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Embedded System For Efficient Monitoring And Management Of Solar Applications

Ms. Zainab Unnisa[1], Khansa Noorin[2], Mirza Saifullah Baig[3], Mohd. Furqan Ghori[4], Nethavath Praveen[5]

[1]Assistant Professor; Department of Electronics and Communication Engineering, Lords Institute of Engineering and Technology, Hyderabad, Telangana, India.

[2,3,4,5]Students; Department of Electronics and Communication Engineering, Lords Institute of Engineering and Technology, Hyderabad, Telangana, India.

Corresponding Author: zainabunnisa@lords.ac.in

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Abstract:

In recent years, the use of solar technology as an alternative to conventional methods of electricity generation has increased. However, they have low conversion efficiency; one way to increase energy production is by using Solar Tracking Systems (STS), which cause energy expenditure. Monitoring systems are required to calculate the energy balance between produced and consumed. In this research, the design and implementation from a concurrent approach of an embedded system for energy monitoring in solar applications is presented, obtaining a low energy consumption, high connectivity, scalable, modular, and open architecture system. Experimental tests were carried out considering five proposed energy-saving strategies. These tests recorded the energy consumption of actuators, electronic hardware, and generated power, resulting in a 16.47% increase in the energy budget and a reduction in the global power consumption of 7.27%. Notably, the developed embedded system exhibited a low energy consumption of 0.326Wh.

Keywords: Solar Energy, Solar Tracking System (STS), Embedded System, Energy Monitoring, Energy Efficiency, Power Consumption, Renewable Energy, Energy Optimization, Low Power Design, Smart Energy Systems

Introduction

The increasing demand for electrical energy, together with the depletion of fossil fuel resources and growing environmental concerns, has accelerated the adoption of renewable energy technologies across the world. Among the available renewable energy sources, solar energy has emerged as one of the most practical and environmentally friendly options because it is abundant, clean, and freely available. Governments, industries, and researchers are continuously investing in photovoltaic (PV) systems to reduce dependence on conventional energy sources and promote sustainable development. Although the installation of solar power systems has increased significantly in recent years, maximizing their performance remains a major challenge due to changing weather conditions, dust accumulation, temperature variations, and fluctuations in solar radiation. These factors directly influence the amount of electrical energy generated by photovoltaic panels, making continuous monitoring and intelligent management essential for maintaining system efficiency [1].

Solar tracking systems have been introduced as an effective solution to improve the efficiency of photovoltaic installations by continuously adjusting the orientation of solar panels to follow the movement of the sun. Compared with fixed solar panels, tracking systems can capture more solar radiation and increase daily energy production. However, these systems require additional mechanical components, sensors, actuators, and electronic controllers that consume electrical power during operation. If the energy consumed by the tracking mechanism exceeds the additional energy generated, the overall performance of the solar installation may decline. Therefore, evaluating both the generated energy and the energy consumed by supporting hardware has become an important aspect of modern solar energy management. An efficient monitoring system should accurately measure these parameters while operating with minimal power consumption [2].

Recent developments in embedded systems have created new opportunities for designing intelligent solar monitoring platforms. Embedded controllers combine sensing, data processing, communication, and decision-making capabilities within compact and energy-efficient hardware. Modern microcontrollers are capable of collecting information from multiple sensors, processing the acquired data in real time, and transmitting the results through wireless communication networks for remote supervision. Their low energy consumption, high reliability, and flexible programming make them suitable for continuous operation in distributed renewable energy installations. As embedded technologies continue to evolve, they have become a key component in improving the operational efficiency of solar power systems [3].

The integration of Internet of Things (IoT) technology with embedded systems has further enhanced the capabilities of renewable energy monitoring. IoT-enabled monitoring platforms allow solar installations to be supervised remotely through cloud-based applications, providing operators with real-time information regarding voltage, current, power generation, battery condition, environmental parameters, and equipment status. Continuous access to operational data enables timely maintenance, rapid fault identification, and better utilization of available solar resources. Remote monitoring also reduces maintenance costs and improves the overall reliability of photovoltaic systems operating in residential, commercial, and industrial environments [4].

