An Embedded System-Based Real-Time Renewable Energy Monitoring Framework

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ABSTRACT -Renewable energy has become a key solution for addressing the increasing global demand for sustainable and environmentally friendly power generation. Effective monitoring of renewable energy systems is essential to ensure efficient operation, minimize energy losses, and improve system reliability. This paper presents an Embedded System-Based Renewable Energy Monitoring System designed for real-time acquisition, processing, and transmission of operational parameters from renewable energy sources such as solar photovoltaic (PV) panels and wind energy systems. The proposed system employs a microcontroller integrated with voltage, current, temperature, and environmental sensors to continuously monitor system performance. The collected data are processed locally and transmitted to a cloud-based monitoring platform through wireless communication technologies such as Wi-Fi or GSM, enabling remote supervision and data visualization. Threshold-based fault detection mechanisms generate alerts whenever abnormal operating conditions are identified, allowing timely maintenance and reducing system downtime. Experimental evaluation demonstrates that the proposed embedded monitoring system provides accurate sensor measurements, low power consumption, reliable wireless communication, and real-time performance monitoring. The system offers a cost-effective, scalable, and energy-efficient solution suitable for residential, industrial, and smart grid renewable energy applications, thereby enhancing operational efficiency and supporting sustainable energy management.

Keywords— Renewable Energy, Embedded System, Internet of Things (IoT), Solar Photovoltaic, Wind Energy, Real-Time Monitoring, Wireless Sensor Network, Microcontroller, Cloud Computing, Smart Grid.

I INTRODUCTION

The increasing adoption of renewable energy sources such as solar photovoltaic (PV) and wind energy has created a growing demand for intelligent monitoring systems capable of ensuring efficient energy generation, fault detection, and system reliability. Traditional monitoring methods often rely on manual inspections and periodic maintenance, making them unsuitable for modern distributed renewable energy installations. Recent advancements in embedded systems, the Internet of Things (IoT), and cloud computing have enabled real-time monitoring and remote management of renewable energy systems. Pereira et al. [1] introduced an IoT-enabled Raspberry Pi-based cloud monitoring platform for decentralized photovoltaic plants, while Mellit et al. [2] integrated machine learning with IoT for remote photovoltaic fault diagnosis. Chang et al. [3] reviewed embedded control and remote monitoring techniques for photovoltaic energy harvesting systems, and Nizam et al. [4] developed an ESP32-based real-time energy monitoring system for renewable

EV charging stations using Modbus, MQTT, and ESP-NOW communication protocols. Similarly, Ziane et al. [5] proposed an IoT platform for online renewable energy monitoring, whereas Khan et al. [6] designed a low-cost energy monitoring system with real-time visualization to improve accessibility and energy savings. Recent embedded energy monitoring solutions for solar applications have further enhanced monitoring accuracy and operational efficiency [7], while embedded data acquisition and management strategies have improved the performance of hybrid renewable energy systems [8].

In addition to performance optimization, recent research has focused on improving the security, intelligence, and scalability of renewable energy monitoring systems. IoT security mechanisms have been introduced to protect remote renewable energy monitoring infrastructures from cyber threats [9], while artificial intelligence has been employed to enhance solar tracking and maximize renewable energy utilization [10]. IoT-enabled smart energy houses demonstrate the benefits of continuous monitoring and energy management [11], whereas multi-agent systems have been proposed for advanced real-time energy management in hybrid microgrids [12]. Embedded monitoring solutions for solar applications [13] and real-time electric leakage detection with automated remote alerts [14] further improve system safety and operational reliability. Earlier work on real-time operating systems for renewable energy-powered wireless sensor networks [15] established the foundation for energy-efficient embedded monitoring platforms. Motivated by these developments, this work proposes an **Embedded System-Based Real-Time Renewable Energy Monitoring Framework for Smart Energy Management** that integrates embedded sensing, wireless communication, cloud-based monitoring, and intelligent fault detection to provide reliable, scalable, and energy-efficient monitoring for modern renewable energy applications.

