Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

Design and Development of a Smart Solar PV Fault Detection and Protection System using IoT

A. Siddu
UG Scholar, Department of Electrical and Electronics Engineering
Hyderabad Institute of Technology and Management, India

Salava V. Satyanarayana
Associate Professor, Department of Electrical and Electronics Engineering, Hyderabad Institute of Technology and Management, India

G. Shashidhar
UG Scholar, Department of Electrical and Electronics Engineering
Hyderabad Institute of Technology and Management, India

G. Aravind
UG Scholar, Department of Electrical and Electronics Engineering
Hyderabad Institute of Technology and Management, India

V. Madhu Vardhan
UG Scholar, Department of Electrical and Electronics Engineering
Hyderabad Institute of Technology and Management, India

Abstract

Solar photovoltaic (PV) systems can experience abnormal conditions that reduce electrical output and may affect safe operation. Manual inspection is not suitable for continuous monitoring because a fault may remain unnoticed until the system is checked. This work presents a compact IoT-enabled solar PV monitoring and protection system based on an ESP32 microcontroller. An INA219 sensor is used to obtain PV voltage and current, while a DHT11 sensor measures ambient temperature and humidity. An LDR is also installed to sense relative changes in incident light. The controller processes the sensor readings and identifies four conditions considered in the prototype: open circuit, short circuit, over-temperature, and partial shading. When an abnormal condition is identified, the system provides a local indication through a 16 × 2 LCD and buzzer and controls a relay to isolate the affected PV path. A battery-backed supply is included to support the load during the isolation period. The measured parameters and fault status are made available through a Wi-Fi-based remote dashboard. The developed prototype was tested under normal operation and intentionally created fault conditions. The available hardware and dashboard observations demonstrate the integration of PV monitoring, fault indication, isolation, backup supply and remote status reporting in a single small-scale prototype. Quantitative performance claims require additional calibrated and repeated measurements.

Keywords— Solar PV, ESP32, INA219, DHT11, LDR, Fault Detection, Fault Isolation, Open Circuit, Short Circuit, Partial Shading, Over-Temperature, Battery Backup, IoT Monitoring.

I. Introduction

Solar photovoltaic generation converts solar radiation into electrical energy and is increasingly used in distributed and renewable-energy applications. The performance of a PV system is influenced by both electrical operating conditions and the surrounding environment. During operation, a PV source may experience conditions such as an open circuit, short circuit, partial shading or excessive temperature. These conditions can change the expected voltage, current and power output and, if they are not identified in time, can reduce system availability and reliability.

Conventional inspection generally depends on visual observation or periodic measurements. Such an approach can introduce a delay between the occurrence of an abnormal condition and the corrective action. A continuously monitored system can reduce this delay by collecting electrical and environmental parameters and evaluating them using programmed decision rules.

The proposed work develops an ESP32-based prototype that combines sensing, local indication, relay-based isolation, battery backup and IoT monitoring. The system is intended for small-scale experimental PV applications where a simple and economical protection arrangement is preferred over complex diagnostic equipment. The design also provides a practical platform for demonstrating different PV fault conditions in hardware.

II. Literature Survey

Recent studies have examined the use of connected sensors and embedded controllers for monitoring photovoltaic systems. Rouibah et al. developed an IoT-based PV monitoring prototype that collects electrical and environmental information and makes the measurements available for remote observation [2]. This work demonstrates the value of continuous data acquisition and wireless monitoring. The present prototype follows a similar monitoring approach and additionally includes programmed fault indication and relay-based PV-path isolation.

PV fault identification has also been studied through different inspection and diagnostic techniques. Hong and Pula reviewed electrical, visual and thermal methods for detecting and classifying PV faults [3]. Their review shows that the selection of a detection method depends on the fault type and the measurements available. In the present work, electrical measurements from the INA219 are considered together with the LDR light-level indication and DHT11 ambient-temperature reading to identify the selected experimental conditions.

