (R6_J1) with 6 years of operation life that measured 41.5 mΩ with degradation of almost 300% of the initial value. Different samples exhibited varying rates of increase in contact resistance which implies that some connectors may be more prone to changes over time than others. Contact resistance is further increased in connectors from hot semi-arid and tropical wet and dry regions after the dielectric voltage and IP test indicating that the connectors experienced further stress or degradation.

Correlation with contact resistance over time by material, climate and location. Figure 10 shows how contact resistance of connectors, based on its region, climate and material, changes with time. It is seen that the connector made of PPO material had a increased value of contact resistance. It begins at almost 7.5 mΩ at 0 hours to around 22.5 mΩ after 1000 hours. On the other hand, PC mateial does a better job as it starts out at around 5 mΩ at 0 hours before increasing to approximately 15 mΩ in 1000 hours. The way the connectors are made bears a lot of significance to the contact resistance and its change over time. Out of the three connector materials, the PPO connectors record the highest increase followed by PC. However, contact resistance increases with time for all materials indicating a possible wearing out, or degradation over time.

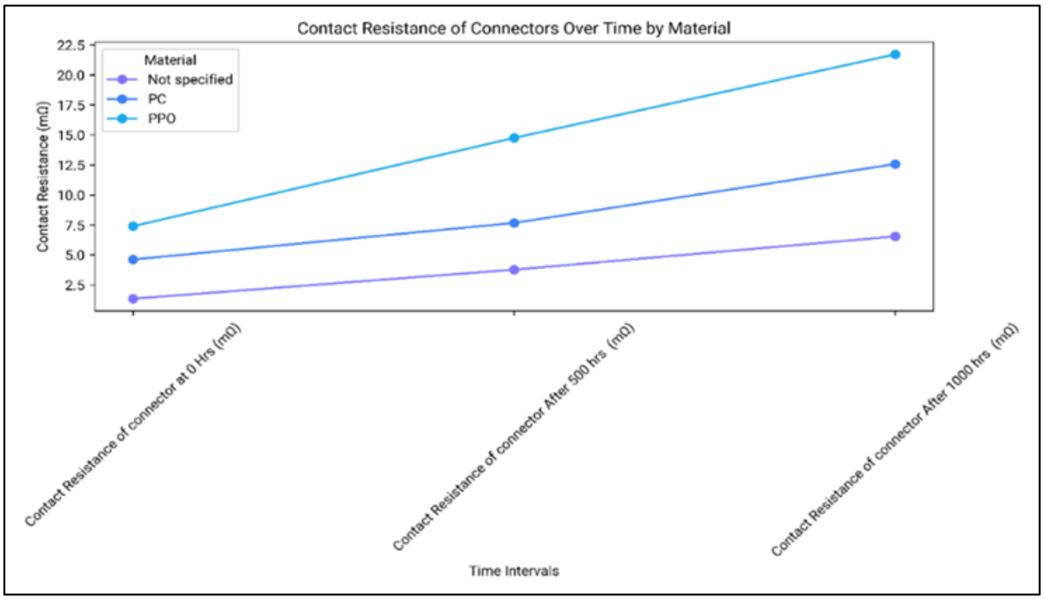


Figure 10. Depicts contact resistance of 12 connectors over time by material, climate and location during Thermal Cycle testing of 1000 hours.

Damp Heat Testing

A total of 14 connectors underwent the testing cycle for 1416 hours however, only 11 could complete the cycle. As depicted in Figure 11, the contact resistance showed a linear stable increase for connectors that had a low contact resistance value at the start however the connectors that had high contact resistance values in the beginning showed a considerable nonlinear increase in their contact resistance till the completion of the cycle. Four connectors with six to ten years of operational life showed a maximum increase in contact resistance beyond 20 mΩ which were sampled from Pune (P6_C7), Jharkhand (J10_B3), Rajasthan (R6_I2), and Delhi (DE6_G2). Almost all connectors passed the dielectric voltage withstand test however, insulation resistance for the connector from Jharkhand (J10_B3) (sub-tropical humid) failed with 10 years of operational life. All connectors passed the subsequent testing of IP, and glow wire except the connector from Delhi (Hot Semi-arid climate) with six years of operational life which failed in all parameters with a degradation of 600% from its initial value.

Despite passing the dielectric voltage withstand test, IP test, and glow wire test, it should be noted that the connector has failed or is almost failing at a contact resistance of 200% of the initial value. This indicates that the failure of the connector is unrelated to the results of IP and glow wire tests; nevertheless, the opposite is also true.