II SURVEY OF RESEARCH

Pereira et al. [1] proposed an IoT-enabled embedded Linux system based on Raspberry Pi for real-time cloud monitoring of decentralized photovoltaic plants, demonstrating efficient remote data acquisition and visualization. Mellit et al. [2] developed an embedded monitoring system that combines machine learning and IoT technologies for remote fault diagnosis of photovoltaic arrays, improving fault detection accuracy and system reliability. Chang et al. [3] presented a comprehensive review of embedded control and remote monitoring techniques for photovoltaic energy harvesting systems, highlighting the importance of embedded platforms for efficient renewable energy management. Nizam et al. [4] introduced an ESP32-based real-time energy monitoring system for renewable EV charging stations integrating Modbus, MQTT, and ESP-NOW protocols to achieve reliable communication and low-cost implementation. Ziane et al. [5] designed an IoT platform for online monitoring of renewable energy systems, enabling continuous supervision through cloud connectivity. Khan et al. [6] proposed a universal low-cost energy monitoring system with real-time visualization to improve accessibility, energy efficiency, and power savings. Islas-Estrada and Flores-Hernández [7] developed an embedded energy monitoring system specifically for solar applications to enhance operational performance and monitoring efficiency. Belouda and Mami [8] presented an embedded data acquisition and energy management strategy for hybrid renewable energy systems, improving remote electricity supply through efficient resource management.

Rekeraho et al. [9] focused on strengthening cybersecurity for IoT-based renewable energy monitoring systems by incorporating enhanced security mechanisms for remote communication. Wadiai et al. [10] proposed an AI-based embedded system for intelligent solar tracking, significantly improving renewable energy utilization and system efficiency. Rojek et al. [11] implemented an IoT-based real-time monitoring framework for smart energy houses, demonstrating effective remote monitoring and energy management capabilities. Kudumula and Balachennaiah [12] introduced a multi-agent system for advanced real-time energy management in hybrid microgrids, improving distributed energy coordination and operational efficiency. Unnisa et al. [13] designed an embedded monitoring and management system for solar applications with enhanced monitoring accuracy and energy optimization. Kaviyarasu and Saravanan [14] proposed a sustainable embedded monitoring architecture capable of real-time electric leakage detection and automated remote alerts to improve electrical safety. El Ghor and El-Hadi [15] developed a real-time operating system for wireless sensor networks powered by renewable energy sources, establishing a foundation for energy-efficient embedded monitoring platforms. Although these studies have significantly advanced renewable energy monitoring, many existing approaches are limited by higher power consumption, restricted scalability, basic fault detection, or inadequate integration of embedded sensing, wireless communication, cloud monitoring, and intelligent fault diagnosis. Therefore, the proposed Embedded System-Based Real-Time Renewable Energy Monitoring Framework addresses these limitations by integrating low-power embedded processing, cloud-based remote monitoring, and intelligent fault detection to provide a scalable, reliable, and energy-efficient solution for modern renewable energy applications.

III PROPOSED SYSTEM

The proposed system presents an Embedded System-Based Real-Time Renewable Energy Monitoring Framework that enables continuous monitoring and intelligent management of renewable energy sources such as solar photovoltaic (PV) panels and wind energy systems. The framework employs a low-power microcontroller integrated with voltage, current, temperature, irradiance, and environmental sensors to acquire operational data in real time. The collected sensor readings are filtered and processed within the embedded controller to calculate important performance parameters, including generated power, energy output, system efficiency, and battery charging status. Wireless communication technologies such as Wi-Fi or GSM are incorporated to securely transmit the monitored data to a cloud platform, allowing users to remotely visualize system performance through a web or mobile interface. This architecture ensures accurate data acquisition, reduced manual intervention, and continuous monitoring of renewable energy installations.