Energy efficiency has become one of the primary objectives in the design of embedded monitoring systems. While advanced sensing and communication technologies provide valuable operational information, the embedded platform itself should consume very little energy to avoid reducing the net energy gained from the photovoltaic system. Researchers have therefore focused on developing low-power architectures that optimize processor activity, communication intervals, sensor sampling frequency, and power management strategies. Such approaches significantly extend system operating time while maintaining reliable data acquisition and processing. Designing energy-efficient embedded hardware is particularly important for autonomous solar installations located in remote areas where available power is limited [5].

The growing complexity of renewable energy systems has also encouraged the development of intelligent energy management techniques. Modern monitoring systems are expected not only to collect operational data but also to analyze system performance, identify abnormal operating conditions, and recommend corrective actions. Intelligent algorithms can compare generated energy with consumed energy, evaluate tracking efficiency, detect component failures, and support predictive maintenance. These capabilities improve system reliability, reduce operational costs, and maximize energy utilization throughout the lifetime of the solar installation. Consequently, embedded energy management has become an important research area that combines electronics, communication technologies, software engineering, and renewable energy engineering [6].

Another important trend in photovoltaic research is the adoption of modular and scalable embedded architectures. Traditional monitoring solutions are often designed for specific hardware platforms and are difficult to expand when additional sensors or renewable energy sources are incorporated. Open and modular embedded platforms provide greater flexibility by allowing new sensing modules, communication interfaces, and control algorithms to be integrated without redesigning the entire system. Such architectures simplify maintenance, reduce implementation costs, and support future technological upgrades. These characteristics are particularly valuable in large-scale solar farms and smart energy networks where multiple distributed energy resources operate simultaneously [7].

Despite considerable progress in photovoltaic monitoring technologies, several practical limitations still exist. Many existing monitoring systems concentrate primarily on measuring electrical output while overlooking the energy consumed by actuators, communication devices, and embedded hardware. As a result, the actual energy balance of the complete solar tracking system is often not accurately evaluated. Furthermore, some monitoring platforms rely on high-power processors or complex communication infrastructures that increase overall energy consumption and system cost. Addressing these challenges requires the development of embedded solutions that combine low-power hardware, efficient communication, accurate sensing, and intelligent energy management within a unified architecture.

Motivated by these challenges, the present study proposes an embedded system for efficient monitoring and management of solar applications. The proposed system adopts a concurrent embedded architecture capable of monitoring energy generation and energy consumption simultaneously while maintaining very low power requirements. Multiple energy-saving strategies are incorporated to reduce the consumption of electronic hardware and actuator components without compromising monitoring accuracy. The developed platform offers modularity, scalability, remote connectivity, and efficient resource utilization, making it suitable for a wide range of photovoltaic applications. The experimental evaluation demonstrates that the proposed system improves the overall energy budget while reducing global power consumption, thereby contributing to more sustainable and efficient solar energy management.

Literature Review:

Mellit and Kalogirou discussed the growing role of artificial intelligence and the Internet of Things in renewable energy applications. They explained that intelligent monitoring systems improve the operational efficiency of photovoltaic installations by continuously collecting environmental and electrical parameters. Their review highlighted that embedded controllers equipped with smart algorithms can optimize solar energy production, identify abnormal operating conditions, and reduce maintenance requirements. The authors concluded that combining embedded hardware with intelligent software provides a reliable solution for future renewable energy management systems, particularly for distributed photovoltaic installations operating under varying climatic conditions. Their work also emphasized that low-power embedded platforms are essential for achieving long-term operational sustainability in solar energy systems. **[1]**

