Experimental evaluation of Fire Detection on Different Photovoltaic Installations Using Distributed Fibre Optic Linear Heat Detection

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ABSTRACT

The increasing global deployment of photovoltaic (PV) systems as a sustainable energy source has significantly expanded their use in industrial and residential rooftops, and large-scale solar power plants on the ground. However, PV-installations present specific fire safety challenges due to electrical faults, arc events, and combustible materials located beneath the panels. Early and reliable fire detection is therefore essential to mitigate potential damage and ensure operational safety. This study investigates the application of a distributed Fibre Optic Linear Heat Detection (FO-LHD) system for early fire detection in photovoltaic installations. The FO-LHD technology employs fibre optic sensor cables installed beneath PV-panels to enable continuous temperature monitoring with high spatial resolution over extended distances.
Fire detection performance was evaluated through controlled laboratory experiments on PV-panels. A pre-spliced fibre optic sensor cable with optical connectors was mounted beneath the panels using clips and arranged in an S-shaped configuration to maximize sensing coverage and detect sensing at different locations. The sensor cable was connected to an FO-LHD controller configured according to EN 54-22:2015 + A1:2020 and UL-521/ULC-S530-M91 fire detection standards. For detailed analysis, the sensor cable layout was divided into multiple zones to assess detection time relative to different ignition locations. Experimental results show that the FO-LHD system detected fire events within minutes after ignition across all test scenarios. The distributed sensing capability enabled accurate localization of temperature rise along the sensor cable, providing spatially resolved fire detection. These results demonstrate the suitability of FO-LHD as an effective and scalable fire monitoring solution for PV- panels.

Key words: Distributed Temperature Sensing (DTS), Fibre Optic Linear Heat Detection (FO-LHD), Photovoltaic system fire safety, Early fire detection

SUMMARY

This paper presents an experimental evaluation of fire detection performance in different PV installation configurations using a distributed Fibre Optic Linear Heat Detection (FO-LHD) system. As PV deployment continues to expand, reliable early fire detection has become increasingly important to mitigate fire risks associated with electrical faults, hotspots, and combustible materials beneath solar panels. Controlled laboratory experiments were conducted on four representative PV configurations using arc ignition and wooden crib fire scenarios to assess detection performance under varying installation geometries. The results demonstrate that the FO-LHD system provides rapid fire detection and continuous spatial temperature monitoring, with detection times ranging from within a minute in the ignition zones and effective localization of thermal events beneath both small- and large-scale PV installations. The study further shows that detection performance is influenced by factors including sensor cable layout, installation geometry, roof inclination, fire location, and environmental conditions, highlighting the importance of optimized sensor cable deployment and alarm parameter configuration. Overall, the findings confirm that distributed FO-LHD technology is a promising solution for enhancing fire safety and operational reliability in PV systems, providing continuous monitoring and early warning capabilities suitable for a wide range of PV applications.

Introduction

With the acceptance of PV as a cleaner and long-term source of energy, it is being accepted both for small- and large-scale energy production. It has become one of the fastest-growing renewable energy sources worldwide, playing a crucial role in the global transition towards sustainable energy systems. In 2024, annual PV installations reached a record 601 GW, increasing the cumulative global installed capacity to over 2.26 TW, which is expected to supply more than 10% of the world's electricity demand while avoiding over 1 000 Mt of CO_2 emissions annually [8]. The International Energy Agency (IEA) projects that global renewable power capacity will increase by 4600 GW between 2025 and 2030, with solar PV technology accounting for nearly 80% of this expansion, highlighting the increasing importance of ensuring the safety and reliability of PV installations [9]. With the expansion of the PV systems both for individual rooftop, industrial rooftop installation and Solar plants, it is becoming increasingly important to have a reliable fire detection system. Conventional fire detection technologies, including smoke detectors and flame detectors, exhibit significant limitations in PV applications because of delayed response, restricted coverage beneath solar panels, and susceptibility to environmental conditions [4] [10]. As PV installations continue to expand, ensuring their operational safety has become increasingly important because electrical faults such as DC arc faults, hotspots, connector failures, and insulation degradation can lead to overheating and fire [11]. The rapid growth of PV systems therefore demands the need for reliable fire detection technologies that can identify thermal anomalies early, improving system safety, reliability, and reducing economic losses [8]. Consequently, fibre optic sensing technologies have emerged as a promising alternative for continuous thermal monitoring in electrically harsh environments. FO-LHD system which is widely accepted in the market for fire detection provides a great advantage both to detect fire quickly and spatially accurate for both small and large installations. The quick measurement time, long measurement range, multiple measurement channels on a single controller and straightforward installation method makes it suitable for fire detection on PV installations. To ensure that appropriate fire detection and safety measures are incorporated from the start, Fire risk assessment should be integrated into the design and development of PV systems. Regular system testing, continuous monitoring, and periodic evaluation of component failures are essential to enhance system reliability, maintain power generation, and minimise fire risks [7].

Literature review

PV systems operate under high direct-current (DC) voltages that remain active whenever sunlight is present. This creates unique fire hazards compared to conventional electrical installations. DC arc faults are particularly dangerous because the current does not naturally pass through zero as in alternating current (AC) systems, allowing electrical arcs to persist for extended periods and ignite surrounding combustible materials [1]. Early detection of DC arc faults is critical for preventing PV fire incidents and advanced sensing technologies like FO-LHD capable of real-time monitoring are needed as they enable continuous temperature measurements with high spatial resolution over several kilometres while remaining immune to electromagnetic interference [3]. The temperature-based fault detection remains one of the most reliable approaches for identifying abnormal operating conditions in PV systems before catastrophic failures occur [4]. Fibre optic linear heat detection (FO-LHD) systems can accurately detect and localise fire under realistic fire scenarios, supporting their application in safety-critical infrastructures [5] [2]. The International Energy Agency (IEA) reports that the rapid deployment of distributed and utility-scale solar PV systems is accompanied by growing challenges related to grid integration, system reliability and operational management, reinforcing the need for advanced monitoring and early fault detection technologies for PV installations [9]. The literature anyhow shows a lack experimental studies for evaluating fire detection performance underneath PV panels, thereby providing a case for the present research.

Methodology and results

During the laboratory experiments, the FO-LHD sensor cable was installed beneath the PV panels in a

predefined routing configuration and secured using stainless-steel clips to maintain consistent cable placement and ensure repeatable thermal measurements.
The Fibre Optic LHD system consisting of the following components was used for the tests under the PV panels.