Pimpalkar, Sahu and Roy presented an IoT-based solar PV monitoring arrangement in which operating parameters can be observed remotely [4]. Their study highlights the usefulness of connected monitoring for examining changes in PV operation. Sait et al. proposed a more advanced framework that combines IoT communication with fuzzy-based fault detection and experimental validation [5]. This provides an example of how embedded monitoring can be extended toward more detailed fault analysis.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

Rao, Sahoo and Yanine reported a cloud-based monitoring system for solar PV energy generation, emphasizing the collection and remote presentation of PV operating information [6]. "Solar energy has also been explored in wireless electric vehicle charging applications. Suresh et al. presented a solar wireless electric vehicle charging system, demonstrating another application of solar-based energy utilization [1]."Taken together, these studies indicate that remote monitoring, fault identification and protection are important areas of PV-system development. The work presented in this paper focuses on a compact hardware implementation that combines voltage and current measurement, light and ambient-condition sensing, local fault indication, relay control and a battery-backed load arrangement. Unlike advanced diagnostic frameworks, the prototype uses programmed decision conditions and is intended as a practical small-scale demonstration.

III. Problem Statement

A solar PV system may show abnormal electrical or thermal behaviour because of open-circuit conditions, short-circuit conditions, partial shading or excessive temperature. If these conditions are identified only through manual inspection, the response to the fault may be delayed. Therefore, there is a need for a low-cost system that can continuously observe important PV parameters, identify predefined abnormal conditions, provide a local warning, isolate the affected PV path and maintain the load supply using a backup source during the isolation period. The system should also make the operating status available remotely through an IoT interface.

IV. Proposed System

The proposed system uses an ESP32 as the central controller. The PV source is connected to an INA219 sensor for measurement of voltage and current. The DHT11 sensor provides temperature and humidity information, while an LDR is installed to sense relative light-level variation. The ESP32 reads these parameters and compares them with programmed conditions associated with the four fault cases considered in the prototype.

For an open-circuit demonstration, the PV path is intentionally opened using a switch. For the short-circuit demonstration, a controlled and current-limited test arrangement is used so that the abnormal electrical condition can be detected without intentionally creating an unsafe direct short. Partial shading is demonstrated by covering a portion of the PV module and observing the resulting reduction in light indication and electrical output. The over-temperature condition is demonstrated by raising the measured ambient temperature above the programmed experimental threshold.

When the controller identifies an abnormal condition, the fault status is displayed locally and the relay is operated to isolate the affected PV path. The battery-backed path is then used to support the load during isolation. The ESP32 also sends system information to the remote dashboard through Wi-Fi. The exact IoT platform name is not specified in the implementation information supplied. Once the abnormal condition is removed and the programmed normal-condition checks are satisfied, the PV path can be restored.

V. System Architecture and Block Diagram

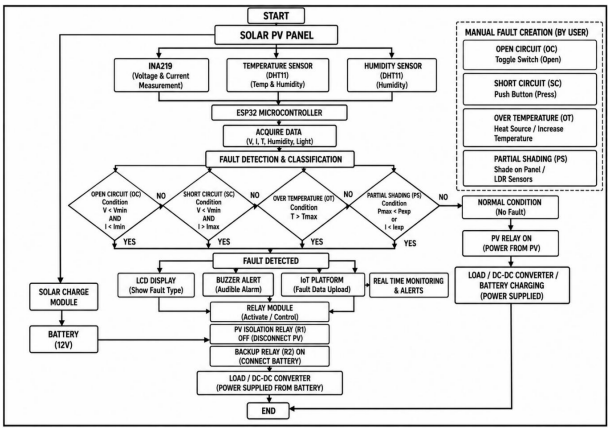


Fig. 1. Overall block diagram of the proposed Smart Solar PV Fault Detection and Protection System.

The block diagram represents the complete signal and power flow of the prototype. The PV panel is the primary energy source. The INA219 provides electrical measurements to the ESP32, while the DHT11 supplies temperature and humidity data. The installed LDR provides a relative light-level measurement that can support the partial-shading decision. The controller evaluates the sensor information and determines whether the system is operating normally or whether one of the programmed fault conditions is present.

The ESP32 drives the LCD and buzzer for local indication, controls the relay module for PV-path isolation and communicates the operating information to the remote dashboard. A solar charging stage and battery are included in the backup arrangement so that the load can continue to receive power while the affected PV path is isolated. Manual switches and a controlled push-button arrangement are used for demonstrating fault conditions during testing.