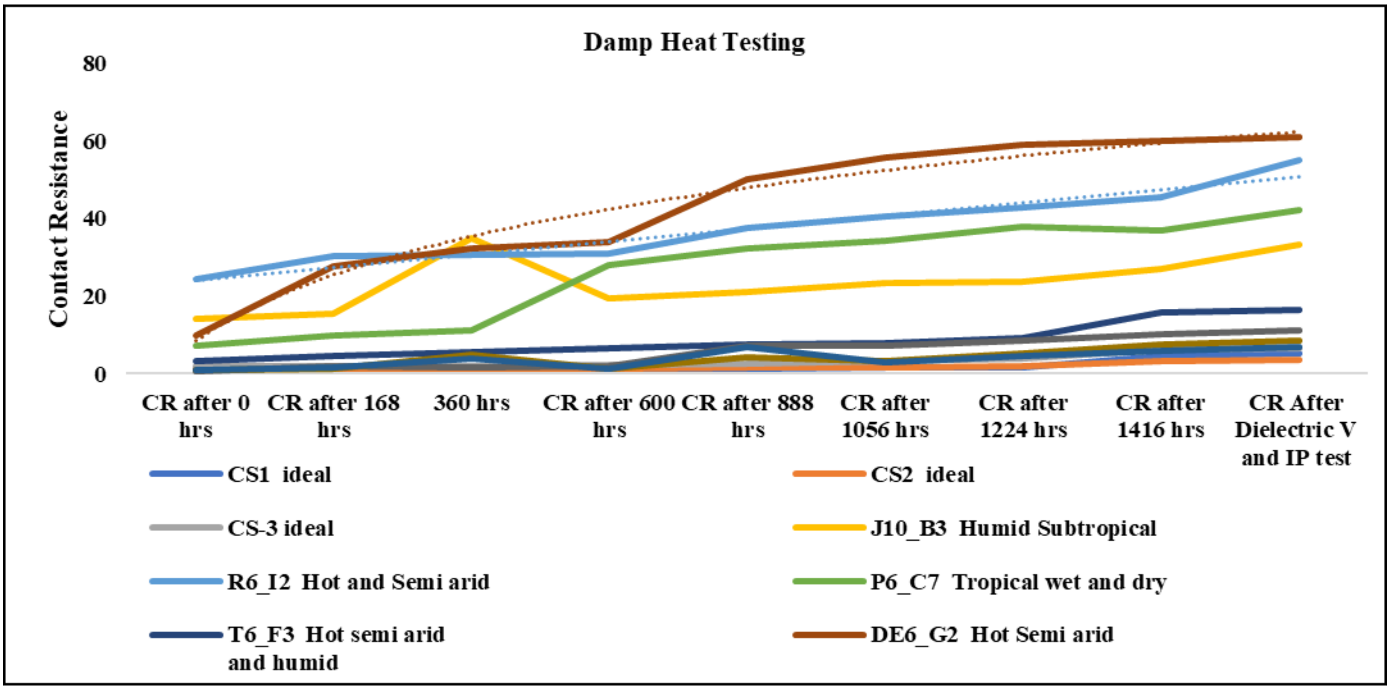


Figure 11. Values of contact resistance of 11 connectors depicted during Damp Heat testing for 1416 hours.

Combined Analysis

Contact Resistance of Connector. Contact resistance of the connector is contributed by various factors depending on the climatological and geographical context. This brings out that environmental factors play a critical role in the degradation of connectors over time as depicted in below Figure 12.

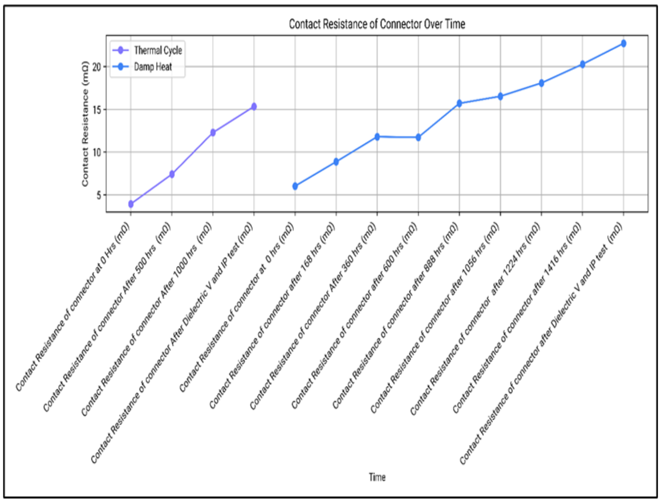


Figure 12. Plotting of contact resistance over time during thermal cycle and damp heat test.