- Pre-spliced sensor cable with pigtails mounted at the back of the PV panels with the help of stainless-steel mounting clips
- FO-LHD controller

This fibre optic sensor cable was connected to the FO-LHD controller which was configured according to the EN54-22:2015 + A1:2020 and UL 521/ ULC-S530-M91 alarm thresholds for room protection. The sensor cable was installed in a S-form (refer Figure 1, Figure 4, Figure 7, Figure 10) at the bottom of the PV panels. This cable was then divided into different zones for determining the detections time at different areas under the PV panel with respect to the ignition location.
The tests performed showed that the FO-LHD system was able to detect the fire under the PV panels within a minute after the ignition (arc-ignition or wood crib-ignition). In the following sections the setup and data collected during the tests is presented. Each subsection corresponds to one test configuration and reports the alarm activation time, the temperature evolution for the different sensor cable zones and maximum temperature recorded by the FO-LHD.

Test Setup 1: Small PV Panel in East-West configuration

For this test a single off the shelf PV panel was installed in an East-West configuration angle on the roof surface. The sensor cable was installed at the bottom of the panel in a S-form as shown in the Figure 1. For the measurement with the FO-LHD the sensor cable was divided into 3-different measurement and alarming zones. The sensor cable in Zone 1 was directly above the ignition source and Zones 2 & 3 were farther away as seen in the Figure 1.

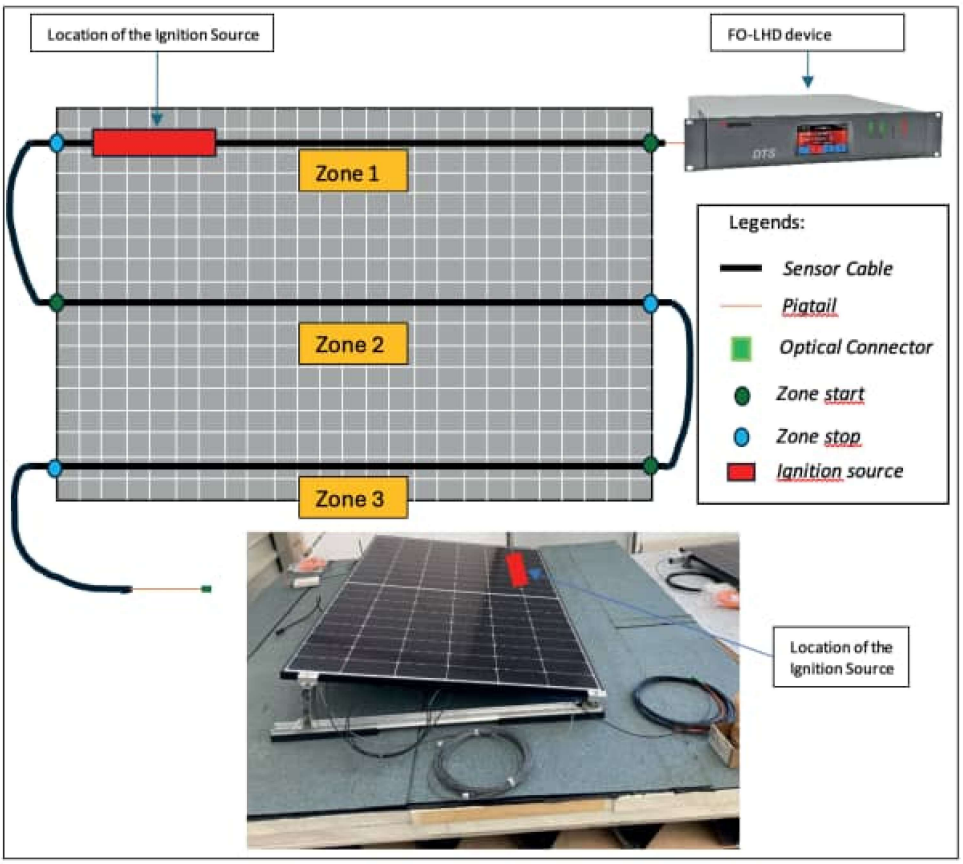

Figure 1: Sensor cable installation and zone configuration on Test Setup: 1

For the test an arc ignition source was used below the sensor cable installed for Zone 1. The source ignition was started at 13:14:41 with the alarm first detected on the FO-LHD device at 13:14:50.

Table 1: Detection times for the Test Setup: 1 on the PV panel

Zone	A1N – EN54-22				UL521 /ULC- S530		Time for Detection (s)
	GB1 (14°C/ 120s)	GB2 (20°C/ 240s)	GB3 (26°C/ 360s)	Max. A (60°C)	GA1 (11.1°C/ 80s)	Max. A (57°C)	
Zone 1	13:14:50 (59.40°C/120s)	13:14:50 (59.11°C/240s)	13:14:50 (59.55°C/360s)	13:14:55 80.77°C	13:14:50 (39.07°C/80s)	13:14:55 80.77°C	A1N: 9 UL: 9
Zone 2	13:15:35 (16.24°C/120s)	13:16:15 (21.50°C/240s)	13:16:40 (29.97°C/360s)	13:17:50 61.77°C	13:15:25 (13.51°C/80s)	13:17:25 58.69°C	A1N: 54 UL: 44
Zone 3	13:14:50 (22.00°C/120s)	13:14:55 (26.97°C/240s)	13:15:00 (32.74°C/360s)	13:15:25 62.33°C	13:14:55 (21.30°C/80s)	13:15:20 60.46°C	A1N: 9 UL: 14

Table 1 shows the trigger times for each alarm criteria according to A1N (EN 54-22) and UL521 /ULC- S530 configured for the lab conditions. The value of the detected parameter at the time of alarming can also be seen for every alarming criterion.
With the installation in the above manner the temperature profile for the start of the test (Figure 2) and for the entire test (Figure 3) can be seen to show the temperature rise based on the heat propagation below the PV panels.

