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Efficiency Maximization: Real-Time Solar Panel Monitoring with Bluetooth Connectivity

Abstract *This article thoroughly examines the integration of Bluetooth technology and the Internet of Things (IoT) in the real-time monitoring of solar panels, highlighting their essential contribution to improving efficiency and reliability. Our research utilises Bluetooth connectivity to develop efficient communication channels that connect individual solar units to a centralised monitoring station; this enables the wireless transmission of crucial performance data such as temperature, voltage, and current. Our system uses Arduino microcontrollers and sensors to acquire data, enabling real-time analysis and presentation of essential indicators and ensuring efficient and effective monitoring; moreover, evidence confirms that HC-05 Bluetooth modules effectively facilitate strong and reliable connectivity. Furthermore, our research presents a PV monitoring system that utilises IoT technology, focusing on simplicity and cost-efficiency. This comprehensive system measures solar irradiance, ambient temperature, PV output voltage, and current; it redundantly stores data on MicroSD cards to prevent potential data loss. This system achieves enhanced dependability, precision, and cost-effectiveness, indicating notable progress in solar panel monitoring technology.*

Streszczenie. *W artykule szczegółowo zbadano integrację technologii Bluetooth i Internetu rzeczy (IoT) w monitorowaniu paneli słonecznych w czasie rzeczywistym, podkreślając ich istotny wkład w poprawę wydajności i niezawodności. Nasze badania wykorzystują łączność Bluetooth do opracowania wydajnych kanałów komunikacji, które łączą poszczególne jednostki fotowoltaiczne ze scentralizowaną stacją monitorującą; umożliwia to bezprzewodową transmisję kluczowych danych dotyczących wydajności, takich jak temperatura, napięcie i prąd. Nasz system wykorzystuje mikrokontrolery i czujniki Arduino do pozyskiwania danych, umożliwiając analizę w czasie rzeczywistym i prezentację istotnych wskaźników oraz zapewniając sprawny i skuteczny monitoring; co więcej, dowody potwierdzają, że moduły Bluetooth HC-05 skutecznie zapewniają silną i niezawodną łączność. Ponadto nasze badania przedstawiają system monitorowania fotowoltaiki, który wykorzystuje technologię IoT, kładąc nacisk na prostotę i efektywność kosztową. Ten kompleksowy system mierzy natężenie promieniowania słonecznego, temperaturę otoczenia, napięcie wyjściowe fotowoltaiki i prąd; nadmiarowo przechowuje dane na kartach MicroSD, aby zapobiec potencjalnej utracie danych. System ten zapewnia większą niezawodność, precyzję i opłacalność, co wskazuje na znaczny postęp w technologii monitorowania paneli słonecznych.* (**Maksymalizacja wydajności: monitorowanie paneli słonecznych w czasie rzeczywistym z łącznością Bluetooth)**

Keywords: Photovoltaic Panel, Sensors, Arduino**,** Bluetooth, App-Inventor.
Słowa kluczowe: Panel fotowoltaiczny, czujniki, Arduino, Bluetooth, App-Inventor.

Introduction

There has been a significant global rise in the use of solar energy in recent years, driven by the increasing need for renewable energy sources [1]. Solar panels are crucial in generating solar energy since they capture sunlight and transform it into environmentally friendly electricity [2]; nevertheless, monitoring consistently and meticulously analysing data is imperative to effectively operate and maintain solar panels, ensuring optimal performance and maximum energy production [3]. Efficient monitoring of solar panels is crucial in optimising their effectiveness and output [4]; scholars have recently examined various communication protocols for the wireless assessment of solar panel characteristics [5], [6], and the utilization of Bluetooth technology has garnered interest due to its cost-efficient nature and practical data transmission capacity; plant managers and owners can utilise the advanced capabilities of this innovative system, including real-time monitoring and data analytics, to supervise the performance and effectiveness of their solar panels remotely [7], [8]. Promptly detecting problems or suboptimal panel functioning greatly streamlines maintenance procedures and drastically minimises operational downtime; identifying and correcting faulty components is essential for maximising energy production and maintaining system effectiveness.