- Location and climatic impact: Places of Delhi and Jaipur with hot semi-arid climates observed higher contact resistance values, hence connectors within these climates tend to experience more abrasion which further means an increased amount of degradation over time.
- Time dependency: As factors become time dependent, it is observed that contact resistance of these particular areas increases on the whole in most climates, however, it is the harsher climates that have the largest increase over time.

Analysis of contact resistance of connector in thermal cycle and damp heat testing.

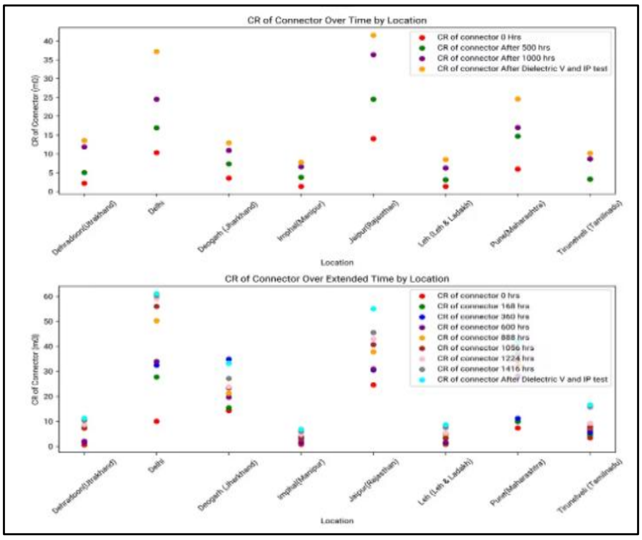


Figure 13. Analysis of contact resistance with location in thermal cycle and damp heat test.

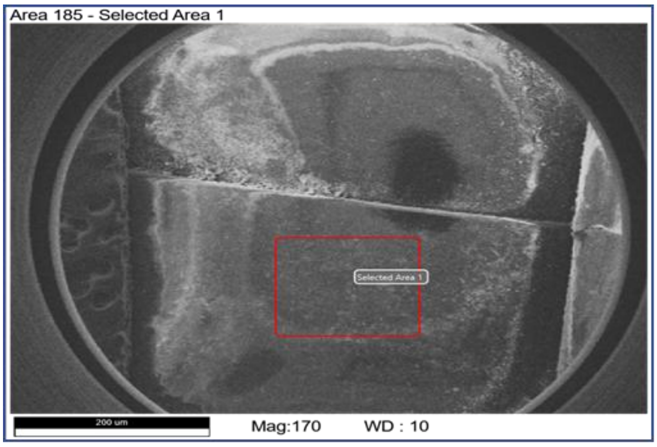
Figure 13 depicts the study of contact resistance, which was observed to be higher for the damp heat dataset in the initial stage, 6.03 mΩ, compared to that for the thermal cycle dataset, 3.94 mΩ. The data from both datasets are shown to increase with time; however, the increase for the damp heat dataset is more significant and it reached a maximum of 59 mΩ, whereas that of the thermal cycle dataset reached only 36.35 mΩ. After the dielectric voltage and IP test, the contact resistance is much higher in the damp heat than that in thermal cycle. The standard deviation is commonly higher in the damp heat dataset, indicating more variability within the contact resistance measurements. These results show that the conditions of damp heat have a more profound effect on the progression of contact resistance of the connector with time than those related to thermal cycling.

SEM Testing

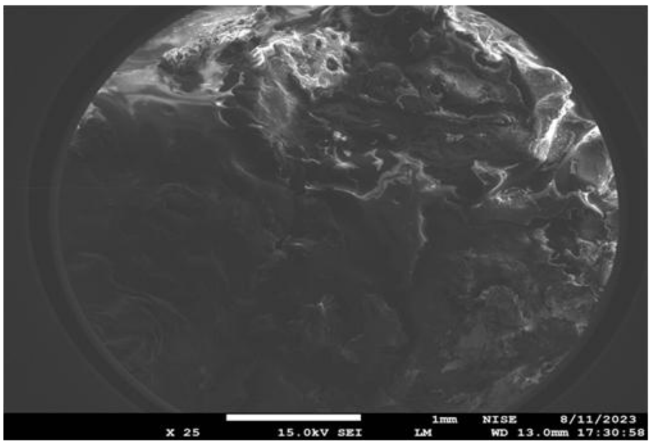
It was noticed during the SEM analysis that the connectors from Leh (High altitude arid, cold region) and Rajasthan (Hot and semi-arid, desert) had polymer material deterioration in the outer insulation casing of the connector as visible in the SEM images Figure 14 (d) (e), and (f). The possible reasons can be due to the extreme climatic conditions and temperature variations in these regions during summer and winter and high intensity of ultraviolet rays in Leh. The next concern that was noticed was the presence of fretting on the metal pins of connectors which had shown high values of contact resistance initially as visible in Figure 14(a) and (c).