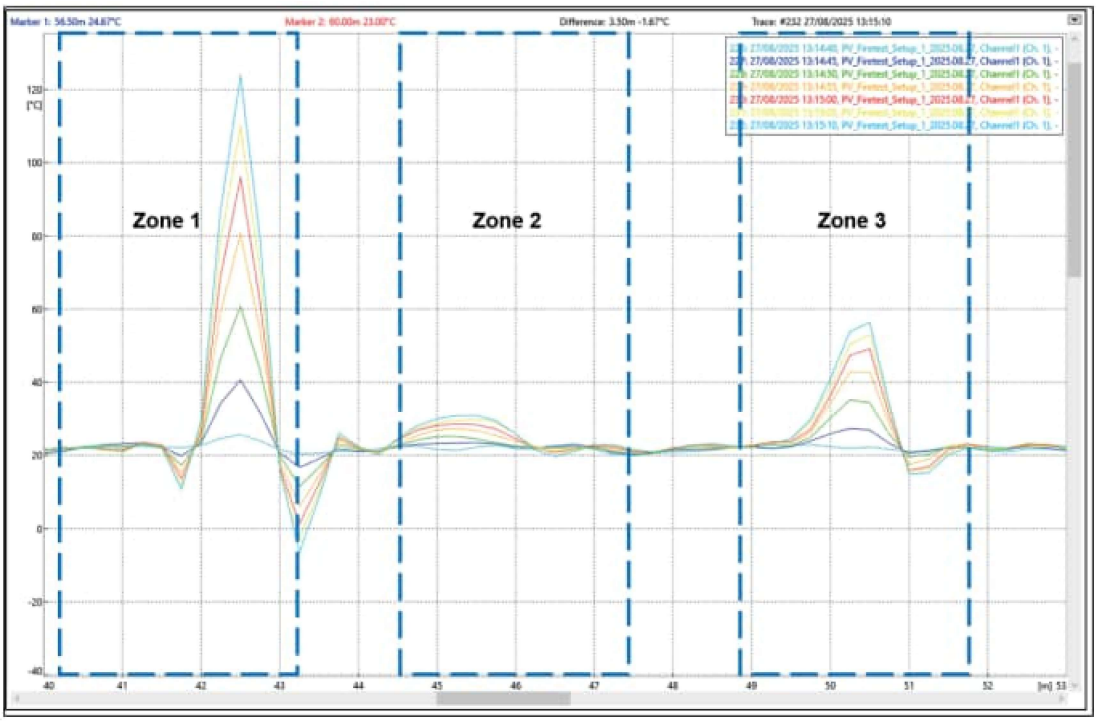

Figure 2: Temperature traces for different zones at the start of the fire test for Test Setup 1

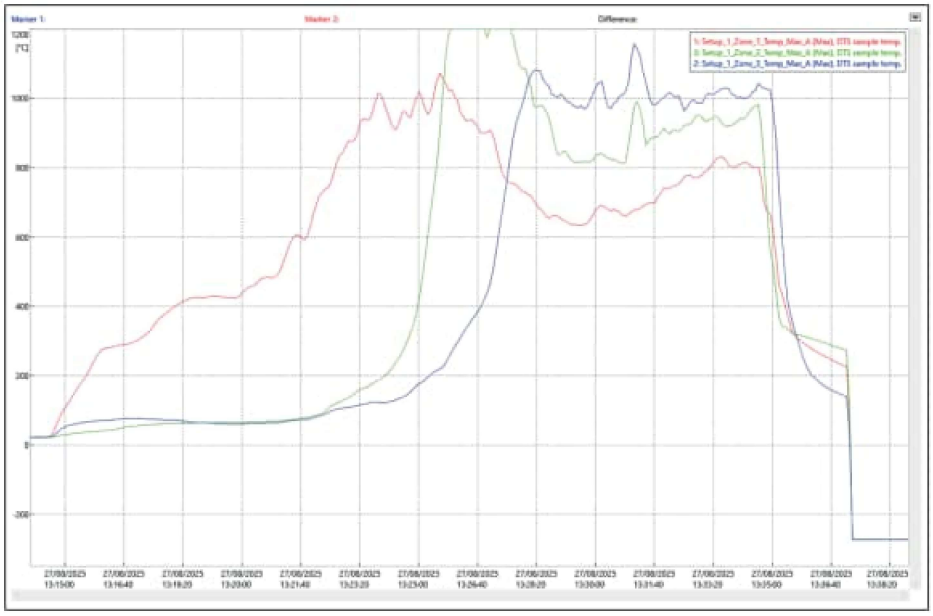

Figure 3: Maximum temperature in the zones for the entire test for Test Setup 1

The test shows that FO-LHD was able to detect the fire in the case of arc ignition at the location below the panel quickly for the lab conditions. The detection times confirm that the FO-LHD was able to provide an early warning, but it should be noted that its performance is influenced by installation geometry, the fire origin location, roof inclination, and fire propagation pathways.

Test Setup 2: Small PV Panel in East-West configuration with a physical barrier

For this test, a single off-the-shelf PV panel was installed at an East-West configuration angle on the roof surface. The sensor cable was installed at the bottom of the panel in a S-form as shown in the Figure 4. For the measurement with the FO-LHD, the sensor cable was divided into 3 different measurements and alarming zones. The sensor cable in Zone 1 was directly above the ignition source and Zones 2 & 3 were farther away as seen in the Figure 4.

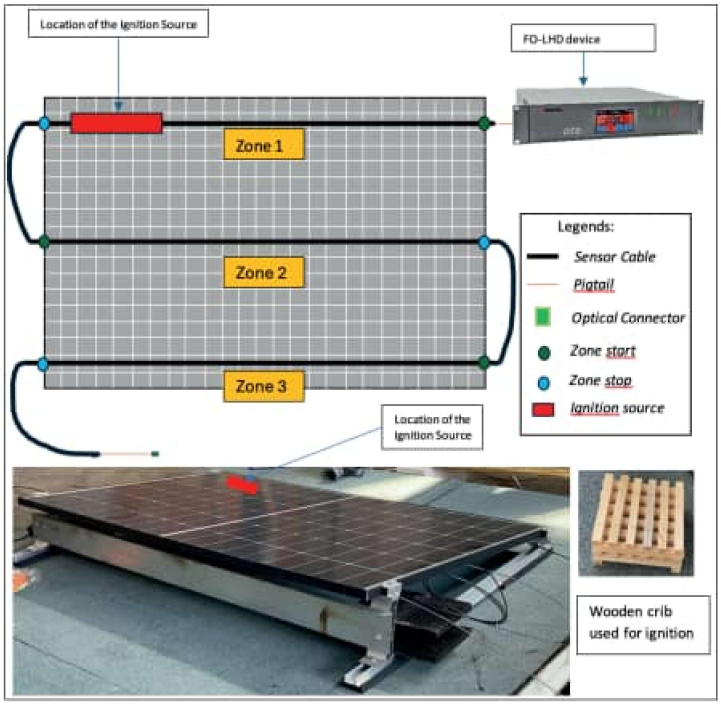

Figure 4: Sensor cable installation and zone configuration on Test Setup: 2.

A physical barrier to the upper side of the PV panel was installed as seen in Figure 4 to see the effect on heat propagation. For the test, a wooden crib was ignited below the sensor cable installed for Zone 1. The source ignition started at 14:51:46 with the alarm first detected on the DTS at 14:51:58. The following table shows the different alarm criteria according to A1N (EN 54-22) and UL521 /ULC- S530 configured for the lab conditions.

