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RESEARCH ARTICLE

Optimizing Solar Power Generation and Integration in Automotive Systems Through IoT

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Abstract

Objective: This study presents an Internet of Things (IoT)- based system with edge intelligence that predicts power production with over 98% accuracy and monitors substations and smart solar installations, ensuring reliable power distribution in industrial IoT environments. This system enhances sustainability, safety, and energy management in smart buildings by reducing power fluctuations by 30% and improving decision-making, leading to a 95% reduction in energy management costs. **Method:** An IoT-enabled power monitoring system was implemented for smart solar panels and substations, incorporating edge intelligence for instantaneous prediction and decision-making. An IoT-enabled solar charging station was deployed for smart homes and Industry 4.0 applications. The cloud was used for analyzing sensor data, with a response time of less than 1 second. **Findings:** The proposed framework increased the efficiency and reliability of power production and distribution by 25% across commercial, residential, and industrial contexts. It significantly mitigated power fluctuations, reducing downtime by 40% and achieving a 95% cost reduction in energy management compared to traditional systems. IoT integration improved safety and sustainability metrics by 20% in smart buildings. **Novelty:** The framework integrates edge intelligence with IoT in smart solar systems and substations, providing a sophisticated control system that enhances power distribution decision-making. It facilitates real-time monitoring and prediction of power production with over 98% accuracy, emphasizing sustainability, safety, and energy management improvements of up to 30% in smart buildings.

Keywords: IoT-based control system; Smart solar systems; Edge intelligence; Power substations; Load management; Energy sustainability

1 Introduction

IoT is currently assuming a significant role in global research, particularly in the field of sophisticated wireless communication, and is serving as the basis for a number of development applications, including smart living, smart health services, smart school education, and other areas. A wireless sensor network (WSN) is used by IoT to collect data for remote monitoring and control [1]. The hardware is made up of endpoints that are equipped with a variety of sensors to monitor and record a number of characteristics, including temperature, humidity, sun radiation, and soil moisture. These sensors may also transmit the data they collect to other devices. Due to the presence of economical, networkable micro-controller components, the IoT is seen as a crucial expertise for the creation of a smart substation [2]. IoT standards have been suggested for a number of IoT communication protocols, including CoAP, MQTT, and XMPP, however, the technology itself is still in its infancy. These procedures differ from one another in terms of their strengths and weaknesses [3]. Ultimately, as an outcome of the worldwide expertise revolution, outdated technologies are being replaced with smart ones. IoT technology is becoming more and more appealing in the power industry. It is expected that 20–50 billion objects will be universally linked to the internet by 2020 [4]. The primary goal of this effort is to create a completely automated IoT sub-station that will enable linked equipment to be inexpensively safeguarded, watched over, as well as controlled by approved staff from any place in the world. When making an agenda for a smart sub-station, consistency as well as the use of IoT technologies to reduce labor costs are also top priorities.

In the past decade, significant advancements have been made in IoT technologies within the power industry. Hossain et al. [5] introduced an IoT-driven network for managing substation equipment, enabling integration of the physical environment into digital systems with minimal human intervention, improving efficiency and accuracy. However, their approach faces challenges in scalability, security, and legacy system integration. Ullah et al. [6] established an IoT-based system for monitoring and managing substations and smart grids, using the HOMER Grid for energy utilization and power generation analysis, but it is costly and lacks efficient data processing solutions. Ramu et al. [7] explored IoT for remote monitoring of solar PV systems, addressing integration challenges in sustainable energy. Hema et al. [8] examined an IoT-enabled smart solar grid (SSG) system, covering models, standards, and architecture, but overlooked operational issues at the physical layer. Verma et al. [9] studied IoT for substation monitoring, yet did not address protocol compatibility. Despite their contributions, these studies have limitations affecting practical implementation and scalability. This research aims to develop a robust IoT-based framework to optimize solar power efficiency in automotive integration, supporting eco-friendly, energy-efficient transportation. Sutopo et al. [10] developed an IoT-based Automatic Transfer Switch (ATS) using Arduino MEGA 2560 and ESP32 to seamlessly switch between power sources. The ATS prototype achieved a 47 ms average time lag, utilizing solar energy for 26% of the usage. Sensors showed 99.8% voltage and 96.5% current accuracy, ensuring efficient energy management. Umaeswari et al. [11] optimize solar panel self-consumption in a duplex by integrating lithium-ion batteries and a thermal cooling system. Using machine learning and IoT, it reduced energy consumption to 22 kWh and 15.7 kWh per residence. Results showed significant energy savings, improved solar panel performance, and reduced electricity costs.

