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Research paper

Low-Cost Real-Time Monitoring for Enhanced Efficiency in PV Systems

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ABSTRACT

In this paper, we successfully created a low-cost, facile and reliable solution for real-time monitoring of grid-connected photovoltaic (PV) system. Our solution simplifies the connection and access to database of system performances, dependent on various parameters and environmental conditions. The real-time monitoring enables swift fault rectification, enhancing system efficiency, and providing insights into energy consumption of the PV system. We implemented our solution using low-cost electronic devices and sensors connected to 1.75 kW PV system installed in Adrar city situated in the Saharan region of southern Algeria. The electrical characteristics were measured using multiple sensors and stored in SD memory card and in server. Following the design and implementation of our data acquisition system for monitoring parameters from grid-connected photovoltaic system, we conducted a comparative study with the Fluke 2635A HYDRA Series II data acquisition system. The proposed system can be easily scaled to monitor higher power and larger PV stations with minimal adjustments by changing the high-range sensors and their parameters in the software.

1. INTRODUCTION

Nowadays, the economic prosperity is driven by energy, making it a crucial cornerstone sector for the financial advancement of nations. In this respect, the abundance and accessibility of cost-effective and green energy play a pivotal role in supporting countries economic growth (Coban et al., 2023). The

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predominant reliance on fossil fuels for energy generation presents significant environmental challenges, including the unregulated release of greenhouse gases (Agoundedemba et al., 2023; Hossain et al., 2023). In response to this pressing issue, the exploration of cost-effective and sustainable energy sources has become imperative for alleviating environmental pollution and mitigating the impact of climate change (Aravindan et al., 2023). Among these sustainable energy sources, photovoltaic systems (PV) are a promising choice for electricity generation (Gorjian et al., 2022). This technology is versatile and applicable in both isolated areas (stand-alone) (Khan et al., 2021) and integration into the electrical grid (connected to the grid) (Shafiullah et al., 2022). It offers advantages such as compensation of the public network (Marcelino et al., 2023). Furthermore, its capacity is anticipated to surpass coal by 2027, making it the world's largest energy source (Coldrick et al., 2023) .

Effective monitoring of PV systems is essential in order to ensure their optimal performance and maximize the energy production (Asgher & Iqbal, 2023). Another advantage of PV systems monitoring is gathering critical data which enables users to manage and optimize system efficiency while reducing maintenance costs (Mansour et al., 2023). Despite the prevalence of various PV monitoring systems, existing conventional solutions often present challenges related to cost, complexity, and limited parameter monitoring capabilities (Katche et al., 2023). In fact, various tools, including multimeters, have been suggested for measuring PV cur-rent and voltage. However, a significant drawback of this approach is the inherent challenge associated with data recording. To address this limitation, researchers often resort to the use of expensive numerical oscilloscopes for PV data acquisition (Ciocia et al., 2020). Alternatively, some researchers advocate for the adoption of data-loggers as a more feasible solution (El Hammoumi et al., 2018). It's crucial to note that these instruments are not readily available as open-source solutions. In the realm of existing acquisition systems, predominantly software-based systems demand operating licenses. In addition, these systems tend to be intricate, costly to implement, and, in some cases, are characterized by a limited number of monitored parameters, whether in DC or AC. Despite their prevalence, commercial solutions come with drawbacks related to communication protocols and user familiarity, hindering users from seamlessly incorporating new functions (Dupont et al., 2019). These challenges are particularly evident in monitoring systems integrated into the most widely used commercial inverters. This emphasizes the ongoing need for accessible and cost-effective solutions in the field of PV data measurement and acquisition.

In this paper, we addressed the development of a cost-effective monitoring system capable of measuring electrical parameters in both direct and alternating currents. Our developed system provides comprehensive data on energy production under exposed climatic conditions. We conducted a comparative analysis against traditional data logger electrical measurements. Using a 1.75 kWp grid-connected PV system located in the Saharan region of southern Algeria (Adrar), our research extends to enhancing system efficiency, optimizing project design, and evaluating system performance under diverse conditions. Our designed system demonstrates proficiency in assessing critical solar photovoltaic metrics, including voltage, current, and power output from the PV array. This comprehensive approach opens avenues for bolstering the reliability of electrical photovoltaic systems.