Table 2: Detection times for the Test Setup: 2 on the PV panel with physical barrier

Zone	A1N – EN54-22				UL521 /ULC- S530		Time for Detection (s)
	GB1 (14°C/ 120s)	GB2 (20°C/ 240s)	GB3 (26°C/ 360s)	Max. A (60°C)	GA1 (11.1°C/ 80s)	Max. A (57°C)	
Zone 1	14:51:58 (46.80°C/120s)	14:51:58 (48.56°C/240s)	14:52:03 (71.78°C/360s)	14:52:08 91.90°C	14:52:03 (46.83°C/80s)	14:52:08 91.90°C	A1N: 12 UL: 17
Zone 2	14:52:03 (18.41°C/120s)	14:52:18 (25.84°C/240s)	14:52:28 (30.53°C/240s)	14:53:33 60.42°C	14:52:08 (16.96°C/80s)	14:53:08 57.84°C	A1N: 17 UL: 22
Zone 3	14:52:18 (16.01°C/120s)	14:52:43 (21.95°C/240s)	14:53:23 (26.65°C/360s)	14:55:33 60.99°C	14:52:18 (13.43°C/80s)	14:54:43 57.27°C	A1N: 32 UL: 32

Table 2 shows the trigger times for each alarm criteria according to A1N (EN 54-22) and UL521 /ULC- S530 configured for the lab conditions. The value of the detected parameter at the time of alarming can also be seen for every alarming criterion.
With the installation in the above manner, the temperature profile for the start of the test (Figure 5) and for the entire test (Figure 6) can be seen to show the temperature rise based on the heat propagation below the PV panels.

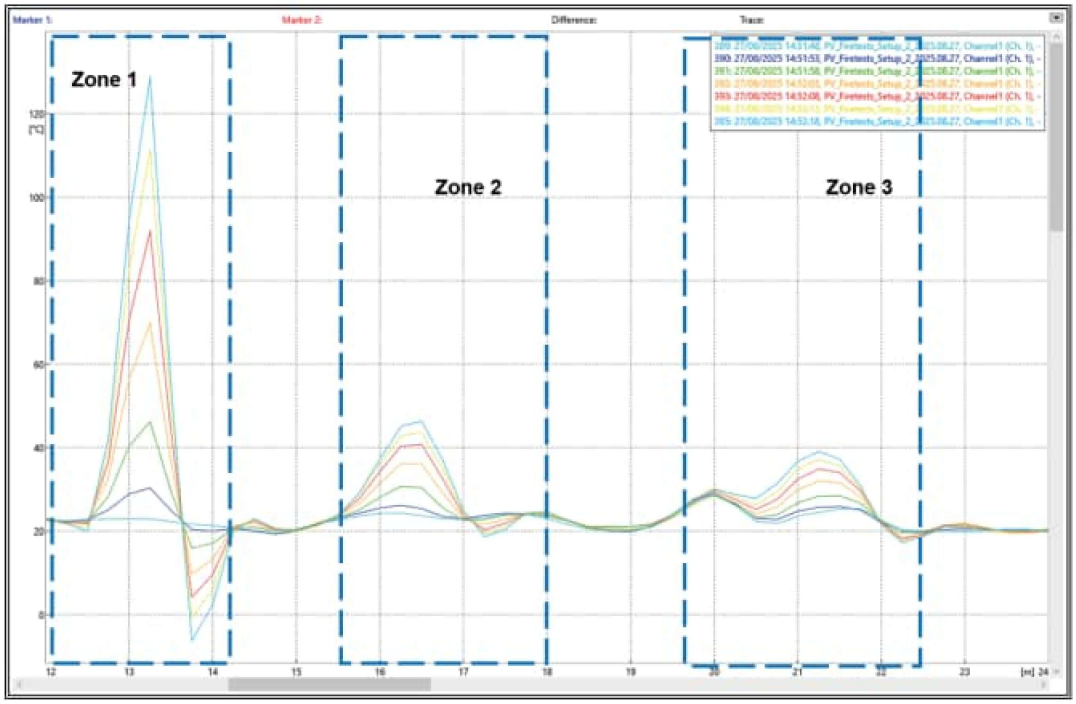

Figure 5: Temperature traces for different zones at the start of the fire test for Test Setup:2

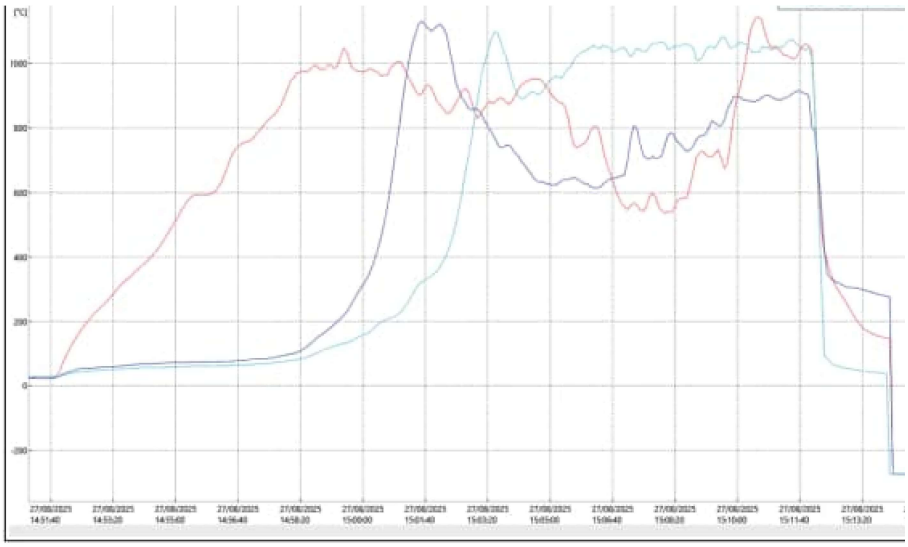

Figure 6: Maximum temperature in the zones for the entire test for Test Setup:2

The test showed that FO-LHD was able to detect the fire in the case of fire by igniting a wooden crib at the location below the panel quickly for the lab conditions. The detection times confirm that the FO-LHD was able to provide an early warning, but it should be noted that its performance is influenced by installation geometry, the fire origin location, roof inclination, and fire propagation pathways.
The physical barrier can be seen to influence the temperature propagation under the PV panels.

Test Setup 3: Small PV Panel parallel to the roof and roof angled at 20°C
For this test, a single off-the-shelf PV panel was installed flat parallel to the roof surface. The roof was at an angle of 20° horizontal.
The sensor cable was installed at the bottom of the panel in a S-form as shown in Figure 7. For the measurement with the FO-LHD, the sensor cable was divided into 3 different measurements and alarming zones. The sensor cable in Zone 1 was directly above the ignition source, and Zones 2 & 3 were farther away as seen in Figure 7.