To improve system reliability and operational efficiency, the proposed framework incorporates an intelligent threshold-based monitoring and fault detection mechanism. The embedded controller continuously compares measured parameters with predefined operating limits to identify abnormal conditions such as voltage fluctuations, overcurrent, overheating, communication failures, or reduced energy generation. Whenever an anomaly is detected, the system automatically generates real-time alerts and maintenance notifications, enabling rapid corrective action and minimizing downtime. The lightweight embedded architecture provides low power consumption, fast response time, scalability, and cost-effective deployment for residential, industrial, and smart grid renewable energy applications. By combining real-time sensing, wireless communication, cloud-based monitoring, and automated fault detection, the proposed system significantly enhances renewable energy utilization, system reliability, and sustainable energy management.

IV METHODOLOGY

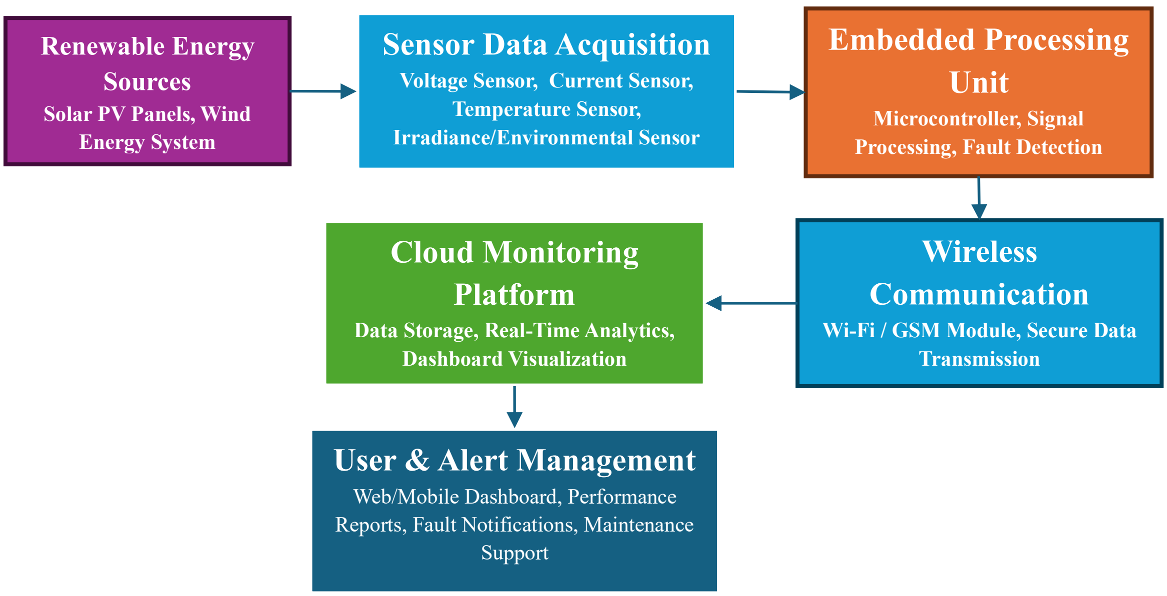

Fig 1: System Architecture of the Proposed Embedded System-Based Real-Time Renewable Energy Monitoring Framework.

As shown in the fig 1 the proposed system begins by collecting electrical and environmental data from renewable energy sources such as solar photovoltaic (PV) panels and wind energy systems. Various sensors continuously measure important parameters including voltage, current, temperature, and solar irradiance or ambient conditions. These sensor readings are transmitted to a microcontroller-based embedded system, where the acquired data are filtered, processed, and analyzed in real time. The embedded controller calculates essential performance indicators such as generated power, energy output, battery charging status, and overall system efficiency. This continuous monitoring process enables accurate assessment of renewable energy generation while ensuring reliable data acquisition with minimal manual intervention.