This paper is structured as follows; Details of the studied photovoltaic system and the proposed photovoltaic monitoring system are presented in the Materials and Method section. The Results and Discussion section presents the measured and calculated electrical parameters performed by the developed Photovoltaic Monitoring system of the PV station. Also, a comparative study by evaluating the performance between the used monitoring tool and the proposed photoelectric monitoring system is given in this section. At the end of the section, a price comparison between the used monitoring instrument and the developed PV monitoring system is also presented. The research work and aim of this paper are summarized in the conclusion section.

2. MATERIALS AND METHODS

2.1 Location and specifications of the Photovoltaic System

The grid-connected PV system has a capacity of 1.75 kWp. It was installed at the Renewable Energy Research Unit in the Saharan Area (URERMS) at the southern-west region of Algeria (Adrar city) (Abderrezzaq et al., 2017).

Fig 1. Meteorological station (NEAL) installed at URERMS in Adrar city.

Adrar city is renowned for its elevated summer temperatures, abundant solar insolation, and low humidity levels (Chabachi et al., 2022). We used New Energy Algeria (NEAL) meteorological station, shown in Figure 1 with the characteristics represented in Table 1 in order to reveal the climatic conditions.

Table 1. Characteristics and technical specifications of the weather station.

Sensor	Specification	
Pyranometer sensor	Max operational irradiance	4000 W m-^{2}
	Resolution	<1 W m-^{2}
	Spectral range	310–2800 nm
	Sensitivity	7–14 µV/W m-^{2}
	Operating temp rate	-40 ºC to +80 ºC
Barometric pressure	Range	600 hPaa –1100 hPa (8.7–15.95 Psi)
	Accuracy	±0.5 hPa (±0.007 Psi)
Relative humidity	Range	0–100% RH
	Accuracy	±2% RH
Air Temperature	Range	-40 ºC to +70 ºC
	Accuracy	±0.3 ºC
Wind speed	Range	1–96 m s^{-1}
	Accuracy	<0.1 m s^{-1}

2.1.1 Photovoltaic array

The photovoltaic array in place comprises 10 mono-crystalline silicon solar modules, namely SHARP (NT-R5E3E), connected in series. The specifications for both the PV module and the array are outlined in the accompanying Table 2.

Table 2. PV modules and array specifications.

Characteristic	**Abbreviation**	**Value**	**Unit**
Technology	/	Silicon mono-crystal	/
Efficiency	η_{pv}	13.5	%
Power at MPP	P_{max}	175	W
Voltage at MPP	V_{pm}	35.4 V	V
Current at MPP	I_{pm}	4.95 A	A
Open circuit voltage	V_{oc}	44.4 V	V
Short circuit current	I_{sc}	5.4 A	A
Tolerance	Tol	-5/+10	%
Power Temperature Coefficient	PTC	0.485	$\%/^0C$
Surface Area	A	1.3	m^2
Number of modules	N	10	/
Nominal Operating Cell Temperature	NOCT	47.5	^0C

2.1.2 Power inverter

We used FRONIUS IG 15 inverter, which transforms the DC power produced by the solar modules into AC power, aligning it with the grid voltage (Rampinelli et al., 2014). The inverter does not have the capability to generate electricity independently from the grid. Table 3 represents the specifications of the FRONIUS IG inverter.

The Fronius IG inverter has the measurements during the operation and can be displayed on the Fronius inverter LCD. This inverter needs external cards for a local network connection.

Table 3. Specification of the FRONIUS IG inverter.

Characteristics	Abbreviation	Value	Unit
Max input power	P_{DC}	2000	W
Max input voltage	V_{DC}	500	V
PV – voltage range at MPPT	V	150–400	V
Max input current	I_{DC}	10.75	A
Max output Active power	P_{ACn}	1500	W
Nominal output Active power	P_{ACn}	1300	W
Nominal output voltage	V_{ACn}	230	V
Nominal output frequency	f	50	Hz
Nominal output current	I_{ACn}	5.7 A	A
Max efficiency	η_{inv}	94.2%	%
Euro-efficiency	η_{eu}	91.4%	%

2.1.3 Monitoring Instruments

Monitoring was handled by Fluke Hydra 2635A data logger and the meteorological station from New Energy Algeria (NEAL). Solar irradiance, ambient temperature, DC and AC voltage and current outputs were recorded at one-minute intervals.