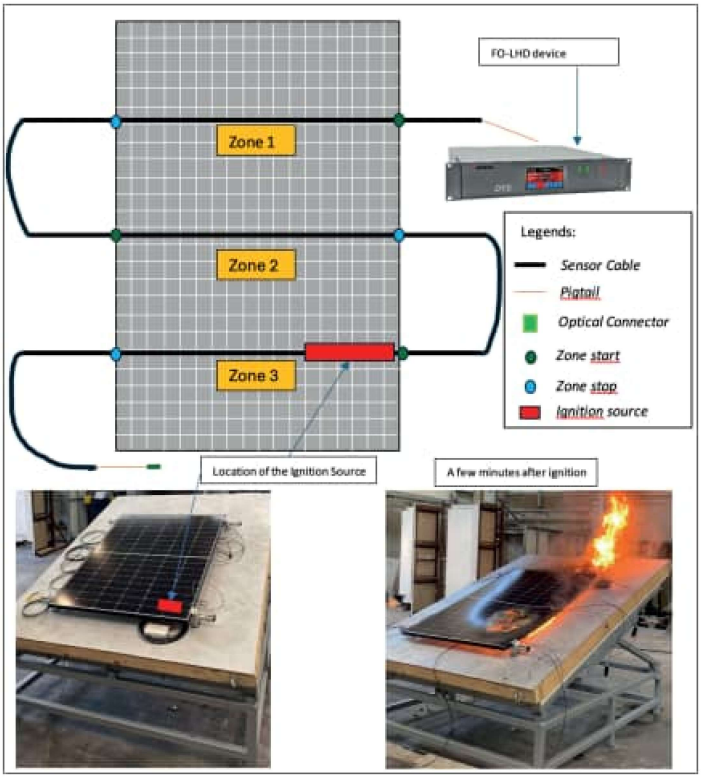

Figure 7: Sensor cable installation and zone configuration on Test Setup: 3

For the test, an electric arc was generated to cause the fire to start below the sensor cable installed for Zone 3. The source ignition started at 10:16:53 with the alarm first detected on the DTS at 10:17:42. The following table shows the different alarm criteria according to A1N (EN 54-22) and UL521 /ULC- S530 configured for the lab conditions.

Table 3: Detection times for the Test Setup: 3 on the PV panel

Zone	A1N – EN54-22				UL521 /ULC- S530		Time for Detection (s)
	GB1 (14°C/ 120s)	GB2 (20°C/ 240s)	GB3 (26°C/ 360s)	Max. A (60°C)	GA1 (11.1°C/80s)	Max. A (57°C)	
Zone 1	10:19:17 (16.12°C/120s)	10:19:42 (21.95°C/240s)	10:20:02 (30.46°C/360s)	10:20:37 64.55 °C	10:19:17 (12.84°C/80s)	10:20:32 61.62 °C	A1N: 144 UL: 144
Zone 2	10:18:22 (14.58°C/120s)	10:18:42 (22.38°C/240s)	10:19:02 (27.94°C/360s)	10:19:32 68.72°C	10:18:22 (13.79°C/80s)	10:19:27 63.58°C	A1N: 89 UL: 89
Zone 3	10:17:42 (14.60°C/120s)	10:18:02 (21.25°C/240s)	10:18:12 (29.81°C/360s)	10:18:37 63.72°C	10:17:42 (14.16°C/80s)	10:18:32 60.54°C	A1N: 49 UL: 49

Table 3 shows the trigger times for each alarm criteria according to A1N (EN 54-22) and UL521 /ULC- S530 configured for the lab conditions. The value of the detected parameter at the time of alarming can also be seen for every alarming criterion.

With the installation in the above manner, the temperature profile for the start of the test (Figure 8) and for the entire test (Figure 9) can be seen to show the temperature rise based on the heat propagation below the PV panels.

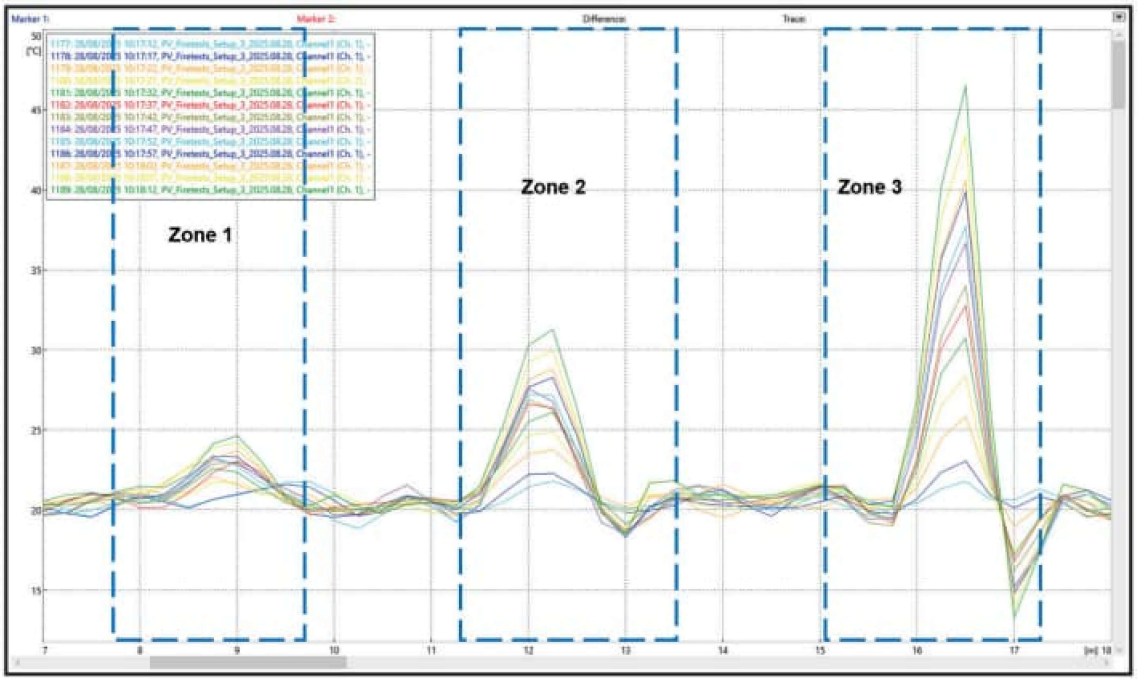

Figure 8: Temperature traces for different zones at the start of the fire test for Test Setup:3