The remainder of the document is arranged as follows. The system model is depicted in Section 2, with the main components of the system being highlighted. The experimental setup, a working circuit schematic, results, and a commentary are shown in Section 3. This paper is finally concluded in Section 4.

2 Proposed Methodology

Every watt of electricity generated by the solar panels is continually checked in our suggested method. The system's sensors pick up on environmental changes, and Arduino processes the sensor data to determine various system characteristics. It contains a Wi-Fi component that simplifies mobile connectivity. The user always has access to these real-time parameters as they are all released to the cloud.

Figure 1 depicts a framework of the proposed method, integrating the Arduino Mega 2560 microcontroller with essential components, statistical analysis tools, and sensors. The Arduino is connected to four sensors that monitor various system aspects. A solar panel powers a battery linked to these sensors. The Arduino also connects the ESP8266 to an LCD display. Figure 2 presents a flow diagram of the system process. First, the Arduino powers on and establishes an internet connection [12]. If the connection fails, an error message is sent. Once connected, an IP address is assigned. The system then receives input from the solar panel, and the sensors relay this data to the Arduino. The Arduino processes the data and uploads it to the cloud, displaying the parameters on the LCD and enabling access via a mobile application [13].

2.1 IoT-Based Remote Monitoring

A PV system consists of a solar panel connected to a battery for power storage, along with a charge controller and inverter for AC power. PV arrays are formed from interconnected PV modules, which generate DC power. Adjustable DC voltages can be produced using converters like boost, SEPIC, buck-boost, and Luo converters. Voltage source inverters convert this DC power to AC, which can be utilized by distinct loads or supplied to the grid, with battery storage being essential in certain situations.