VI. Hardware Components

The main hardware components and their functions are summarized in Table I.

Component	Specification	Function
1 Solar PV panel	18 V, 4.5 W	Converts solar radiation into electrical energy.
2 INA219 sensor	Up to 26 V bus measurement; I²C interface	Measures PV bus voltage and current and provides power-related data.
3 DHT11 sensor	3.3–5 V supply	Measures ambient temperature and relative humidity.
4 LDR	Installed in the prototype	Senses relative changes in incident light.
5 2-channel relay module	DC contact rating depends on module	Connects or disconnects the PV path according to ESP32 control.
6 16 × 2 LCD with I²C	16 × 2 character display	Displays operating values and fault/status messages.
7 DC-DC converter / charging stage	Module-dependent input/output range	Provides regulated/charging interface in backup supply arrangement.
8 ESP32	3.3 V logic; regulated/USB supply	Processes sensor data, applies fault logic, controls outputs and provides Wi-Fi.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

Component	Specification	Function
9 Battery pack	Three Li-ion cells; nominal voltage depends on configuration	Stores energy and supports load during PV-path isolation.
10 DC cooling fan	12 V DC	Acts as the prototype load.
11 Buzzer	As installed	Provides audible fault indication.

VII. Methodology

The operating sequence begins with the PV panel converting sunlight into electrical energy. The INA219 measures the electrical behaviour of the PV source, while the DHT11 measures temperature and humidity around the prototype. The LDR senses relative light variation. These sensor readings are supplied to the ESP32 through its input interfaces. The controller continuously evaluates the readings against the conditions programmed for the prototype.

Under normal operation, the measured values are displayed on the LCD and transmitted to the remote dashboard. When a programmed abnormal condition is detected, the corresponding fault status is generated. The buzzer provides a local warning and the relay isolates the affected PV path. The battery-backed supply is used to support the load during this isolation period. The fault status is also transmitted through Wi-Fi so that the condition can be observed remotely.

After the external fault condition is removed, the controller checks the relevant parameters again. If the readings return to the programmed normal range, the PV path can be reconnected and normal operation resumes. This sequence provides a simple control loop consisting of measurement, decision, indication, isolation, backup supply and restoration.

VII-A. Fault Detection Logic

Fault	Test method / detection principle	Prototype response
Open Circuit (OC)	Test: PV path is opened using the test switch. Detection: Current falls toward zero and expected PV operating condition is lost.	OC indication, buzzer, relay isolation and battery-backed load supply.
Short Circuit (SC)	Test: Controlled current-limited short-circuit test is applied. Detection: Voltage decreases and current changes abnormally relative to normal operation.	SC indication, buzzer, relay isolation and battery-backed load supply.
Over-Temperature (OT)	Test: Temperature is intentionally raised during testing. Detection: DHT11 reading exceeds the experimental threshold programmed in the controller.	Fault indication, buzzer, PV-path isolation by relay and battery-backed load support.
Partial Shading (PS)	Test: Part of the PV module is covered. Detection: LDR reading and PV electrical output are evaluated relative to normal conditions.	Fault indication, buzzer, PV-path isolation by relay and battery-backed load support.

The ESP32 continuously receives electrical and environmental information from the sensors and compares the readings with the decision conditions programmed for the prototype. The INA219 is used to observe PV voltage and current, the LDR indicates changes in relative light level, and the DHT11 measures the surrounding temperature and humidity. The controller considers the readings together rather than relying on one parameter alone, because changes in sunlight and load can also affect PV output.

Open-circuit condition: This condition is introduced by opening the PV connection using the test switch. The controller identifies the condition when the PV current falls close to zero while the voltage reading indicates that the source is still present. After confirming the programmed condition, the ESP32 displays the open-circuit status, activates the warning indication and operates the relay to isolate the affected PV path.

Short-circuit condition: The short-circuit test is introduced using the controlled test arrangement provided in the prototype. The ESP32 checks for an abnormal current response together with a reduction in PV voltage. When this combination satisfies the programmed fault condition, the controller displays the short-circuit status, activates the warning indication and operates the protection relay. The test must remain current-limited; the PV panel must not be directly shorted using an uncontrolled connection.