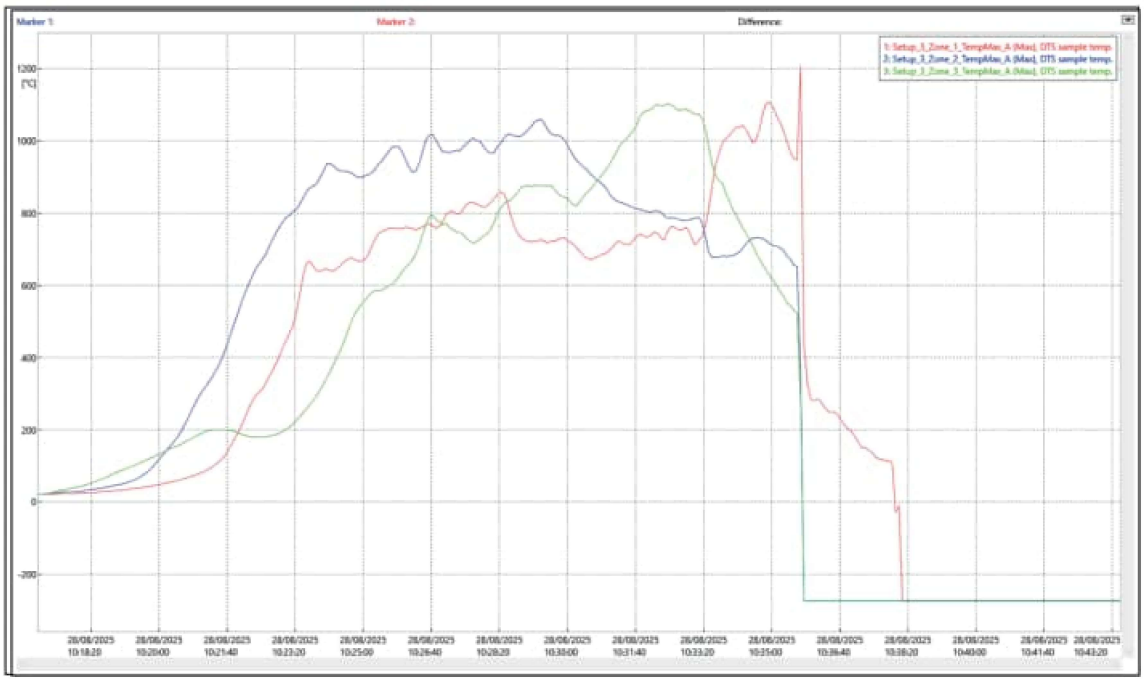

Figure 9: Maximum temperature in the zones for the entire test for Test Setup:3

The test showed that FO-LHD was able to detect the fire in the case of fire caused by an electric arc at the location below the panel quickly for the lab conditions. The detection times confirm that the FO-LHD was able to provide an early warning, but it should be noted that its performance is influenced by installation geometry, the fire origin location, and fire propagation pathways. Figure 9 shows that with the roof inclination the temperature propagation under the PV panels is uniform as compared to Figure 3 and Figure 6.

Test Setup 4: Large PV Panel installation in East-West configuration

For this test, a dual off-the-shelf PV panel was installed in an East-West configuration angle on the roof surface.
The sensor cable was installed at the bottom of the panel in a S-form as shown in the Figure 10. For the measurement with the FO-LHD, the sensor cable was divided into 6 different measurements and alarming zones. The sensor cable in Zone 1 was directly above the ignition source and Zones 2 - 6 were farther away as seen in the Figure 10.

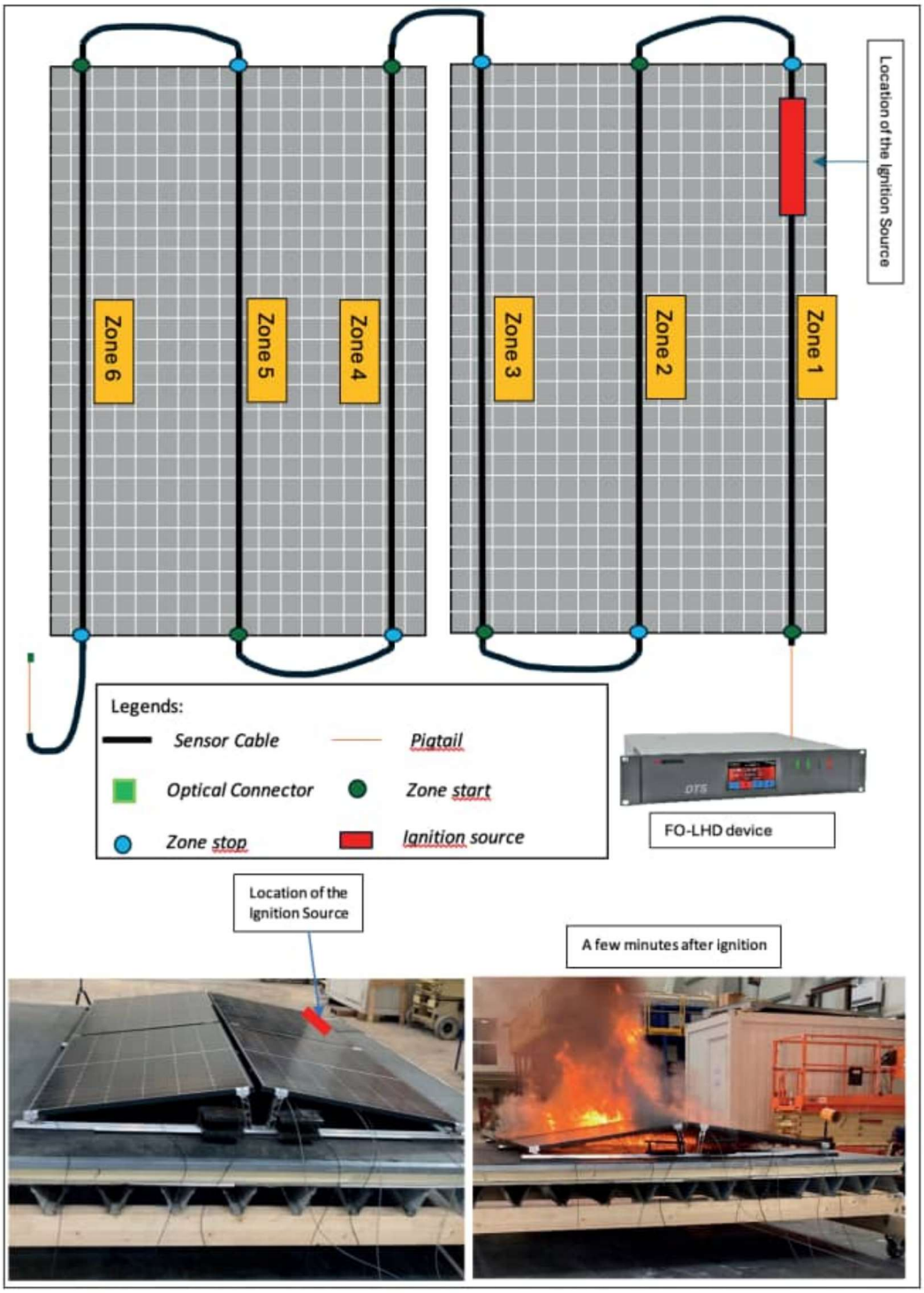

Figure 10: Sensor cable installation and zone configuration on Test Setup: 4

For the test, an electric arc was generated to cause the fire to start below the sensor cable installed for Zone 1. The source ignition started at 10:28:09 with the alarm first detected on the DTS at 10:28:21. The following table shows the different alarm criteria according to A1N (EN 54-22) and UL521 /ULC- S530 configured for the lab conditions.