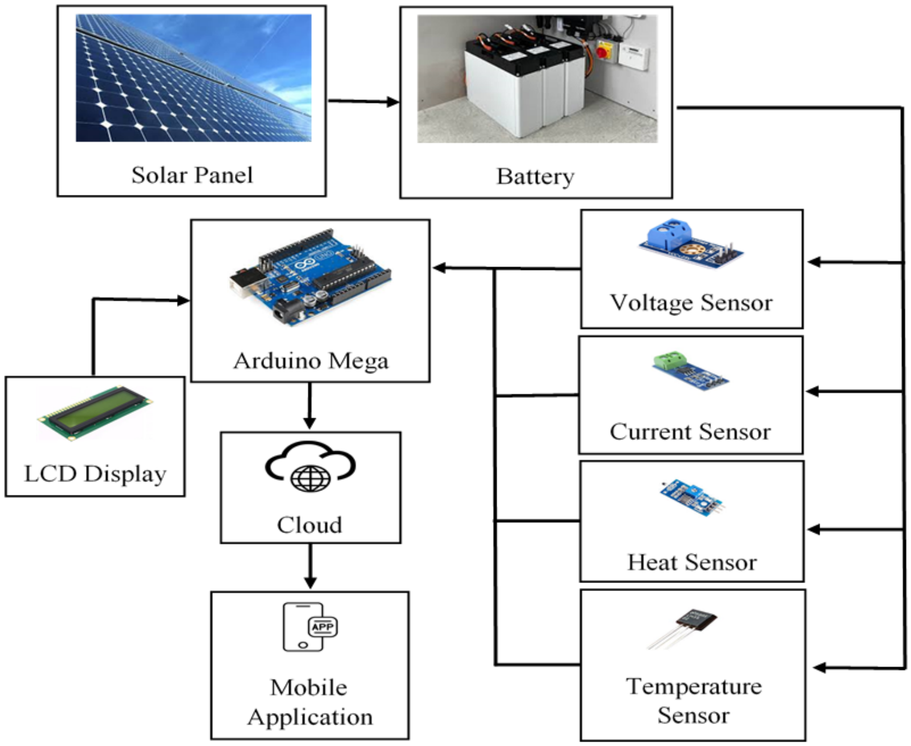

Fig 1. Block Diagram

The IoT-based PV monitoring scheme, illustrated in Figure 3 [14], includes three layers: PV system construction, communication linkages, and remote control and monitoring. The first layer involves setting up the equipment to meet user needs. The second layer connects various components of the PV system to a remote server via internet firewalls and routers, with the Arduino server managing these connections. The Arduino microcontroller oversees and regulates the functions of the PV hardware. The final layer enables users to monitor the system and review reports, receiving data from the second layer. Customers can access this information through an Android app and cloud services, allowing retrieval in reports or visual charts.

Figure 3 depicts an IoT-based solar power management and monitoring system that integrates various components for efficient energy utilization. The solar panel captures sunlight and converts it into DC electricity, which is then regulated by the chopper (a DC-DC converter) to maintain a stable voltage. The generated energy is retained in the battery for future use. When needed, the inverter converts the stored DC power into AC power to supply the AC load, which represents household or industrial devices that require AC power. A smart meter measures energy consumption and sends this data to the central system for monitoring. The Arduino microcontroller collects data from sensors and controls system components, while the router connects the system to the internet, allowing data transmission to remote servers. For security, an internet firewall protects the data being transmitted. The remote monitoring system displays real-time data and provides control options, while the data storage component securely stores historical data in the cloud for analysis and future reference. The system can also interact with the electric grid, either feeding excess energy back to the grid or drawing additional power when necessary. This setup ensures efficient energy management, enhanced monitoring, and optimized power distribution in smart solar installations.

3 Experimental Setup

This project utilizes hardware and software from a charge controller, 50 W solar photovoltaic (PV) array, DC load, auto-moving PV array base, inverter, 12V DC solar battery, light sensors, motors, and IoT sensors.