This work demonstrates a novel Internet of Things (IoT) technology application to transfer parameter data from solar panels to a smartphone application [1]. This study presents a sophisticated monitoring framework that uses the adaptable Arduino platform; the Arduino Uno board uses many sensors to measure important variables such as voltage, current, and solar panel temperature. The Arduino's analogue pins are connected to sensors, enabling real-time data capture. The data is stored on an SD card, and the processed data is a useful asset for academics, allowing them to evaluate the technological features of photovoltaic (PV) systems. By incorporating an Android interface, users can improve their decision-making skills, enabling them to personalise the system for optimal effectiveness. The system's capacity to adjust to the scalability of solar systems renders it a significant resource for operators of solar power facilities; it enables the effortless integration of additional panels and monitoring equipment while expanding the facility, guaranteeing a streamlined expansion procedure. Using Bluetooth-enabled devices like smartphones and tablets allows solar plant operators and technicians to communicate effectively, resulting in significant benefits, this functionality obviates the necessity for expensive and time-intensive on-site examinations, rendering it especially beneficial for expansive solar farms in isolated areas. This study aims to improve this field by examining the efficacy of Bluetooth connectivity in real-time solar panel monitoring and assessing its advantages and limitations compared to other communication-protocols. The objective of this study is to employ a systematic evaluation to provide significant insights that could enhance the efficacy of solar panels. It considers the compromises between cost, speed, and coverage range inherent in various wireless communication methods.

2. Related works

Numerous prior research projects have examined the creation of efficient communication protocols for monitoring solar panels, leading to a diverse range of wireless transmission techniques. Scientists have investigated the use of cellular-based communication and Ethernet connectivity, as well as Bluetooth, WiFi, and radio frequency technologies, such as Zigbee and MiWi, for transmitting solar panel data.

Siregar *et al.* [9] and Nkoloma *et al.* [10] have shown that solar panel data may be efficiently transmitted using existing cellular networks for cellular communication, this method offers extensive coverage and scalability for transmitting data across large distances, however, remote areas with restricted network availability and potential recurrent charges for mobile data may provide challenges. A thorough investigation carried out by Wu *et al*. [11], Chao *et al*. [12], and Shariff *et al*. [13] analysed the utilisation of the Zigbee protocol for sending data from solar panels, zigbee, employing radio frequency, has demonstrated exceptional efficiency in data transmission rate and coverage span, reaching up to 50 metres. The study highlighted the suitability of using localized solar panel arrays near devices, ensuring efficient and dependable data transmission; however, radio frequency costs increase as the desired coverage area expands. According to Himri *et al*. [14], and Ibraheem Al-Naib *et al*. [15], WiFi technology offers faster data transfer speeds and greater range capabilities than Bluetooth; the enhanced speed and extended coverage of WiFi make it an attractive option for circumstances that require fast and extensive data distribution.

The present study aims to evaluate and highlight the significance of Bluetooth technology in the live monitoring of solar panels; Wi-Fi provides remarkable speed and coverage, while Bluetooth excels in energy efficiency, cost-effectiveness, and installation convenience, particularly in scenarios where power conservation and streamlined communication are crucial. The choice between Bluetooth and Wi-Fi for solar panel monitoring depends on the system's specific requirements, considering data transfer speed, range, power consumption, and installation complexity.

Integrating Bluetooth technology into Arduino microcontrollers is especially noteworthy for its robust and dependable characteristics, offering versatility, cost-effectiveness, and operational efficiency; the amalgamation investigated in this study provides a wide range of benefits compared to alternative approaches. Previous studies, exemplified by utilising Wi-Fi and Zigbee protocols, showcase commendable attributes. However, incorporating Bluetooth with Arduino offers a captivating fusion; the efficacy of this integrated system relies on its ability to sustain cost-efficient and energy-conserving operations and its adaptability and scalability for diverse monitoring setups. This integration facilitates the swift collection and analysis of data by academics and experts in real-time, ensuring optimal performance and output from solar panels while managing resource constraints; this research aims to emphasise the integrated strategy's superiority by conducting empirical analysis, demonstrating its effectiveness in creating a harmonious combination of cost, energy efficiency, adaptability, and ease of implementation.