Partial-shading condition: Partial shading is created by covering a portion of the PV panel. The LDR detects the relative reduction in light, while the INA219 measures the resulting change in PV voltage and current. The ESP32 identifies partial shading when the reduction in light is accompanied by an electrical output change that matches the programmed shading condition. Considering both sensor inputs helps the controller distinguish shading from other abnormal electrical conditions. When the programmed shading condition is confirmed, the ESP32 activates the buzzer and operates the PV isolation relay; the battery-backed path supports the load during isolation. The LDR is used only for relative light comparison and does not provide calibrated irradiance.

Over-temperature condition: The DHT11 measures the ambient temperature near the prototype and sends the reading to the ESP32. The controller compares this reading with the temperature threshold set in the program. If the threshold is exceeded, the ESP32 declares an over-temperature fault, activates the buzzer and operates the PV isolation relay. The load is then supported by the battery-backed path during isolation. Since the DHT11 measures surrounding air temperature rather than the PV module surface, this test represents ambient-temperature monitoring and should not be interpreted as a direct measurement of solar-cell temperature.

Protection and recovery: Each of the four selected fault conditions—open circuit, short circuit, over-temperature and partial shading—uses the same basic protection sequence after its programmed detection condition is confirmed. The ESP32 updates the LCD and remote status display, activates the buzzer and operates the relay assigned to PV-path isolation. The battery-backed path supports the load while the PV path is isolated. After the cause of the fault is removed, the controller checks the sensor inputs again. The PV path is allowed to return to normal operation only when the readings satisfy the recovery conditions programmed in the controller.

VIII. Hardware Implementation

The hardware prototype was assembled around the ESP32 controller, INA219, DHT11, LDR, relay module, LCD, buzzer, battery-backed supply and PV load path. The INA219 is connected to the PV electrical path through the appropriate current and bus-voltage connections, while the DHT11 is connected to a digital GPIO of the ESP32. The LDR is connected through a suitable voltage-divider arrangement to an analogue input. The LCD communicates with the ESP32 through the I²C interface. The relay control inputs are connected to ESP32 GPIO pins through the relay module interface, and the buzzer is driven by a digital output.

The backup arrangement is intended to prevent unnecessary interruption of the prototype load when the PV path is isolated.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

The battery is charged through the associated charging/regulation stage and is switched into the load supply path according to the protection logic. The prototype therefore demonstrates fault identification together with a backup-supply arrangement for the load during the isolation interval. The exact battery series/parallel configuration, charge-controller model and relay contact ratings should be recorded from the actual hardware before final publication.

IX. Results and Discussion

The prototype was examined during normal operation and under the selected fault conditions: open circuit, short circuit, partial shading and over-temperature. During normal operation, the sensing unit supplied information to the ESP32, which displayed the system status locally and made operating information available through the remote monitoring interface.

Test condition and observed behaviour	Local indication and protection / remote status
Normal operation PV voltage/current and environmental readings available	Normal-status message on LCD PV path remains connected; Remote: Normal operating status
Open circuit Current drops toward zero after opening the test path	OC/no-PV indication and buzzer Affected PV path isolated; backup supply used; Remote: OC fault status
Short circuit Voltage falls and current changes abnormally	Short-circuit indication and buzzer Affected PV path isolated; backup supply used; Remote: SC fault status
Over-temperature Temperature rises above programmed experimental threshold	Temperature/fault indication Affected PV path isolated by relay; battery-backed supply supports the load; Remote: OT status
Partial shading PV electrical output and LDR reading change under intentional shading	Shading indication Affected PV path isolated by relay; battery-backed supply supports the load; Remote: Shading status

During the fault demonstrations, the controller generated the corresponding fault indication when the programmed decision conditions were met. The LCD and buzzer provided local alerts, and the relay was used to isolate the PV path. The backup arrangement was included to support the load during the isolation period. The tests demonstrate the integration of sensing, controller-based fault identification, local indication, relay protection and remote monitoring in a single prototype.