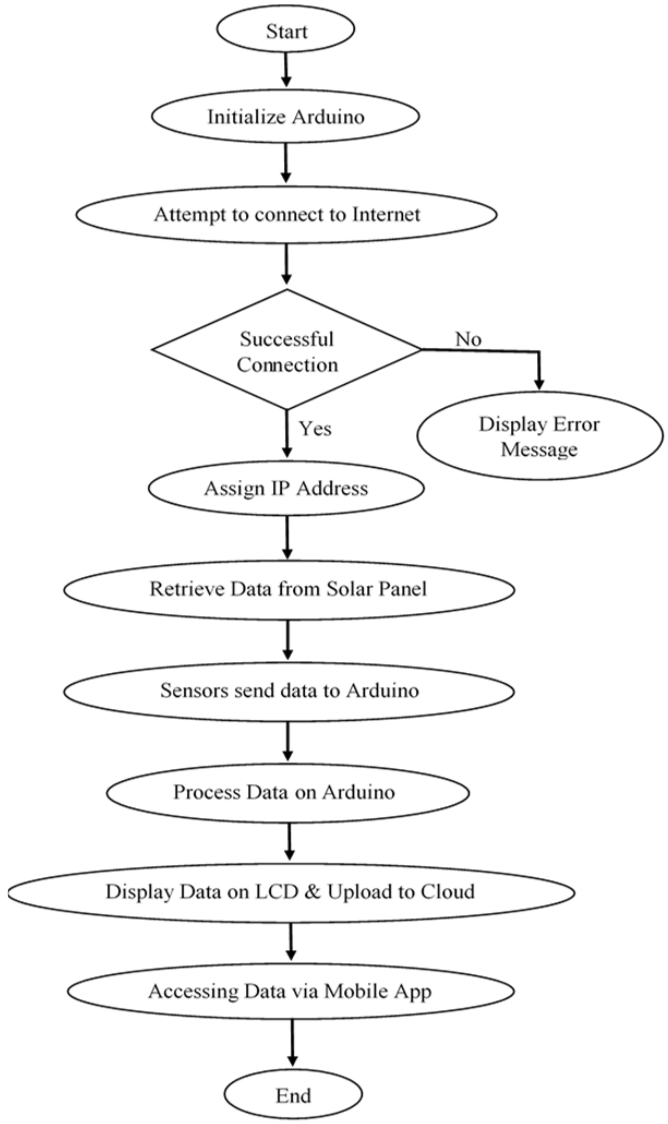

Fig 2. Process Diagram for the Suggested Method

3.1 Hardware Design

A solar panel, commonly referred to as a PV module, consists of PV cells arranged within a framework. These solar cells capture energy from sunlight to generate electricity, converting DC energy from sunlight [15]. PV modules can be connected in parallel or series to provide the required current and voltage for specific systems. Typically, a solar module contains six by ten solar cells, with variations in output wattage and efficiency depending on the type and quality of the cells used. Solar module energy output can range from 100 to 365 DC watts, with higher-wattage modules producing more energy. Thus, a solar array made up of high-energy-producing components generates more electricity in less space compared to one made of lower-energy components, although the former comes at a higher cost. While monocrystalline solar panels are the original PV technology, they now face competition from polycrystalline silicon and next-generation thin-film technologies, providing consumers with various options based on flexibility, durability, efficiency, and cost [16]. The photovoltaic effect generates energy as materials like silicon absorb sunlight and produce electrical current. To connect an Arduino UNO to an LDR for light detection, two LDR driver circuits were designed, as shown in Figure 4 [17].