4. Challenges Faced During Testing

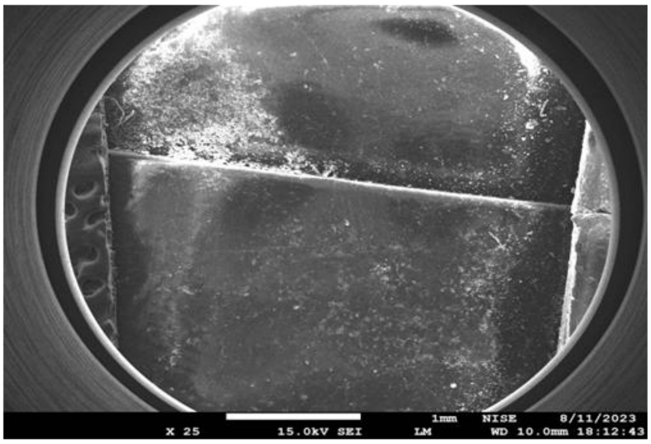
1. It was a heterogeneous mix of connectors of different brands with varied operational life collected from distant regions and climatic zones. Hence number of variables was much more and it was difficult to carry out the statistical analysis.
2. The connectors had different lengths of wire for which contact resistance had to be separately calculated for the connector. Hence it is necessary that during sample collection cable length is the same.
3. Some of the connectors malfunctioned during initial testing. It was felt that the sample size should have been much larger. However, it was difficult to take a large number of working connectors from plants as the operator resisted such procedures.
4. Test apparatus for all the tests mentioned in IEC 62852 for DC connectors (BoS) is not available in all the NABL-certified laboratories. Mostly it is for the photovoltaic panel-based tests. Thermal and damp heat chambers cannot be dedicated to the connectors when module testing is being carried out as far as commercial activities are concerned.
5. The connector technical sheets do not specify the full material specifications of the connector.
6. There are two methods for measurement of contact resistance i.e. V/I method (as per IEC 60512-2-1) and wire method. Though the V/I method is the most accurate, however, the measurements are dependent on the connections made.
7. It was found out that the connector may be good but how it is crimped and tightened during installation is of utmost importance, as the value of contact resistance varies in milliohm and it can vary a lot if proper assembly is not done at the installation level.



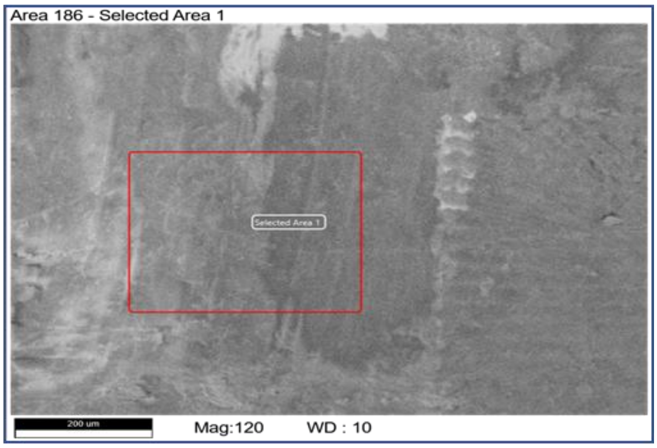
(a)