Table 4: Detection times for the Test Setup: 4 on the PV panel

Zone	A1N – EN54-22				UL521 /ULC- S530		Time for Detection (s)
	GB1 (14°C/ 120s)	GB2 (20°C/ 240s)	GB3 (26°C/ 360s)	Max. A (60°C)	GA1 (11.1°C/ 80s)	Max. A (57°C)	
Zone 1	10:28:21 (39.46°C/120s)	10:28:21 (38.83°C/240s)	10:28:21 (38.99°C/360s)	10:28.36 80.71°C	10:28:21 (24.49°C/80s)	10:28:31 70.49°C	A1N: 12 UL: 12
Zone 2	10:29:01 (16.55°C/120s)	10:29:31 (21.92°C/240s)	10:29:56 (28.59°C/360s)	10:30:36 63.34°C	10:28:56 (13.96°C/80s)	10:30:31 61.07°C	A1N: 52 UL: 47
Zone 3	10:30:06 (17.76°C/120s)	10:30:31 (24.28°C/240s)	10:30:51 (28.55°C/360s)	10:31:36 65.24°C	10:30:01 (12.01°C/80s)	10:31.26 59.58°C	A1N: 117 UL:112
Zone 4	10.31.31 (14.35°C/ 120s)	10:31:41 (21.37°C/240s)	10:32:06 (29.14°C/360s)	10:32:46 62.42°C	10.31.26 (11.44°C/ 80s)	10:32.36 59.20°C	A1N: 202 UL:197
Zone 5	10:32.46 (15.99°C/ 120s)	10:33:16 (21.70°C/240s)	10:33:41 (26.66°C/360s)	10:34:31 66.97°C	10.32.36 (12.58°C/ 80s)	10.34.26 61.25°C	A1N: 277 UL: 267
Zone 6	10.35.46 (15.19°C/ 120s)	10:36:06 (20.96°C/240s)	10:36:41 (32.27°C/360s)	10:37.01 68.25°C	10.35.36 (12.47°C/ 80s)	10.36.56 63.26°C	A1N: 457 UL: 447

Table 4 shows the trigger times for each alarm criteria according to A1N (EN 54-22) and UL521 /ULC- S530 configured for the lab conditions. The value of the detected parameter at the time of alarming can also be seen for every alarming criterion.

With the installation in the above manner, the temperature profile for the start of the test (Figure 11) and for the entire test (Figure 12) can be seen to show the temperature rise based on the heat propagation below the PV panels.

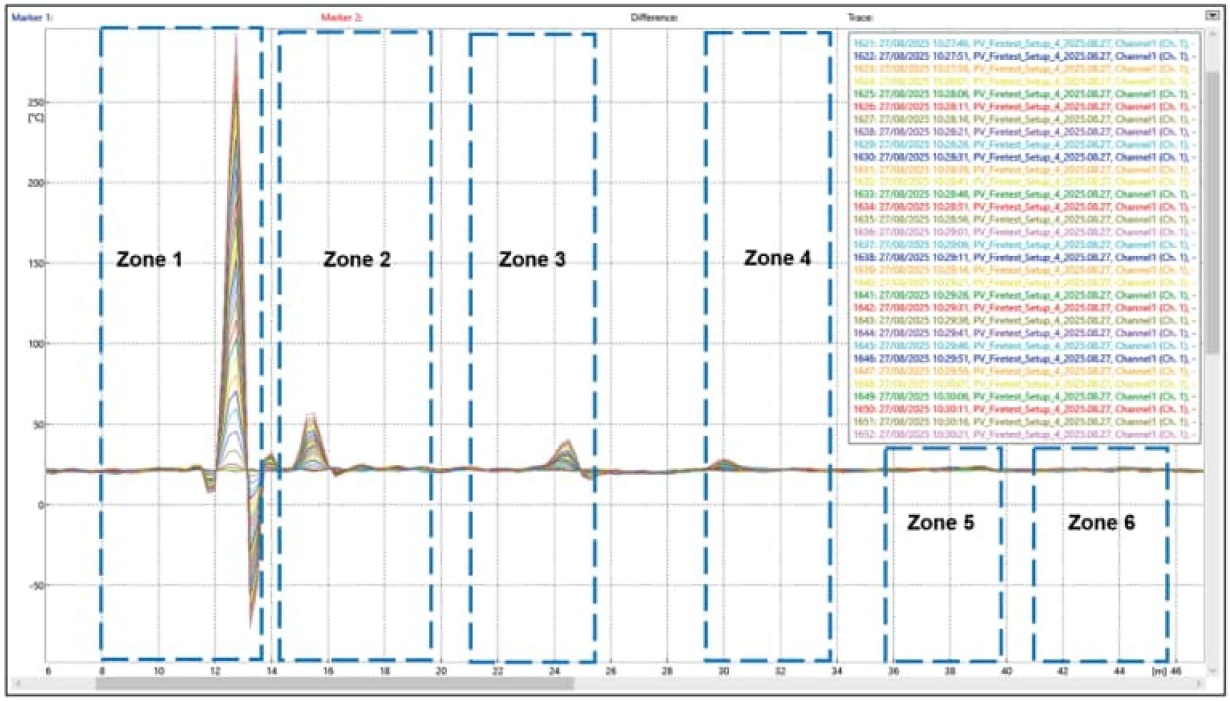

Figure 11: Temperature traces for different zones at the start of the fire test for Test Setup:4