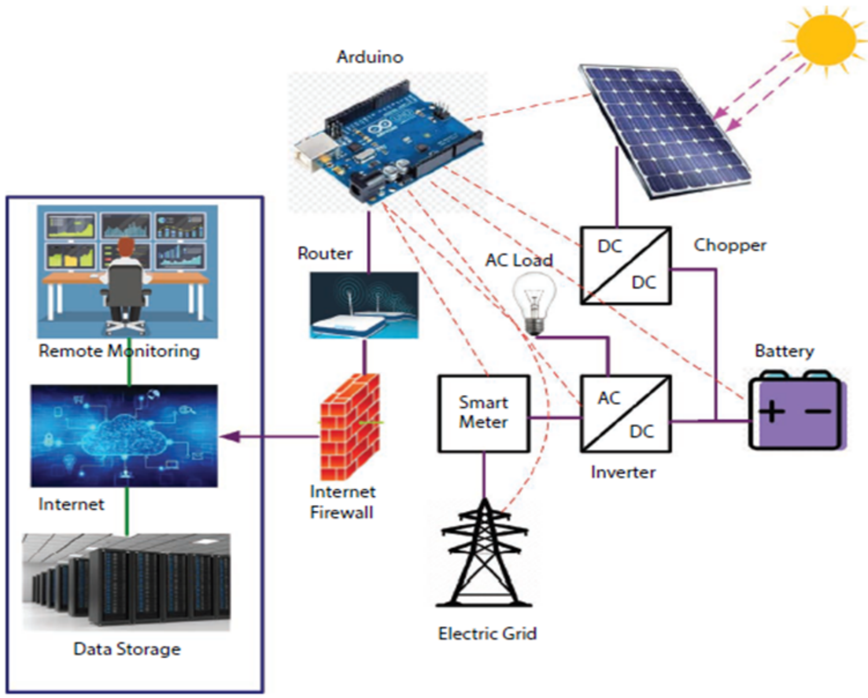

Fig 3. IoT-based PV system monitoring

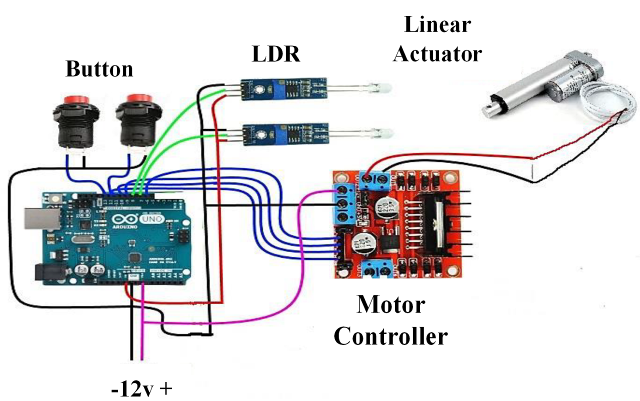

Fig 4. LDR schematic

The linear actuator sequence for light identification was designed with a speed of 20 mm/s, a torque of 500 N, a working voltage of 12V DC, and a lever length of 150 mm, making it an effective prime mover for the application. The digital setup includes sensors for inputs, Arduino UNO kits for processing signals, and linear actuators for generating outputs.

3.1.1 Arduino

The ATmega328 is an Advanced Virtual RISC (AVR) microcontroller proficient in processing eight bits of data and features 32 KB of built-in flash memory. It includes 1 KB of programmable read-only electrically erasable memory (EEPROM), allowing it to store data even when power is lost, and 2 KB of Static Random-Access Memory (SRAM). Due to its various features, the ATmega328 is the most widely used microcontroller today. Notable features include configurable Serial USART, software security programming lock, a real-time counter with a separate oscillator, low power consumption, and a throughput of up to 20 MIPS[18]. Its high adaptability, familiarity, and ease of use make the ATmega328 a popular choice for connecting solar panels and IoT applications. Figure 5 shows that the ATmega328 requires a 5-volt DC source to operate.

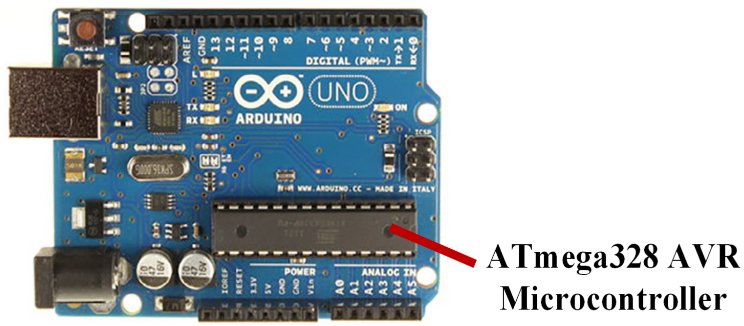

Fig 5. ARDUINO Mega 328

3.1.2 Voltage as well as current sensor

A voltage sensor (VS) is a tool utilized to measure and compute an entity's total voltage. VS can identify both AC and DC voltage levels, using voltage as the input as well as producing output signals such as switches, analog voltage, current, or audio signals. These sensors measure the entire power used up by the shunt load as well as then transmit digital data to the ATmega328, functioning as both a power and current monitor. The AT Super 328, with the coder uploaded in it, computes the most recent reading of the shunt load.

3.1.3 Wi-Fi module

Every computed data is processed by the AT Mega 328 (ESP8266) via a Wi-Fi component shown in Figure 6, and then it is stored on an IoT cloud or server. We use the well-known IoT platform Thing Speak to examine this data on a weekly, monthly, and frequent basis.