2.2. Photovoltaic Monitoring System

The system studied in the current paper is shown in Figure 2, in which the grid-connected PV was connected to solar inverter in order to transform DC voltage and current into AC voltage and current, respectively. The monitoring system for measuring the electrical parameters was installed at two specific points. Firstly, at point 1 positioned between the photovoltaic field and the input of the inverter, enabling measurement of the power generated by the PV field. Secondly, at point 2 located between the output of the inverter and the electrical network, facilitating measurement of the power delivered to the load.

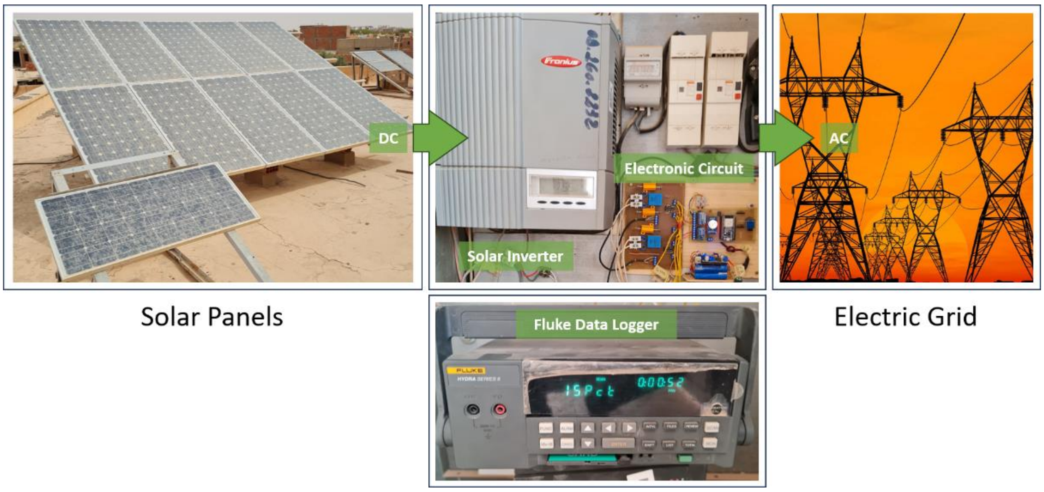


Fig 2. The photovoltaic system studied and the corresponding electrical measurement setup.

2.3 Electronic devices and sensors

The electronic devices and sensors utilized for the measurement and monitoring system are outlined in Table 4. The microcontroller employed was the Development Board ESP-32, capable of connecting via Wi-Fi to either local or public networks (Chen et al., 2023). The features of each element are resumed in the same table.

3. RESULTS AND DISCUSSION

3.1 Electrical measurements and calculation

The monitoring system was developed based on the Arduino open-source electronic prototyping platform. This open-source software has main benefits like:

- Low Cost: Open-source software is typically free to use.
- Customization and Modification: Users have the freedom to modify the source code according to their specific needs.
- Community Collaboration: Open-source projects thrive on community contributions.
- Transparency: The source code is open and accessible. Users can review it for security, privacy, and quality assurance.

- Security: Many eyes scrutinize open-source code, leading to faster identification and resolution of security vulnerabilities.
- Innovation: Open-source fosters innovation by encouraging experimentation, creativity, and the sharing of ideas.

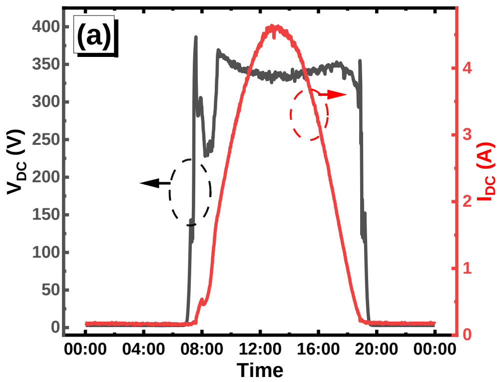
Table 4. Electronic devices and sensors used in our monitoring setup.