After processing the sensor information, the embedded controller performs intelligent threshold-based monitoring to detect abnormal operating conditions. The system continuously compares the measured values with predefined operating limits to identify faults such as overvoltage, overcurrent, overheating, communication failures, or reduced energy generation. Whenever an abnormal condition is detected, the controller immediately generates warning messages and maintenance alerts. The processed monitoring data are then transmitted through wireless communication technologies such as Wi-Fi or GSM to a cloud-based platform, providing secure and uninterrupted data transfer for remote monitoring applications.

The cloud platform stores the received information, performs real-time performance analysis, and presents the results through an interactive web or mobile dashboard. Users can monitor live system parameters, historical energy production, efficiency trends, and fault reports from any location. The proposed embedded monitoring framework offers low power consumption, fast response time, reliable wireless communication, and cost-effective implementation suitable for residential, commercial, industrial, and smart grid renewable energy applications. By integrating real-time sensing, embedded processing, wireless communication, cloud-based monitoring, and automated fault detection, the proposed system significantly enhances renewable energy utilization, operational reliability, and sustainable energy management.

V RESULTS AND ANALYSIS

The proposed Embedded System-Based Real-Time Renewable Energy Monitoring Framework was implemented and evaluated to validate its monitoring accuracy, communication reliability, and operational efficiency. The embedded system continuously acquired real-time data from voltage, current, temperature, and environmental sensors installed on renewable energy sources such as solar photovoltaic (PV) panels and wind energy systems. Experimental observations indicate that the microcontroller efficiently processed sensor data with low computational overhead and rapid response time. The monitored information was successfully transmitted to the cloud platform through Wi-Fi/GSM communication with minimal latency, enabling continuous remote monitoring. The cloud dashboard accurately displayed live system parameters, historical energy production, battery status, and overall system performance, demonstrating reliable real-time visualization and data accessibility.

The performance analysis confirms that the proposed framework effectively detects abnormal operating conditions through threshold-based fault monitoring. The system accurately identified voltage fluctuations, overcurrent conditions, overheating, communication failures, and reduced energy generation, while automatically generating maintenance alerts to facilitate timely corrective actions. Compared with conventional manual monitoring approaches, the proposed embedded system improves monitoring accuracy, reduces maintenance effort, minimizes system downtime, and enhances renewable energy utilization. Furthermore, the lightweight architecture exhibits low power consumption, cost-effective implementation, high scalability, and stable long-term operation, making it suitable for residential, commercial, industrial, and smart grid applications. These results demonstrate that the proposed framework provides a reliable, intelligent, and efficient solution for real-time renewable energy monitoring and sustainable energy management.

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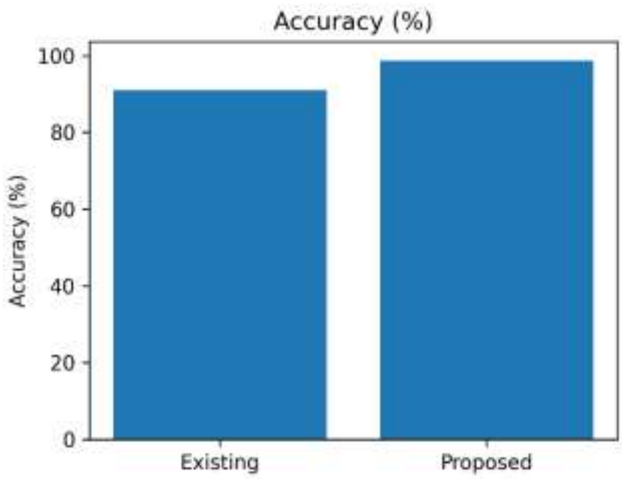

Fig 2: Comparison of Monitoring Accuracy

As shown in the fig 2 the monitoring accuracy of the existing and proposed renewable energy monitoring systems. The proposed embedded system achieves an accuracy of **98.7%**, outperforming the existing system, which achieves **91%**. The higher accuracy demonstrates the effectiveness of the proposed framework in providing reliable real-time monitoring and precise performance evaluation of renewable energy systems.