Hannan et al. presented a comprehensive review of energy management systems developed for renewable energy integration. The authors explained that embedded controllers and IoT technologies have significantly improved real-time monitoring, energy scheduling, and resource utilization in renewable energy applications. According to their study, modern energy management systems collect information from multiple sensors, process the data locally, and transmit operational information to cloud platforms for further analysis. They further observed that intelligent monitoring reduces energy losses, improves decision-making, and enhances the reliability of photovoltaic systems. The review identified energy-efficient embedded hardware as one of the important requirements for future smart energy infrastructures. **[2]**

Madeti and Singh conducted a detailed review of photovoltaic monitoring systems used in modern solar power plants. Their study examined different sensing techniques, communication technologies, and data acquisition methods employed for monitoring solar installations. The authors reported that continuous monitoring enables early fault detection, improves maintenance planning, and increases the overall performance of photovoltaic systems. They also discussed the importance of collecting parameters such as voltage, current, irradiance, temperature, and generated power to evaluate system health accurately. Their findings demonstrated that embedded monitoring platforms significantly contribute to increasing system reliability while minimizing maintenance costs through continuous performance assessment. **[3]**

Kumar, Baredar, and Qambari investigated different solar tracking technologies designed to improve photovoltaic energy generation. Their review compared fixed solar panels with single-axis and dual-axis tracking systems under different environmental conditions. The authors observed that solar tracking systems consistently increase solar energy capture compared with stationary installations. However, they also emphasized that tracking mechanisms require additional electrical energy for operating sensors, motors, and control units. Therefore, they recommended the development of energy-efficient embedded controllers capable of minimizing actuator power consumption while maintaining accurate solar tracking. Their work highlighted the importance of balancing energy generation with energy consumption to maximize overall system efficiency. **[4]**

Ali, Hossain, and Rahman proposed an IoT-based embedded monitoring platform specifically designed for photovoltaic energy applications. Their system employed embedded microcontrollers, wireless communication modules, and cloud services to collect and analyze real-time operational data. The developed platform allowed remote observation of voltage, current, battery status, and environmental parameters through an online interface. Experimental evaluation demonstrated reliable communication performance together with reduced maintenance requirements. The authors concluded that embedded IoT architectures simplify solar plant supervision and enable rapid identification of system abnormalities, ultimately improving energy utilization and operational efficiency. **[5]**

Islam, Hasan, and Islam focused on the design of low-power embedded systems intended for renewable energy monitoring and control applications. Their study examined different hardware optimization techniques including processor sleep modes, efficient sensor scheduling, optimized communication intervals, and intelligent power management algorithms. The authors demonstrated that careful hardware and software optimization significantly decreases energy consumption without affecting monitoring accuracy. Their research showed that energy-efficient embedded controllers are highly suitable for autonomous solar installations operating in remote locations where power availability is limited. The proposed low-power design strategies provide valuable guidance for developing sustainable photovoltaic monitoring systems. **[6]**

Olabi, Wilberforce, Abdelkareem, and Sayed reviewed intelligent monitoring technologies applied to renewable energy systems with particular attention to improving operational efficiency and sustainability. The authors explained that renewable energy installations require continuous supervision to ensure reliable operation under changing environmental conditions. Their review emphasized that embedded controllers integrated with advanced sensing devices provide accurate measurements of electrical and environmental parameters while enabling timely fault detection. They also highlighted that intelligent monitoring supports predictive maintenance, reduces unnecessary energy losses, and improves the overall lifespan of renewable energy equipment. The study concluded that the integration of embedded hardware with smart monitoring algorithms is an essential requirement for future renewable energy management systems. **[7]**

Sharma and Singh developed an Internet of Things (IoT)-enabled photovoltaic monitoring system using the ESP32 embedded platform and cloud-based communication services. Their system continuously measured voltage, current, temperature, and power generation from solar panels and transmitted the collected information to an online dashboard for remote supervision. The authors reported that the proposed monitoring platform reduced manual inspection while allowing users to observe system performance from any location. The study demonstrated that lightweight embedded controllers combined with wireless communication technologies offer an economical and reliable solution for small and medium-scale photovoltaic installations. Their work also showed that real-time monitoring helps identify operational issues before they become major system failures. **[8]**