Device	Features	Figure
Development Board ESP32	Number of cores: 2 (dual core) Wi-Fi: 2.4 GHz up to 150 M_{bits}/s Bluetooth: BLE (Bluetooth Low Energy) and legacy Bluetooth Interface Protocol: UART/GPIO/ADC/DAC/SDIO/SPI /PWM/I2C/I2S Power Supply: Voltage 3.0V ~ 3.6V， Typical 3.3V， Current >500mA	
AC and DC Current Sensor	Rated input: ±50A Input measurement range: ±75A Rated output: 2.5V±0.625V Accuracy: 1%; Linearity: 1%; Supply voltage: +5V±5%	
AC voltage Sensor	Rated input: ±5mA Input measurement range: ±7mA Rated output: 2.5V±0.625V Accuracy: 1%; Linearity: 0.2%; Supply voltage: +5V±5%	
ADS1115	Wide Supply Range: 2.0 V to 5.5 V Programmable Data Rate: 8 SPS to 860 SPS Resolution: 16-bit ADC Channels: 4-channel single-ended input or 2-channel differential input Interface: I2C	
Micro SD Card	Operating voltage: 3V Communication Protocol: SPI	
DS3231	Operating voltage: 3V Operating Temperature: 0℃ to +70℃ Interface: I2C	
Power resistor	Resistance: 39 KJ Wattage: 25 W	

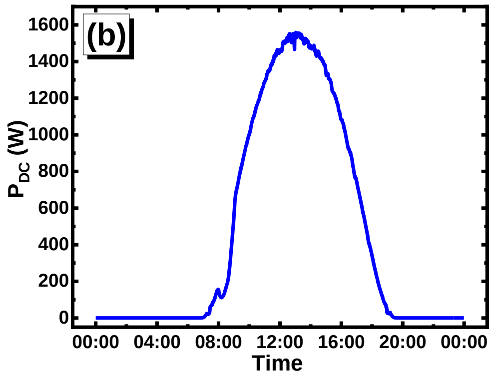
The electrical characteristics were measured using AC and DC Current sensor, and AC voltage sensor. The measured data from ESP32 by sensors were saved on a micro-SD card in a CSV format file. these data can be sent to the local or cloud-hosted data server in real time. At this moment, data is retrieved from the SD card by accessing the ESP32 connected to the local network via a WIFI connection. The data is later processed on a computer. The power generated by a photovoltaic (PV) array is typically measured in watts (W) or kilowatts (kW). It is calculated from the voltage (V_{DC}) and the current (I_{DC}) produced by the array according to the following equation (Afsher & Manoj Kumar, 2023):

$$P_{DC} = I_{DC} \times V_{DC} \tag{1}$$

The electrical measurements and deduced electrical powers obtained through our monitoring system are illustrated and analyzed in Figure 3. As illustrated in Figure 3 (c), between the hours of 19:00 and 8:00, the power output remained consistently negligible due to the absence of sunlight, resulting in minimal photovoltaic activity. However, the power output gradually increased as daylight hours resumed and peaked at around 13:00. As seen in Figure 3 (c), fluctuations in the measurement of alternative voltage were observed during the night-time. This fluctuation was attributed to a technical problem caused by poor connections or contacts. However, as detailed in the last section of this paper (The Comparative Study), we successfully resolved this issue, thereby ensuring the reliability of our electrical measurements.



(a)



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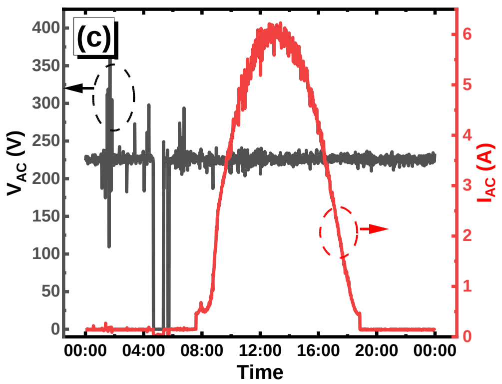
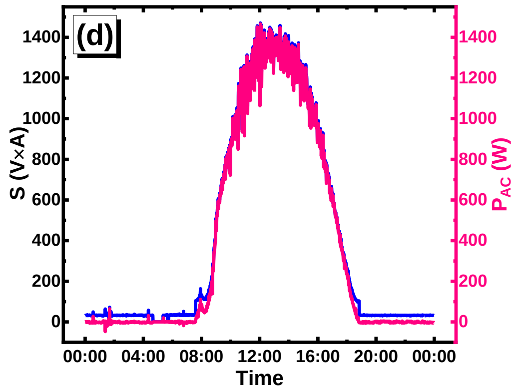


(c)



(d)

Fig 3. The voltage, current and power characteristics obtained from our suggested prototype (a) direct voltage (VDC) and direct current (IDC), and (b) deduced direct power (PDC), (c) alternative voltage (VAC) and alternative current (IAC), and (d) deduced apparent power (S) and alternative power (PAC).