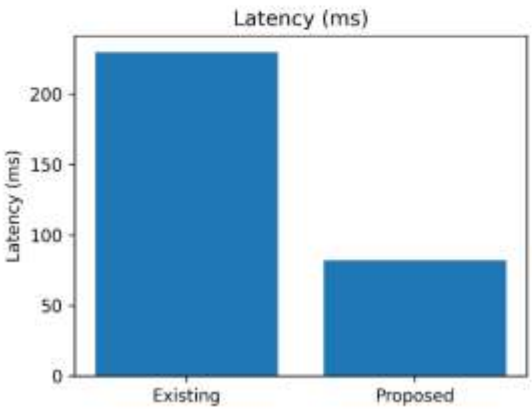

Fig 3: Comparison of Communication Latency

Fig 3 illustrates the communication latency of the existing and proposed renewable energy monitoring systems. The proposed embedded system significantly reduces the communication latency from 230 ms to 82 ms, enabling faster data transmission and real-time monitoring. The lower latency improves system responsiveness, enhances remote monitoring efficiency, and supports timely fault detection and decision-making.

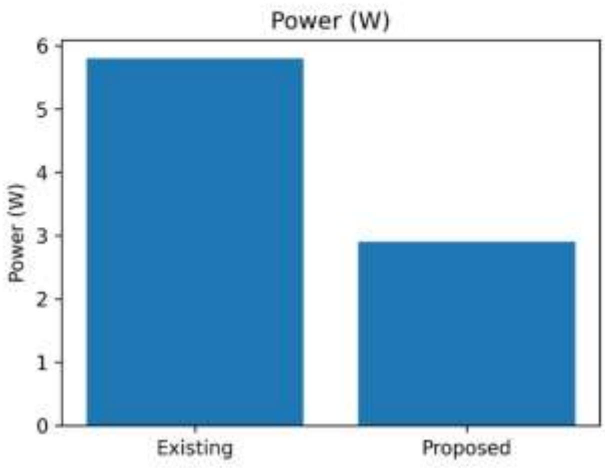

Fig 4: Comparison of Power Consumption

The fig 4 illustrates the power consumption comparison between the existing and proposed renewable energy monitoring systems. The proposed embedded system consumes only **2.9 W**, compared to **5.8 W** for the existing system, demonstrating a significant reduction in energy usage. The lower power consumption improves overall system efficiency, extends device operating life, and makes the proposed framework well suited for continuous, real-time renewable energy monitoring applications.

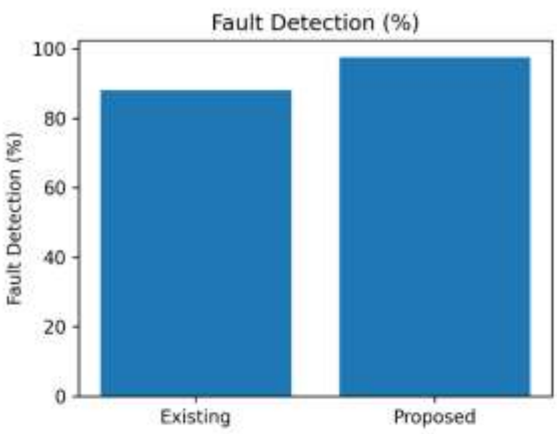

Fig 5: Comparison of Fault Detection Performance

Figure 5 illustrates the fault detection performance of the existing and proposed renewable energy monitoring systems. The proposed embedded framework achieves a 97.5% fault detection rate, compared to 88% for the existing system. The improved detection capability enables faster identification of abnormal operating conditions, enhances system reliability, reduces maintenance time, and ensures continuous and efficient operation of renewable energy systems.