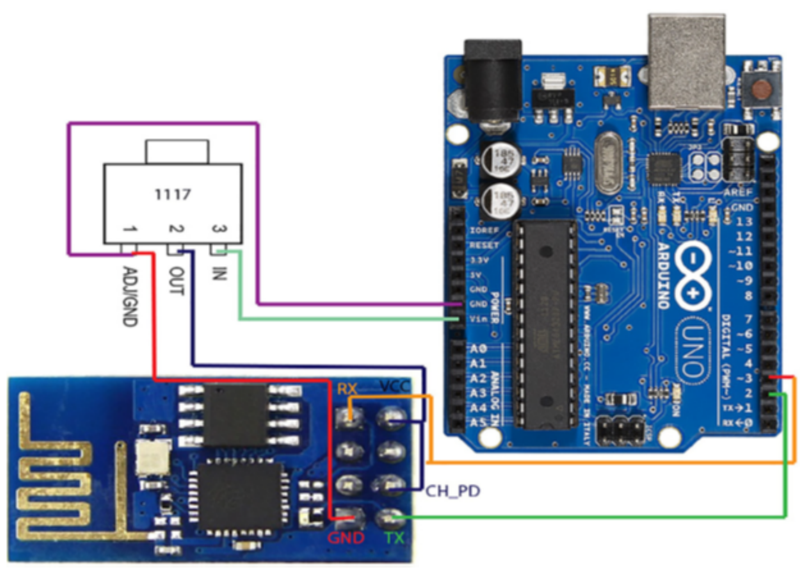

Fig 6. Wi-Fi Module

4 Results and Discussion

The device has two displays: a built-in LCD screen and a mobile app for specific purposes, both of which provide real-time results. As a local interface, the LCD display allows users present on the premises instant access to the system's output. In parallel, a custom mobile application communicates with the cloud infrastructure to retrieve and provide real-time data to users who are logging in from a distance. With the help of this cloud connectivity, the mobile app's information is constantly updated, providing a dynamic and all-encompassing perspective of the system's output. The mobile interface is easy to use and adapts to different devices, making it easy to monitor and engage with the real-time outcomes of the system. Security controls to protect data integrity and restrict user access to sensitive information are probably also in place. All things considered, this integrated strategy improves user accessibility and system functionality by fusing the flexibility of remote access via the mobile application with the ease of on-site monitoring through the LCD display.