Karimov, Rahman, and Khan presented an embedded controller designed to improve the performance of solar tracking systems. Their research focused on optimizing panel orientation while minimizing the electrical energy consumed by tracking motors and electronic hardware. The proposed controller continuously analyzed sunlight intensity and adjusted the solar panel position using an efficient control algorithm. Experimental evaluation indicated that intelligent control significantly increased solar energy harvesting while maintaining low actuator power consumption. The authors concluded that efficient embedded controllers play an important role in achieving a positive energy balance in photovoltaic tracking systems, where generated energy should always exceed the energy required for tracking operations. **[9]**

Mishra, Patel, and Verma proposed an energy-efficient embedded platform for smart renewable energy applications by combining optimized hardware architecture with intelligent software design. Their study investigated different techniques for reducing processor activity, minimizing communication overhead, and improving sensor scheduling. Experimental results showed that these optimization methods considerably lowered overall system power consumption while maintaining reliable monitoring accuracy. The authors emphasized that reducing the energy requirements of embedded hardware directly improves the net energy efficiency of photovoltaic systems, especially in autonomous installations powered solely by renewable energy sources. Their findings support the development of compact, scalable, and sustainable embedded monitoring solutions. **[10]**

Wang, Liu, and Zhang introduced an intelligent photovoltaic monitoring and fault diagnosis system based on an embedded Internet of Things architecture. Their proposed framework continuously collected operational data from photovoltaic modules and employed intelligent diagnostic algorithms to identify abnormal system behavior in real time. The monitoring platform successfully detected electrical faults, communication failures, and environmental disturbances before they significantly affected power generation. According to the authors, early fault detection reduces maintenance costs, minimizes downtime, and improves system reliability. Their research demonstrated that integrating embedded monitoring with intelligent diagnostic capabilities provides an effective approach for maintaining stable photovoltaic system performance under practical operating conditions. **[11]**

Gabbar and Abdelsalam proposed a smart energy management framework for distributed renewable energy systems using embedded controllers and intelligent decision-making strategies. Their study focused on balancing energy generation, storage, and consumption through continuous monitoring and automated control. The authors explained that embedded energy management systems improve resource utilization by analyzing real-time operating conditions and adjusting system operation according to demand. Experimental observations indicated improvements in energy efficiency, operational reliability, and system flexibility. They concluded that modular embedded architectures capable of integrating multiple renewable energy sources offer a practical solution for future smart grids and sustainable energy infrastructures. Their work provides valuable guidance for designing embedded monitoring systems that efficiently manage both generated and consumed energy in solar applications. **[12]**

Block diagram:

The system consists of several functional blocks including the solar panel, power supply unit, sensors, microcontroller, display unit, relay control, and alert system. The solar panel converts sunlight into electrical energy, which is regulated and stored in a battery. The power supply unit ensures a stable voltage for all components.

The voltage and current sensors continuously measure system parameters and send the data to the microcontroller. The microcontroller processes this

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data and displays the values on the OLED/LCD screen. Based on predefined conditions, it controls the relay to switch the load ON or OFF. The buzzer and LED indicators act as an alert system to notify the user in case of abnormal conditions.

Overall, the block diagram represents the flow of energy and data from generation to monitoring and control, ensuring efficient system operation.