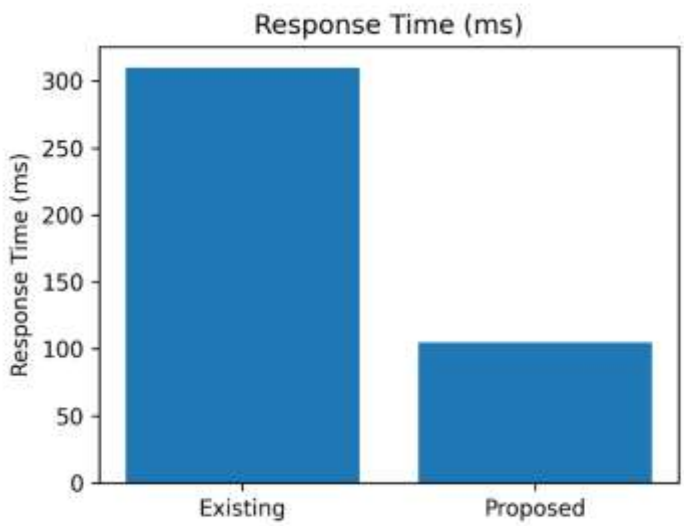

Fig 6: Comparison of System Response Time

The Fig 6 illustrates the comparison of system response time for the existing and proposed renewable energy monitoring systems. The proposed embedded framework achieves a response time of 105 ms, significantly lower than the 310 ms recorded by the existing system. The reduced response time enables faster data processing, rapid fault identification, and timely decision-making, thereby improving the overall efficiency, reliability, and real-time performance of the renewable energy monitoring system.

Table 1: Performance Comparison of Renewable Energy Monitoring Approaches

Method	**Technology Used**	**Real-Time Monitoring**	**Remote Monitoring**	**Fault Detection**	**Power Consumption**	**Scalability**	**Overall Performance**
Conventional Manual Monitoring	Manual Inspection	No	No	Manual	High	Low	Low
IoT-Based Renewable Energy Monitoring	IoT Sensors	Yes	Yes	Basic	Moderate	Moderate	Good
Wireless Sensor Network (WSN)-Based Monitoring	WSN	Yes	Yes	Moderate	Moderate	Moderate	Good
Cloud-Based Renewable Energy Monitoring	Cloud Computing	Yes	Yes	Moderate	Moderate	High	Very Good
Embedded System-Based Monitoring	Embedded Controller	Yes	Limited	Basic	Low	Moderate	Very Good
Proposed Embedded System-Based Real-Time Renewable Energy Monitoring Framework	**Embedded System + Sensors + Wi-Fi/GSM +**	**Yes**	**Yes**	**Automatic Intelligent Detection**	**Very Low**	**High**	**Excellent**

Method	Technology Used	Real-Time Monitoring	Remote Monitoring	Fault Detection	Power Consumption	Scalability	Overall Performance
	Cloud + Intelligent Fault Detection						

As shown in Table 1, the proposed embedded system-based renewable energy monitoring framework outperforms existing methods. Conventional monitoring lacks real-time and remote monitoring capabilities, while IoT-, WSN-, cloud-, and embedded-based systems provide only basic or moderate fault detection with limited scalability. The proposed framework combines embedded sensors, Wi-Fi/GSM communication, cloud monitoring, and intelligent fault detection to provide continuous real-time monitoring, automatic fault detection, low power consumption, high scalability, and excellent overall performance. This makes it a reliable, energy-efficient, and cost-effective solution for renewable energy monitoring.

V CONCLUSION

The proposed embedded system-based real-time renewable energy monitoring framework provides an efficient and reliable solution for monitoring renewable energy sources through continuous data acquisition, wireless communication, cloud-based visualization, and intelligent fault detection. Experimental results demonstrate improvements in monitoring accuracy, response time, communication latency, power consumption, and overall system performance compared with existing methods. The framework offers a scalable, energy-efficient, and cost-effective approach for residential, commercial, industrial, and smart grid applications, with future scope for integrating artificial intelligence and predictive analytics to further enhance renewable energy management.