3. Method

This section will offer an in-depth analysis of the photovoltaic (PV) system, as seen in Figure 1. The PV system comprises two fundamental components: sensors and monitoring. The hardware circuits play a vital role in this system, integrating sensors intricately connected to an amplifier circuit to ensure precise measurements; furthermore, the hardware comprises the Arduino UNO microcontroller and HC-05 Bluetooth module, establishing a cohesive sensor system. The primary objective of this system is to efficiently obtain and evaluate data from the sensors, facilitating real-time monitoring of the solar panel's performance.

To enhance data management, the system incorporates an SD card. The SD card is a reliable storage solution, allowing the PV system to save and retrieve data effortlessly, ensuring uninterrupted data continuity and analysis. In addition, the system is equipped with a real-time clock (RTC) module, which plays a crucial role in guaranteeing the precision of time records and enabling accurate timestamping of the collected data. The RTC module ensures that the system not only monitors the real-time performance of the solar panel but also accurately records the time aspect. Conversely, the monitoring component is a crucial element that includes a sophisticated smartphone application built to monitor the system continuously.

The PV system delivers accurate and instantaneous data collection by efficiently integrating the sensors, SD card for data storage, and real-time clock module. Furthermore, it offers a user-friendly interface via a smartphone application. This collaboration ultimately contributes to maximising efficiency in monitoring solar panels, rendering it a smart and user-friendly solution for individuals seeking optimal performance from their photovoltaic systems.

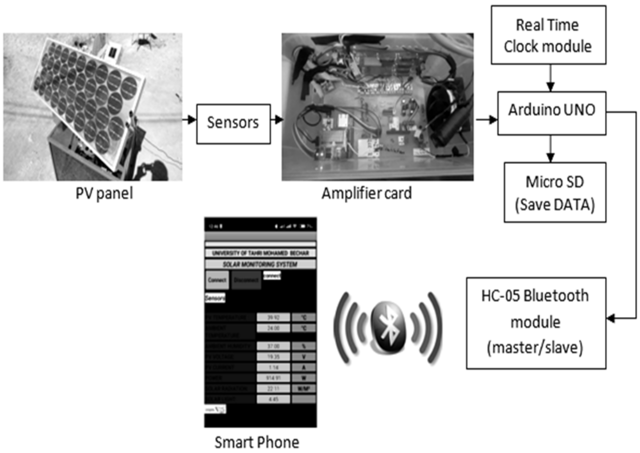


Fig.1. Full monitoring system diagram of photovoltaic (PV) system

3.1. Hardware development of the system

In this report, we provide a comprehensive analysis of the hardware design development of the system and its numerous trial deployments. We have recently achieved a significant milestone by effectively integrating the many modules comprising the electronic components of the sensors. Figure 2 presents a comprehensive depiction of the electronic components employed in our project, conveyed through a meticulously documented schematic. The conversation can be organised using many subdivision

3.2. Arduino Uno board

Arduino Uno is a widely used microcontroller board in electronics. It is based on the ATmega328P microcontroller [16] which operates at 16MHz. It has a variety of input and output pins, including 14 digital input/output (I/O) pins, of which six can be used as pulse-width modulation (PWM) outputs [16]. Moreover, 6 analogue input ports allow users to interface with various analogue sensors and devices. This adaptability makes it ideal for electronic circuit prototyping and experimentation.