The observations are qualitative and describe the behaviour demonstrated by the prototype. A detailed performance evaluation would require calibrated sensor readings, repeated trials and recorded response times. Such numerical performance results are not presented here because they were not established from a complete set of verified test records.

X.Prototype

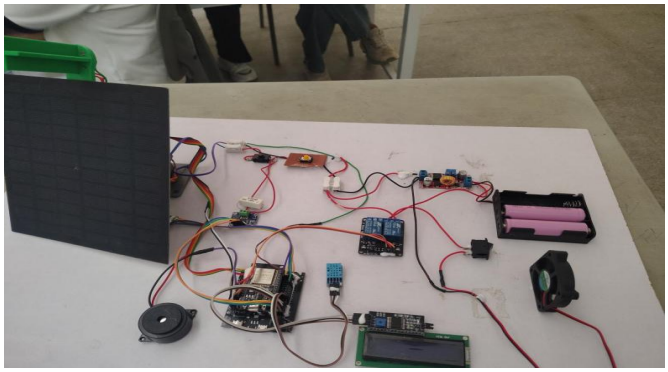


Fig. 2. Developed hardware prototype of the proposed system.

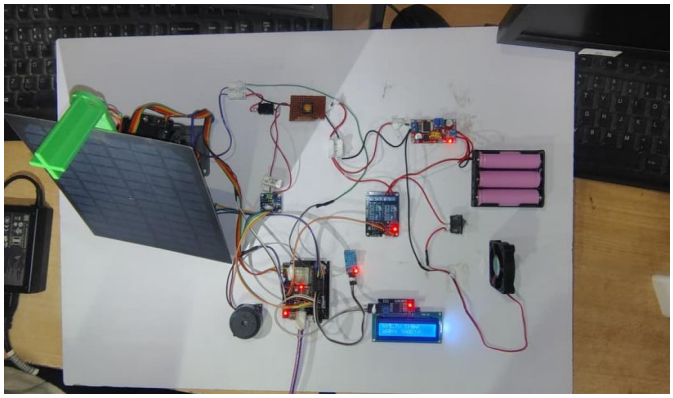


Fig. 3. Prototype showing the connected PV, sensing, control, relay and backup-supply

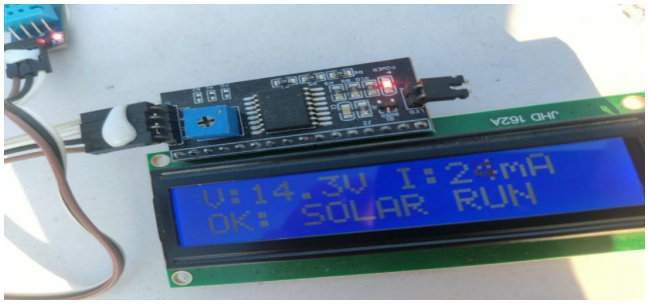


Fig. 4. 16 × 2 LCD showing the real-time PV status and measured parameters.

XI. IoT Dashboard and Remote Monitoring



Fig. 5. Dashboard plots showing PV voltage, current and power channels.

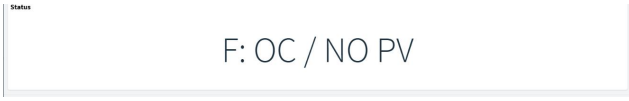


Fig. 6. Remote indication for an open-circuit condition.

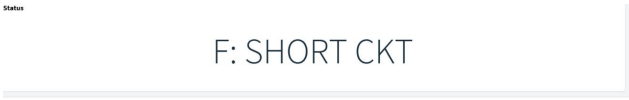


Fig. 7. Remote indication for a short-circuit condition.

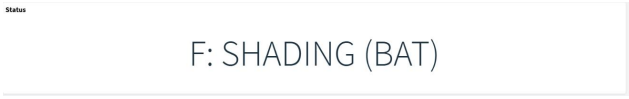


Fig. 8. Remote indication associated with the partial-shading/battery condition.