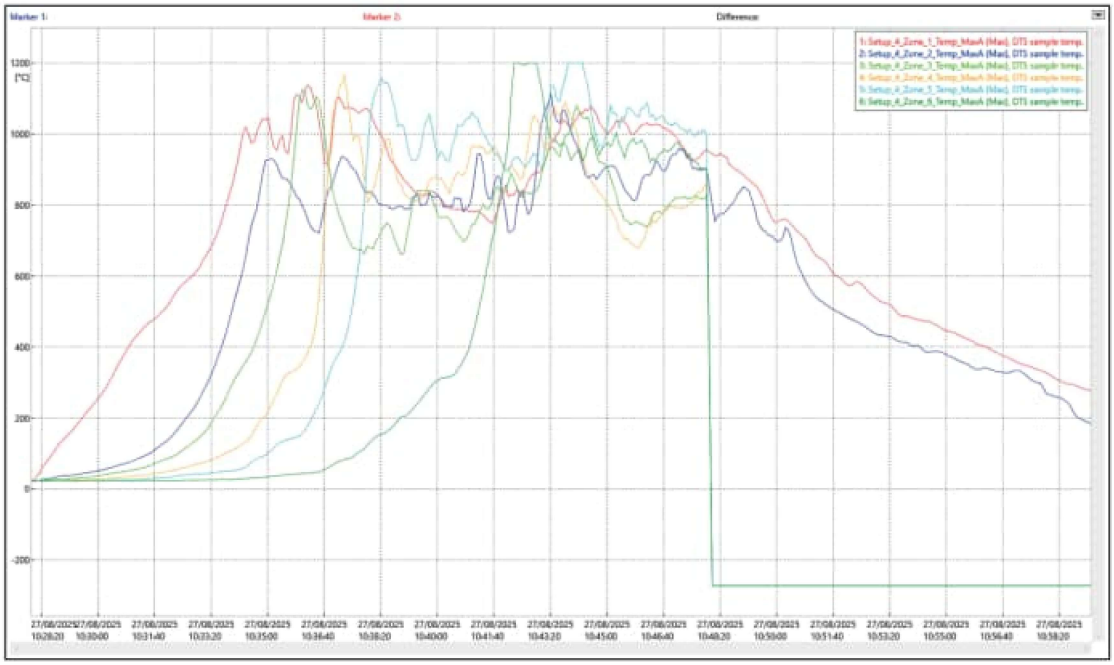

Figure 12: Maximum temperature in the zones for the entire test for Test Setup:4

The test showed that FO-LHD was able to detect the fire in the case of fire caused by an electric arc at the location below the panel quickly for the lab conditions. The detection times confirm that the FO-LHD was able to provide an early warning, but it should be noted that its performance is influenced by installation geometry, the fire origin location, roof inclination, and fire propagation pathways. It can be seen from the temperature profile in Figure 12 and trigger time from Table 4 that the temperature propagation occurs gradually and the detection is the fastest when the sensor cable is located above the ignition location.
As the real installations would have external environmental influences like wind, sunlight and the different ignition locations, the sensor cable installation should therefore take the factors into consideration for the design of the fire detection system setup.

CONCLUSION

Test Setup 1: Small PV Panel in East-West Configuration

A single PV panel was tested with the sensor cable divided into three zones. An arc ignition source below Zone 1 was detected within 9 seconds according to A1N and UL standards. Detection times for Zones 2 and 3 were longer, reflecting their distance from the ignition source. Temperature profiles showed heat propagation beneath the panels. The test confirmed the FO-LHD system's capability to provide early fire warnings, though performance depends on installation geometry and environmental factors.

Test Setup 2: Small PV Panel with Physical Barrier

Like Test 1 but with a physical barrier above the panel, a wooden crib ignition below Zone 1 was detected within 12 seconds (A1N) and 17 seconds (UL). Detection times increased with distance from the ignition source. Temperature profiles demonstrated heat propagation influenced by the barrier. The test reaffirmed the FO-LHD system's early detection capability, highlighting the impact of installation and environmental conditions

Test Setup 3: Small PV Panel Parallel to Roof at 20° Angle

A single PV panel installed parallel to a roof angled at 20° was tested with an electric arc ignition below Zone 3. Detection times were longer compared to previous tests, with the earliest alarm at 49 seconds (A1N) and 49 seconds (UL) in Zone 3. The results showed the influence of roof inclination and

fire location on detection times, affirming the importance of thoughtful sensor cable installation. The higher detections times as compared to the other setups can be attributed anyhow to the imperfection in the ignition process during the test.

Test Setup 4: Large PV Panel Installation in East-West Configuration

A dual PV setup was tested with a sensor cable divided into six zones. An electric arc ignition below Zone 1 was detected within 12 seconds (A1N and UL). Detection times increased progressively in zones further from the ignition source, with the last zone detecting fire after several minutes. Temperature profiles illustrated heat propagation under the panels. The test confirmed the FO-LHD system's scalability and effectiveness for larger installations, while emphasizing the influence of installation and environmental factors on performance.

Environmental factors such as extreme temperatures and rapid temperature fluctuations can affect detection outcomes, increasing the likelihood of false alarms [6]. The experimental results demonstrate that distributed FO-LHD system can detect fire events beneath PV panels rapidly, often within minutes of ignition. The system's distributed sensing capability allows accurate localization of temperature rises, enabling spatially resolved fire detection possible for both small and large PV installations. However, detection performance is influenced by factors such as installation geometry, fire origin location, roof inclination, fire propagation pathways, and environmental conditions like wind and sunlight. Therefore, sensor cable installation design and alarm parameter determination must consider these factors to optimize fire detection effectiveness in real-world PV system deployments.

As solar PV continues to dominate global renewable energy growth through 2030, the development of reliable early fire detection technologies, including distributed fibre optic linear heat detection systems, will become increasingly important for ensuring the safe and resilient operation of PV installations [9]. Future research in the area can focus on actual flame propagation under PV panels for different ignition location relative to the sensor cable in outdoor environments based in different geographical location to take into consideration the effect of local environmental factors.

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CURRICULUM VITAE

Avinash Virale
Avinash Virale is the Project Engineering Team Lead at AP Sensing for the engineering team handling projects related to FO-LHD systems. On graduating from Savitribai Phule Pune University, he went on to complete his Master of Science in Mechanical Engineering from Rhine-Waal University of Applied Sciences. He has more than 7 years of experience in the field and has led and commissioned FO-LHD systems for fire detection and temperature monitoring for a variety of assets.

Anja Rätzke
Anja Rätzke holds a Master of Arts in Management from TU Kaiserslautern and a Bachelor of Engineering in Electrical Engineering from Baden-Württemberg Cooperative State University (DHBW) Stuttgart. She has many years of experience in project engineering at AP Sensing, including Fiber Optic Linear Heat Detection (FO-LHD) systems. In her current role as Program, Operations and Integration Manager, she focuses on process optimization, cross-functional collaboration, system integration, and project management.

Felix Heck
Felix Heck is the sales manager responsible for the fiber optic Linear Heat Detection system in Europe at AP Sensing. After finalizing his studies as Electrical engineer at the University of Applied Sciene in Hannover took a short look into the automotive industry before starting his career in special fire detection in 2004. Since then, he has worked in various sales and business development positions in international sales with intensive travel globally. For him it is an intrinsic motivation to provide the best possible solution for each individual project to ensure that human and animal lives as well as important assets are protected as best as possible.

Uwe Keppler
Uwe Keppler is Operations Director at AP Sensing and has over 30 years of experience in the fibre optic industry. After graduating from Baden-Württemberg Cooperative State University (DHBW) Stuttgart, he began his career in the field of fibre optic transmission and telecommunications networks. Since joining AP Sensing in 2009, he has played a key role in delivering hundreds of Distributed Fiber Optic Sensing (DFOS) projects across applications such as Fiber Optic Linear Heat Detection, HV Power Cable Monitoring, and other DFOS solutions.

Bülent Toksoz
Bülent Toksoz is a technology and business development professional specializing in fiber optics. His work focuses on applying advanced sensing and monitoring technologies to improve the safety, reliability, security, and operational performance of critical assets. He currently serves as Regional Sales Manager for Central Asia at AP Sensing, supporting customers and partners in the development of technology-driven solutions for complex industrial and infrastructure applications.