The power factor (PF) is a key indicator for maintaining the photovoltaic system's efficient and cost-effective operation (Rajput & Dheer, 2023). It can be calculated using the following formula:

$$PF = P_{ac}/S \tag{2}$$

Where the active power (P_{ac}) can be calculated by integrating the instantaneous power over time using the equation $P_{ac} = \int p(t) \cdot dt$; $p(t)$ represents the instantaneous power as a function of time and which is deduced from the instantaneous voltage and current as: $p(t) = I(t) \times I(t)$. The active power is calculated using numerical integration over a discrete time interval using methods such as the trapezoidal rule or Simpson's rule, or simply summing up the products of voltage and current values at discrete time points.

In the other hand, the calculation of the apparent power (S) of PV inverter is the product of the voltage (V) and the current (I). Once you have measured the voltage (V_{ac}) and current (I_{Inv}), multiply them to obtain the apparent power (S), which is often measured in volt-amperes (VA):

$$S = V_{ac} \times I_{Inv} \quad (3)$$

Finally, the injected energy of the PV inverter (E_{ac}) allows for understanding the amount of energy that the PV system has contributed to inject, whether it is into the electrical grid or a storage system. The equation used to calculate the injected energy is given as follows:

$$E_{ac} = P_{ac} \times t \quad (4)$$

Where t is given in hours and represents the time duration over which the energy is being calculated. The calculated power factor and total energy generated by the PV-system and measured using our prototype circuit, are shown in Figure 4. The power factor remained nearly constant, maintaining a value of 1 during daylight hours. The energy is a crucial indicator for evaluating the performance and productivity of your photovoltaic installation, with a maximum value reaching approximately 18 kWh.

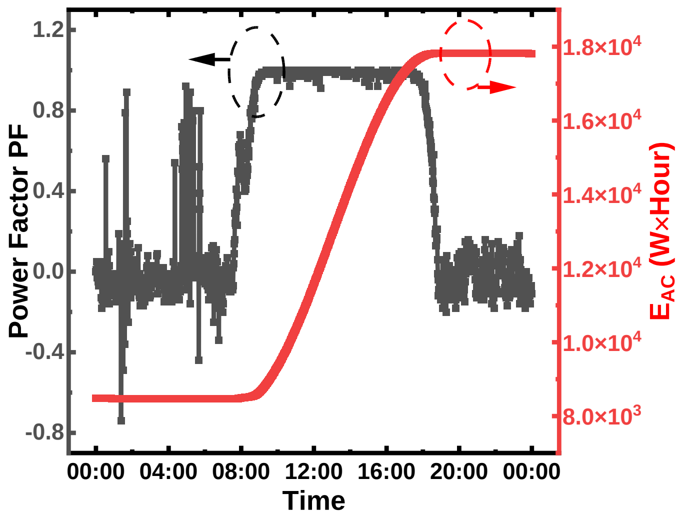


Fig 4. Calculated power factor and total energy generated by the PV-system, as measured using our prototype circuit.

3.2 Comparative study

Figure 5 represents the electrical measurement revealed at the point 1 during day 1 (Figure 5 (a) and (c)) and day 2 (Figure 5 (b) and (d)). The direct voltage and current obtained from our suggested electronic prototype (depicted by the black line graphs) closely align with those obtained from the data logger (Fluke Hydra 2635A) (represented by the red line graphs). The fluctuation in the values of the direct voltage during the daylight hours is related to weather conditions variation.