The remote interface provides a convenient way to observe the operating condition without being physically close to the prototype. The dashboard includes electrical and environmental information and displays the status generated by the ESP32. The screenshots demonstrate that different programmed conditions can be represented as distinct status messages. The specific IoT platform name has not been confirmed in the supplied implementation details and is therefore not identified by brand in this paper.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 11 , November - 2026

XII. Advantages

- Continuous monitoring of important PV electrical and environmental parameters.
- Automatic identification of selected abnormal conditions using programmed decision rules.
- Local fault indication through the LCD and buzzer.
- Relay-based isolation of the affected PV path.
- Battery-backed load support during the PV isolation period.
- Remote observation of parameters and fault status through Wi-Fi connectivity.
- Low-cost hardware suitable for a small-scale experimental prototype.
- Simple architecture that can be extended with additional sensors or diagnostic methods.

XIII. Future Scope

- Expand the fault library to include additional PV faults and abnormal operating conditions.
- Add data logging and long-term trend analysis for voltage, current, temperature, humidity, light level and power.
- Introduce machine-learning or other data-driven methods for more detailed fault classification after collecting a labelled experimental dataset.
- Improve the backup power-management circuit for longer and more controlled load support.
- Develop a more advanced IoT dashboard with historical plots, event logs and notification services.
- Calibrate the LDR response or use a calibrated irradiance sensor for quantitative light measurements.
- Add a contact temperature sensor to measure PV module surface temperature directly.

XIV. Conclusion

A smart solar PV fault detection and protection prototype was developed using an ESP32, INA219, DHT11, LDR, relay module, LCD, buzzer, battery-backed supply and Wi-Fi connectivity. The system monitors PV electrical parameters together with ambient temperature, humidity and relative light level and uses programmed decision rules to identify open-circuit, short-circuit, over-temperature and partial-shading conditions. When an abnormal condition is identified, the system provides a local indication and controls the relay to isolate the affected PV path, while the backup arrangement is intended to support the prototype load during the isolation period. The remote dashboard further allows the operating condition and fault status to be observed remotely.

The hardware tests and dashboard observations demonstrate the feasibility of combining monitoring and basic protection functions in a compact low-cost PV prototype. Further work is required to provide calibrated numerical measurements, repeated test results, response-time data and battery-runtime measurements. The electrical dashboard units must also be verified against the panel rating before quantitative output claims are made.

References

[1] O P. Suresh., S. V. M. Satyanarayana., Parayil, Sankaran Bindu., Anand Konjengbam., Nikhil Kumar., V. Sujith. (2024). 8. Solar wireless electric vehicle charging system. E3S web of conferences, DOI: 10.1051/e3sconf/202454703012

[2] N. Rouibah, A. El Hammoumi, A. Bouttout, S. Haddad, S. Oukaci, A. Limam, and M. Benghanem, “Smart Monitoring of Photovoltaic Energy Systems: An IoT-Based Prototype Approach,” Scientific African, vol. 30, e02973, 2025. DOI: https://doi.org/10.1016/j.sciaf.2025.e02973

[3] Y.-Y. Hong and R. A. Pula, “Methods of photovoltaic fault detection and classification: A review,” Energy Reports, vol. 8, pp. 5898–5929, 2022. DOI: https://doi.org/10.1016/j.egyr.2022.04.043

[4] R. Pimpalkar, A. Sahu, and A. Roy, “A Smart Solar PV Monitoring System Using Internet of Things (IoT),” Concurrent Engineering: Research and Applications, vol. 33, 2025. DOI: https://doi.org/10.1177/1063293X251325155

[5] O. Sait, M. Khemliche, S. Latreche, B. Sait, H. Khemliche, M. Bajaj, A. F. Güven, and O. Rubanenko, “An experimentally validated long-range-enabled fuzzy–Internet of Things framework for real-time and cost-efficient fault detection in photovoltaic systems,” Energy Exploration & Exploitation, 2026. DOI: https://doi.org/10.1177/01445987261439953

[6] C. K. Rao, S. K. Sahoo, and F. F. Yanine, “Development of a smart cloud-based monitoring system for solar photovoltaic energy generation,” Unconventional Resources, vol. 6, article 100173, 2025. DOI: https://doi.org/10.1016/j.uncres.2025.100173

(This work is licensed under a Creative Commons Attribution 4.0 International License.)