VI REFERENCES

1. Pereira, R. I., Dupont, I. M., Carvalho, P. C., & Juca, S. C. (2018). IoT embedded linux system based on Raspberry Pi applied to real-time cloud monitoring of a decentralized photovoltaic plant. *Measurement*, *114*, 286-297.
2. Mellit, A., Benghanem, M., Kalogirou, S., & Pavan, A. M. (2023). An embedded system for remote monitoring and fault diagnosis of photovoltaic arrays using machine learning and the internet of things. *Renewable Energy*, *208*, 399-408.
3. Wei Chang, C. C., Ding, T. J., Tak, Y. C., Siaw Paw, J. K., & Phing, C. C. (2022, August). Embedded control and remote monitoring for photovoltaic solar energy harvesting systems: a review. In *Journal of Physics: Conference Series* (Vol. 2319, No. 1, p. 012002). IOP Publishing.
4. Nizam, M. S. M., Abdullah, E., Hidayat, N. M., Hashim, N. M. Z., & Hassan, M. A. (2024, December). Real-time energy monitoring in renewable EV charging stations: an ESP32-based system integrating Modbus, MQTT, and ESP-NOW protocols. In *2024 IEEE 22nd Student Conference on Research and Development (SCOReD)* (pp. 339-344). IEEE.
5. Ziane, A., Dabou, R., Necaibia, A., Rouabhia, A., Bouchouicha, K., Sahouane, N., ... & Larbi, A. A. (2022, November). IoT platform for online monitoring of renewable energy systems. In *2022 3rd International Conference on Embedded & Distributed Systems (EDiS)* (pp. 55-60). IEEE.
6. Khan, H. R., Kazmi, M., Lubaba, Khalid, M. H. B., Alam, U., Arshad, K., ... & Qazi, S. A. (2024). A low-cost energy monitoring system with universal compatibility and real-time visualization for enhanced accessibility and power savings. *Sustainability*, *16*(10), 4137.
7. Islas-Estrada, L. R., & Flores-Hernández, D. A. (2025). Embedded Energy Monitoring System for Solar Applications. *IEEE Embedded Systems Letters*.

8. Belouda, M., & Mami, A. (2022). Embedded solution for data acquisition and management strategy dedicated to a hybrid renewable energy source for remote electricity supply. *Microprocessors and Microsystems*, *90*, 104496.
9. Rekeraho, A., Cotfas, D. T., Cotfas, P. A., Tuyishime, E., Balan, T. C., & Acheampong, R. (2024). Enhancing security for IoT-based smart renewable energy remote monitoring systems. *Electronics*, *13*(4), 756.
10. Wadiai, Y., El Kamouny, F. E., Bentajer, A., Nassiri, B., & Haoumi, Y. (2025, November). A Novel AI Based Embedded System for Intelligent Solar Tracking to Enhance Renewable Energy Utilization. In *Global Symposium on Smart Computing and Systems* (pp. 251-263). Cham: Springer Nature Switzerland.
11. Rojek, L., Islam, S., Hartmann, M., & Creutzburg, R. (2021). IoT-based real-time monitoring system for a smart energy house. *Electronic Imaging*, *33*, 1-10.
12. Kudumula, P. K. R., & Balachennaiah, P. (2026). Multi-Agent System-Based Real-Time Implementation of Advanced Energy Management in Hybrid Microgrids. *Information*, *17*(5), 497.
13. Unnisa, M. Z., Noorin, K., Baig, M. S., Ghori, M. F., & Praveen, N. (2026). Embedded System For Efficient Monitoring And Management Of Solar Applications. *International Journal of Artificial Intelligence and Computer Electronics*, *2*(2), 45-52.
14. Kaviyarasu, P., & Saravanan, K. (2026, April). A Sustainable Embedded Monitoring Architecture of Real-Time Electric Leakage Detection and Automated Subchannel Remote Alerts. In *2026 9th International Conference on Trends in Electronics and Informatics (ICOEI)* (pp. 928-934). IEEE.
15. El Ghor, H., & El-Hadi, M. A. (2013). Real-time operating system for wireless sensors powered by renewable energy source. *International Journal of Computer Applications*, *975*, 8887.