Similarly, Figure 6 illustrates the electrical measurement revealed at the point 2 during day 1 (Figure 6 (a) and (c)) and day 2 (Figure 6 (b) and (d)). Figure 6 (a) and (b) correspond to the effective value alternative voltages measured using our suggested electronic prototype (depicted by the black line graphs) and using data logger (Fluke Hydra 2635A) (represented by the red line graphs). Figure 6 (c) and (d) correspond to the effective value alternative currents. It is evident that the data logger exhibited better measurement performance; however, both measurements demonstrate a high degree of similarity.

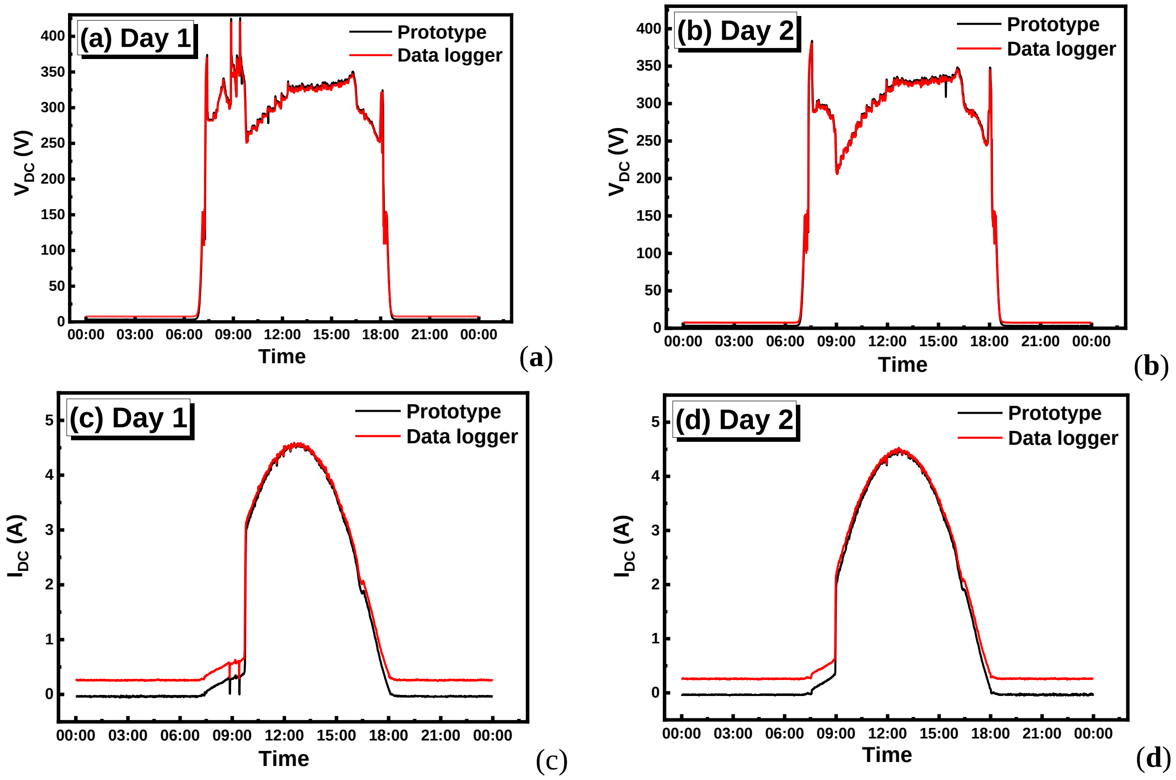


Fig 5. The prototype/data logger recorded direct voltage (VDC) during (a) day 1 and (b) day 2, and the prototype/data logger recorded direct current (IDC) during (c) day 1 and (d) day 2.