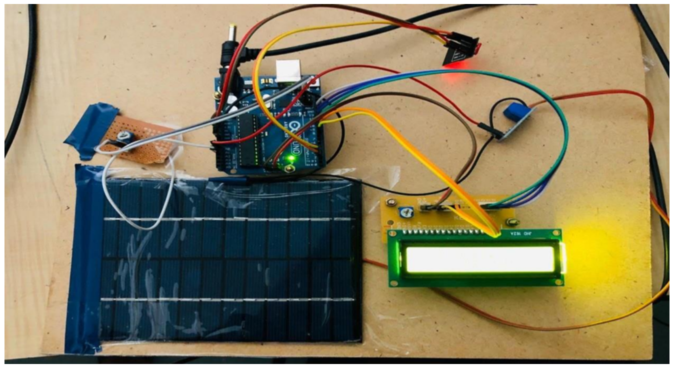

Fig 7. Proposed Approach Prototype with Results

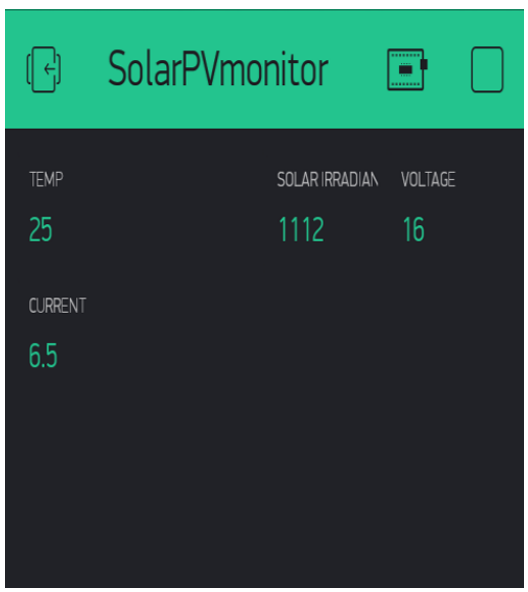

Fig 8. Real-Time Results over Mobile Application

Figure 7 and Figure 8 showcase the prototype and real-time results of the proposed approach via a mobile application. Figure 7 illustrates the physical prototype, highlighting the integration of sensors, Arduino components, and other essential hardware for monitoring solar panel parameters. In contrast, Figure 8 displays the mobile application interface, demonstrating the real-time data obtained from the prototype. Users can access crucial information like voltage, current, and temperature of the solar panels directly through the app. This mobile integration allows users to remotely monitor and manage their solar panels, contributing to efficient electricity usage and control.

Figure 9 displays real-time data for voltage, current, and temperature on a mobile interface, with information seamlessly uploaded to the cloud for remote access. Users can monitor the system's performance from anywhere, with continuously updated data providing insights into operational status and trends. The mobile interface's user-friendly design enables easy navigation and interpretation, enhancing the monitoring experience and supporting effective decision-making.