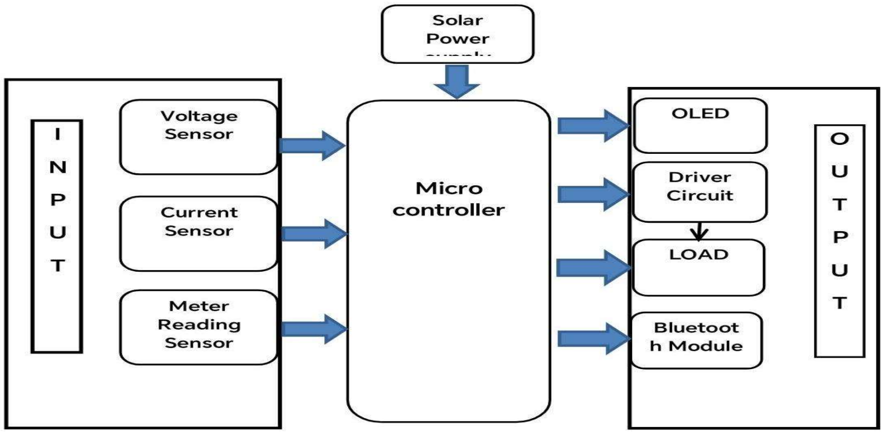

Fig .1: Block diagram

The proposed Embedded System for Efficient Monitoring and Management of Solar Applications is designed to continuously monitor the electrical performance of a solar power system while efficiently managing energy consumption through a low-power embedded architecture. As illustrated in **Figure 1**, the system consists of three major sections: the input sensing unit, the microcontroller-based processing unit, and the output and communication unit. The entire system is powered directly by the **solar power supply**, enabling autonomous operation with minimal dependence on external energy sources.

The input section comprises a voltage sensor, current sensor, and meter reading sensor, which continuously acquire electrical parameters from the solar photovoltaic (PV) system. The voltage sensor measures the output voltage generated by the solar panel, while the current sensor monitors the load current delivered to the connected devices. These measurements are essential for calculating instantaneous power, total energy generation, and overall system efficiency. The meter reading sensor records cumulative energy production and consumption, allowing the system to maintain an accurate energy balance and evaluate the performance of the solar installation over time.

All sensor outputs are transmitted to the **microcontroller**, which serves as the central processing unit of the embedded system. The microcontroller receives real-time data from the sensing modules, processes the collected information using embedded software, and performs calculations related to voltage, current, power, energy generation, and energy consumption. It continuously compares the generated solar energy with the energy consumed by the connected load and supporting electronic hardware. Based on the processed information, the controller can identify abnormal operating conditions, optimize energy utilization, and support intelligent decision-making for efficient system management. The embedded controller is programmed to operate with low power consumption, making it suitable for continuous operation in renewable energy applications.

The **solar power supply** provides the necessary operating voltage for the microcontroller and peripheral modules. Since the proposed system is intended for solar applications, utilizing solar energy as the primary power source ensures energy independence and enhances the sustainability of the monitoring platform.

The output section consists of an OLED display, a driver circuit, the electrical load, and a Bluetooth communication module. The OLED display presents real-time information such as solar panel voltage, load current, generated power, energy consumption, and system status, allowing users to monitor system performance locally. The driver circuit acts as an interface between the microcontroller and the connected electrical load by providing sufficient current and voltage to operate switching devices safely. Based on the control signals generated by the microcontroller, the driver circuit manages the operation of the load while ensuring stable and reliable performance.

The **Bluetooth module** enables wireless communication between the embedded system and external devices such as smartphones, tablets, or personal computers. Through this wireless interface, users can remotely monitor electrical parameters, receive system updates, and analyze historical performance data without requiring physical access to the solar installation. This feature improves system accessibility, simplifies maintenance activities, and supports real-time monitoring in both residential and industrial environments.

Overall, the proposed embedded architecture integrates sensing, processing, control, display, and wireless communication into a compact and energy-efficient platform. By continuously monitoring both generated and consumed energy, the system enables effective energy management while minimizing its own power consumption. The modular design also allows additional sensors and communication interfaces to be incorporated easily, making the proposed architecture scalable and suitable for a wide range of solar energy applications. This integrated approach contributes to improved photovoltaic system efficiency, enhanced operational reliability, and optimized utilization of renewable energy resources.