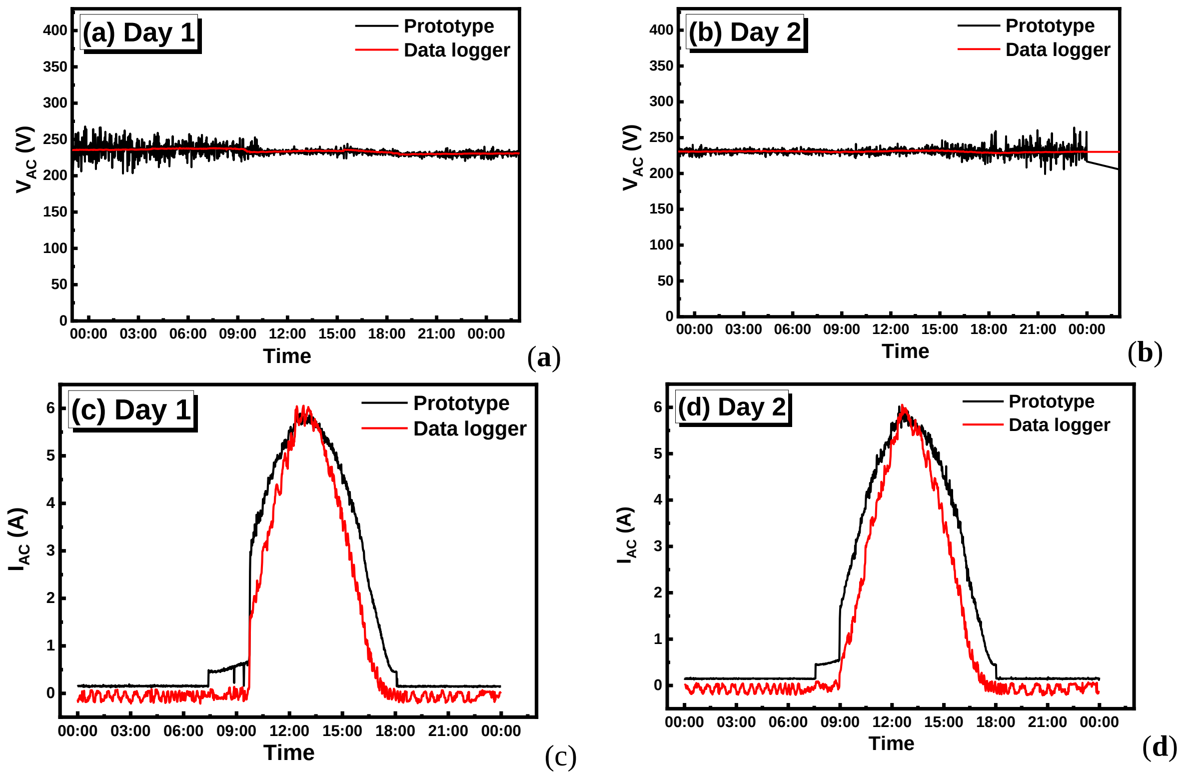


Fig 6. The prototype/data logger recorded alternative voltage (VAC) during (a) day 1 and (b) day 2, and the prototype/data logger recorded alternative current (IAC) during (c) day 1 and (d) day 2.

Finally, we have provided a comprehensive price comparison of the proposed instrumentation systems, as shown in Table 5. Our real-time monitoring electronic system is priced at around $72, significantly lower than the cost of the Fluke 2635A HYDRA Series II data acquisition system, which is assessed at $595.

Table 5. Price comparison of the proposed instrumentation systems.

Components	**Unit price**	**Price**
Microcontroller (ESP32)	$ 3.56 [a]	$ 3.56
AC and DC Current Sensor	$ 8.34 [a]	$ 16.68
AC voltage Sensor	$ 10.63 [a]	$ 21.26
ADS1115	$ 1.39 [a]	$ 2.78
Micro SD Carte	$ 0.37 [a]	$ 0.37
DS3231	$ 1.10 [a]	$ 1.10
Power resistance	$ 0.85 [a]	$ 2.55
Shipping fees	**$ 23.82**	
The total amount	**$ 72.12**	
Fluke 2635A HYDRA Series II	**$ 595** [b]	

[a] www.aliexpress.com; [b] https://accusrc.com

4. CONCLUSION

In conclusion, we have introduced an innovative and cost-effective data acquisition system designed for real-time monitoring of grid-connected photovoltaic (PV) systems. The implementation of this system enables the rapid, secure, and reliable collection of essential performance data, including voltage, current, and power production. Our prototype, initially designed with basic electronic devices and sensors, has undergone successful testing on a 1.75 kWp grid-connected PV system in the Saharan region of southern Algeria. By demonstrating strong agreement with a renowned data logger, our system offers a practical and affordable solution for solar monitoring needs. Moreover, the system's adaptability ensures scalability, making it suitable for monitoring larger PV installations with minimal adjustments. This research represents a significant advancement in enhancing the efficiency and reliability of PV systems, contributing to the global transition towards sustainable energy sources.

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