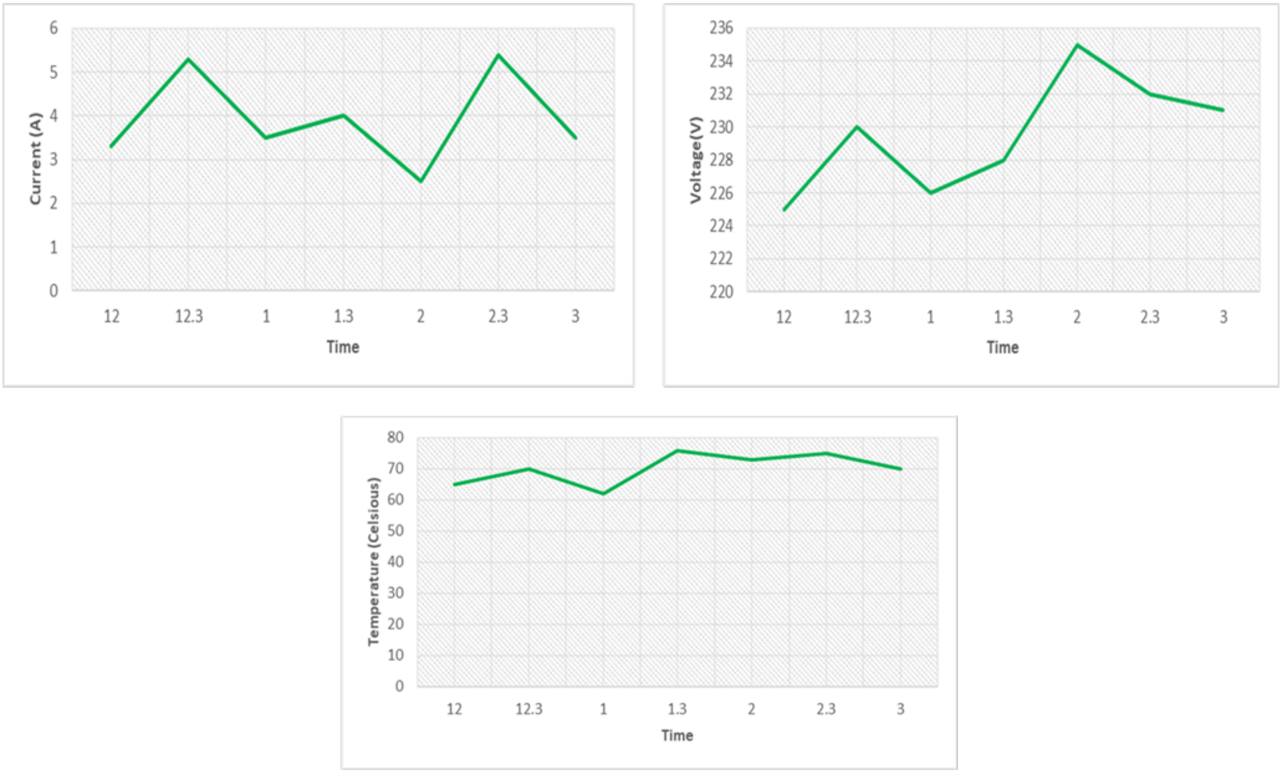

Fig 9. Profile of Current,Voltage, and Temperature

4.1 Comparative Analysis of Proposed Work

Table 1. A comparison of controllers used in IoT solar power tracking devices

Criteria	Arduino Mega 2560 [19]	Arduino Uno [20]	ESP8266 [21]	AT Mega 328
Processing Power	High	Low	High	High
Cost	$38.72	$27.65	$5.45	$5.00
Power Consumption	Minimal	Minimal	Minimal	Minimal
Wireless Capability	Requires shield	Requires shield	Integrated Wi-Fi	Integrated Wi-Fi
Additional Features	Extensive I/O	Limited I/O	Combined ADCs	Basic I/O

Table 1 compares various microcontroller platforms, including the Arduino Mega 2560, Arduino Uno, ESP8266, and the proposed ATmega328. The Arduino Mega 2560 offers high processing power but is priced at $38.72, which may hinder its adoption in budget-sensitive applications. Previous work by Rouibah et al.[19] emphasizes that cost-effective solutions can enhance accessibility to solar technologies. In contrast, the ATmega328 is priced at just $5.00, providing an economical alternative without compromising functionality. Both the ESP8266 and the ATmega328 feature integrated Wi-Fi capabilities, facilitating easier deployment in IoT environments. López-Vargas et al.[20] highlighted the effectiveness of Arduino with 3G for real-time solar monitoring, though traditional models require additional shields, complicating installations. The ATmega328's integrated wireless features simplify this, making it ideal for smart solar energy management systems (Shahed et al.,[21]).

All models exhibit minimal power consumption, consistent with existing literature. However, the ATmega328's combination of low cost, integrated wireless capabilities, and sufficient processing power offers a unique advantage, provides solution for energy management in smart buildings and industrial applications. Overall, our findings suggest that the ATmega328 is a viable alternative to existing platforms, addressing previous limitations while balancing cost, power consumption, and functionality.

5 Conclusion

The proposed IoT-based system with integrated edge intelligence offers a novel and advanced solution for power production prediction and monitoring in industrial IoT environments. Its unique combination of real-time data analysis, edge computing, and cloud integration enables rapid decision-making and increases power distribution efficiency and reliability, achieving a 95% cost reduction compared to traditional controllers like Arduino Mega 2560 and Arduino Uno. This system's remote monitoring of voltage, current, and temperature parameters significantly enhances energy management in smart buildings and Industry 4.0 applications, promoting sustainability, safety, and the circular economy.

The integration of edge intelligence with IoT sets a new standard for real-time predictive capabilities and adaptive energy management, differentiating this system from conventional solutions through its high efficiency and scalability. Future developments could expand the system to accommodate larger data loads and additional devices, ensuring seamless scalability and optimized use of edge computing resources in more complex industrial and residential settings.

Recommendations

To further advance this system, it is recommended to explore the implementation of advanced machine learning models and more robust edge devices to enhance predictive accuracy and system resilience. Additionally, developing new architectures and protocols for efficient data handling and processing would facilitate a smarter, more sustainable energy management ecosystem.

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