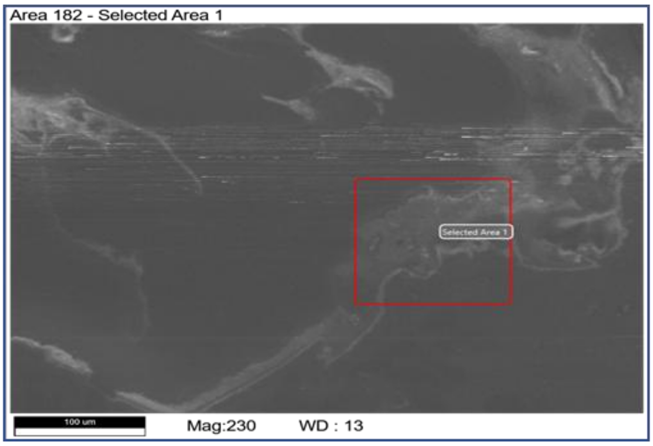
(b)



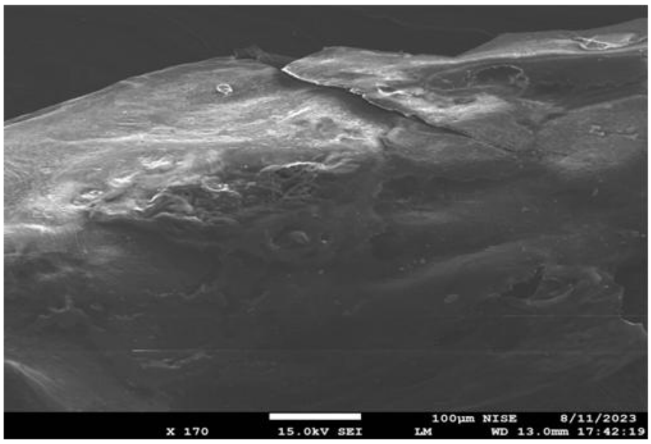
(c)



(d)



(e)



(f)

Figure 14. (a), (b) and (c) SEM analysis showing the dust and corrosion inside the connector interior surface (d), (e) and (f) SEM analysis showing fragmentation of material on the outer surface of a connector.

5. Conclusion

Photovoltaic (PV) connectors are crucial in solar photovoltaic power plant performance, safety, and longevity. A detailed evaluation of solar PV connectors collected from various regions of India, considering their age and usage in the field, has resulted in significant findings and has practical consequences for the photovoltaic sector. The lack of consistency in the standardization, material composition, and markings of PV connectors has been shown through site visits and market surveys. In addition, the existence of counterfeit connectors and significant price discrepancies among supposedly approved alternatives question the credibility of more affordable solutions. The unskilled workforce difficulties at several plants are evident, as shown by inadequate management of cables and connectors, resulting in the ingress of dust and moisture highlighting the necessity for enhanced practices in both installation and maintenance. The results of comprehensive testing based on IEC 62852 have revealed a high contact resistance in certain connectors, accompanied by observed weaknesses in insulation resistance, notably in cold arid, and desert regions. The aforementioned findings highlight the need to take regional factors into account while choosing connectors. During thermal cycling failures were noticed, predominantly in connectors sourced from Leh and Pune. Despite passing the dielectric voltage withstand, IP, and glow wire test, the connectors have failed or are on the verge of failing at a contact resistance of 200% from the initial value, which is beyond the permissible value of 150%. Both thermal cycle and damp heat testing exhibited discernible patterns in contact resistance, characterized by non-linear increments in contact resistance of connectors that initially possessed high resistance with a maximum degradation value of 300% in thermal cycle and 600% in damp heat test. The investigation using SEM revealed evidence of material degradation in the casings of connectors, particularly in climatic regions of Leh and Rajasthan. This deterioration can be linked to significant variations in climatic conditions. Furthermore, it was noticed that connectors exhibiting high contact resistance displayed fretting, thereby highlighting the relationship between contact resistance and deterioration of connectors. The adoption of region-specific material selection, and the enhancement of workmanship throughout both installation and maintenance phase is essential in enhancing the reliability and longevity of solar PV systems, ensuring their continued effectiveness in harnessing clean energy across diverse landscapes.

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Abbreviations

BoS	Balance of Systems
DC	Direct Current
EN	European standards
IEA	International Energy Alliance
IEC	International Electrotechnical Commission
IR	Infrared Imaging
kWp	kilo Watt Peak
MWp	Mega Watt Peak
NEC	National Electric Codes
NREL	National Renewable Energy Laboratory
PC	Polycarbonate
PPE	Polyphenylene Ether
PPO	Polyphenylene Oxide
PV	Photovoltaic
PVEL	Photovoltaic Evolution Labs
Riso	Insulation Resistance
SEM	Scanning electron microscopy
STC	Standard Test Condition
TI	Thermal Imaging
TUV	Technischer Überwachungsverein
UL	Underwriter laboratories