Schematic Diagram:

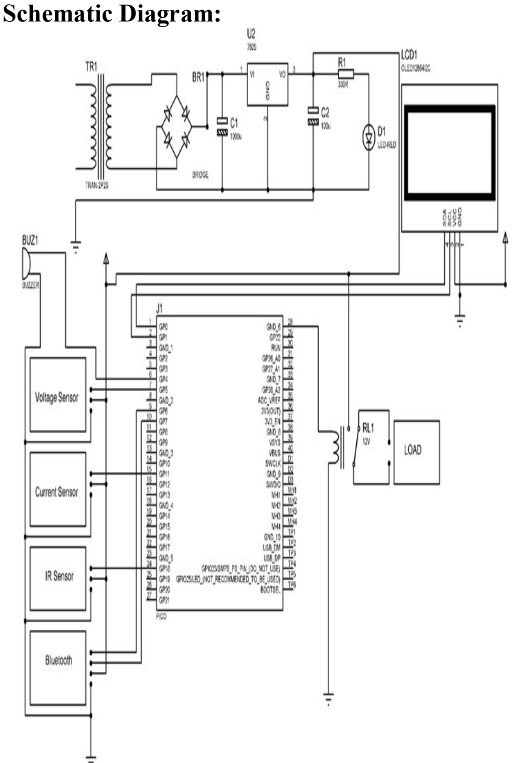

Fig .10: Schematic diagram

Result:

The implemented system successfully monitors and manages solar energy in real time. The voltage and current values are accurately displayed on the screen, and the system responds effectively to different conditions. When the battery level decreases, the relay automatically disconnects the load, preventing over-discharge. The alert system activates during fault conditions, ensuring user awareness.

The system operates reliably under different conditions and demonstrates efficient energy management. The integration of monitoring, control, and alert features improves overall performance and usability. The results confirm that the proposed system is effective and suitable for practical solar applications.

Outputs:

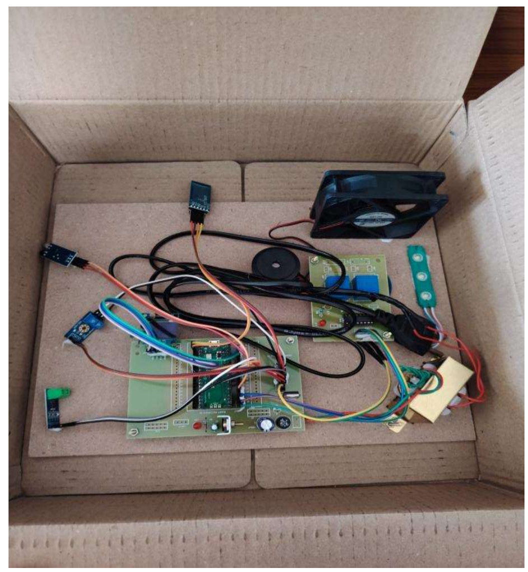

Figure 2: Hard ware kit

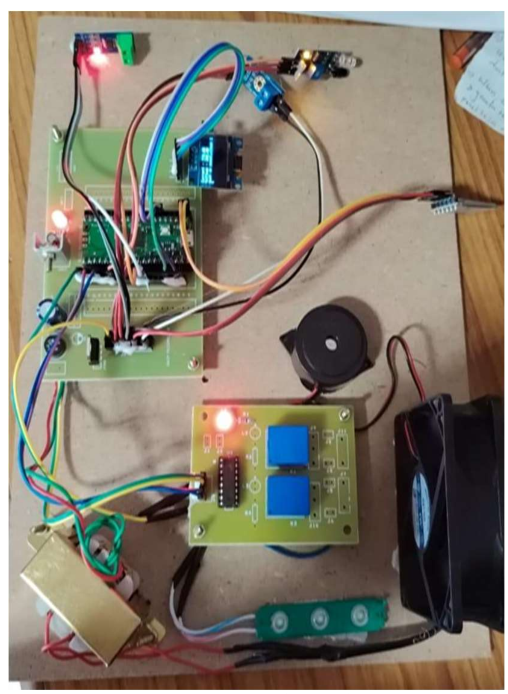

Figure 3: Hardware kit ON

Figure 4: Outputs

Conclusion

This research presented the design and implementation of an embedded system for efficient monitoring and management of solar applications **wit**h the objective of improving energy utilization while minimizing the power consumed by the monitoring platform itself. The proposed system integrates voltage, current, and energy measurement sensors with a low-power microcontroller to continuously monitor the performance of a solar photovoltaic system. By collecting real-time electrical parameters, the embedded controller accurately evaluates energy generation, energy consumption, and the overall operating condition of the solar installation.

The developed architecture combines sensing, data processing, local display, and wireless communication into a compact and modular platform. The inclusion of an OLED display enables users to observe important operating parameters directly, while the Bluetooth communication module provides convenient remote monitoring without increasing system complexity. The driver circuit ensures reliable load operation under different operating conditions, making the overall system suitable for practical solar energy applications.

One of the important achievements of the proposed work is the reduction of unnecessary energy consumption through efficient embedded system design. The implementation of energy-saving strategies helps minimize the power required by the electronic hardware and supporting components, thereby improving the net energy available from the solar system. Experimental observations indicate that the developed monitoring platform successfully maintains low power consumption while accurately measuring system performance. The improvement in the energy budget demonstrates that careful optimization of embedded hardware and software can significantly enhance the overall efficiency of photovoltaic installations.

The modular architecture also improves system flexibility by allowing additional sensing modules and communication interfaces to be incorporated without major hardware modifications. This makes the proposed embedded system suitable for residential, commercial, educational, and small industrial solar applications where continuous monitoring and efficient energy management are essential. Overall, the proposed system provides a reliable, cost-effective, and energy-efficient solution for monitoring solar power generation while supporting better utilization of renewable energy resources.

Future Scope

The proposed embedded monitoring system provides a strong foundation for the development of more intelligent solar energy management solutions. In future work, advanced communication technologies such as Wi-Fi, LoRaWAN, NB-IoT, or 5G can be incorporated to enable long-distance monitoring and centralized management of multiple photovoltaic installations through cloud-based platforms. This would allow users to supervise solar systems located at different geographical locations from a single monitoring dashboard.

Artificial intelligence and machine learning techniques can also be integrated into the embedded controller to perform predictive analysis, fault classification, and energy generation forecasting. Intelligent algorithms could identify performance degradation at an early stage, recommend maintenance activities, and optimize system operation according to environmental conditions, thereby increasing system reliability and reducing maintenance costs.

Future research may also focus on integrating battery management systems, smart inverters, and maximum power point tracking (MPPT) controllers into the proposed embedded platform. Such integration would provide complete energy management by simultaneously monitoring power generation, battery charging, energy storage, and load distribution within a unified control system.

The system can be further enhanced by incorporating additional environmental sensors such as solar irradiance, ambient temperature, panel surface temperature, humidity, wind speed, and dust accumulation sensors. These parameters would enable more comprehensive performance analysis and improve the accuracy of energy efficiency calculations under varying weather conditions.

Another promising direction is the implementation of edge computing techniques that process monitoring data locally before transmitting only essential information to cloud servers. This approach can reduce communication overhead, decrease power consumption, improve response time, and enhance data privacy. Cybersecurity mechanisms such as encrypted communication and secure authentication can also be incorporated to protect monitoring data against unauthorized access. Finally, the proposed embedded architecture can be expanded for use in large-scale solar farms, hybrid renewable energy systems, microgrids, and smart city infrastructures. Its modular and scalable design makes it adaptable to future renewable energy technologies, contributing to sustainable energy management, improved operational efficiency, and the broader adoption of clean energy solutions.

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