3.3. The temperature of the solar panel (PV)

We used an LM35 temperature sensor to calculate the solar panel's temperature. The LM35 sensor is commonly used to measure temperatures between -55°C and +150°C [17]. To obtain accurate measurements, we inserted a TL084 operational amplifier (AOP) with continuous voltage capability between the LM35 sensor and Arduino.

The TL084 operational amplifier can provide a gain of up to 3.2, resulting in a change in the voltage applied to the Arduino A0 input. This results in a voltage applied to the A0 port of the Arduino that is 32 mV per °C rather than the 10 mV per °C provided by default by the LM35 sensor. Figure 2 depicts the LM35 connection circuit to the TL084 operational amplifier (AOP), which calculates the voltage Vs applied to the Arduino's A0 pin by equation (1).

$$V_s = \left(1 + \frac{R_4}{R_2}\right).V_e = 3{,}2.V_e \quad (1)$$

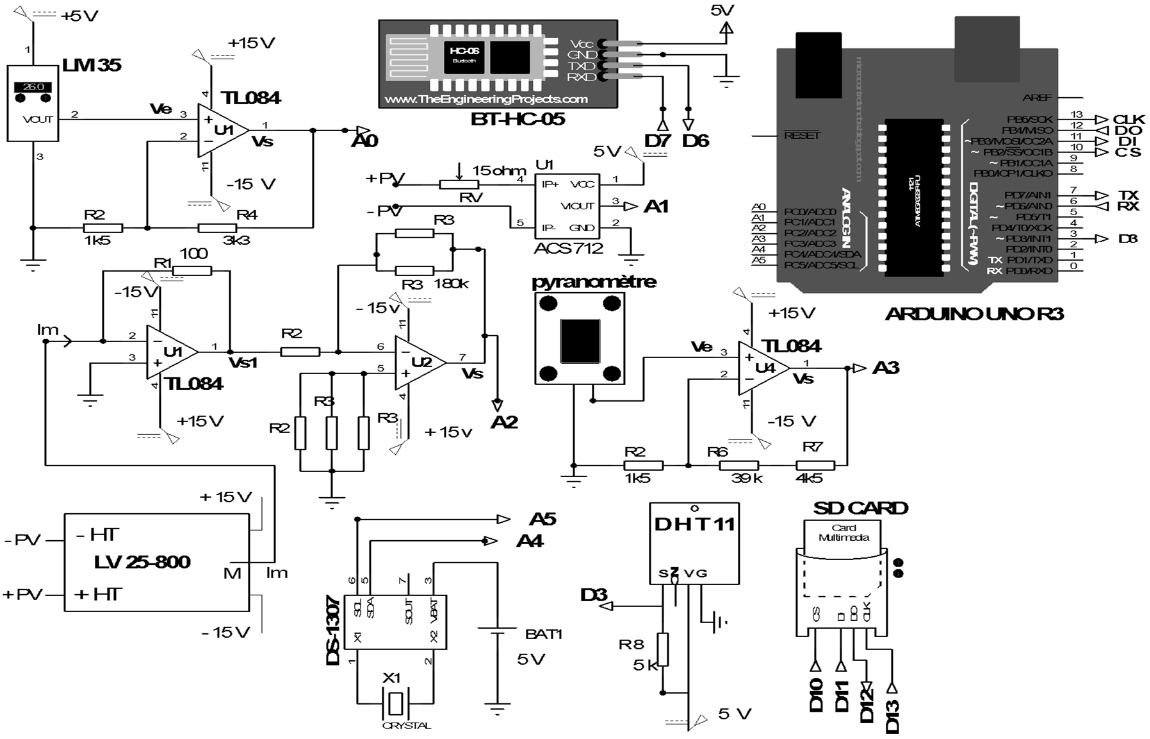


Fig.2. The Amplifier Card's Global Scheme

3.4. Ambient temperature and humidity of the solar panel

The DHT11 sensor is created to offer a calibrated digital output for sensing the surrounding temperature and humidity. The device features three pins: Vdd for power supply, D0 for data transmission to the Arduino, and a ground (GND) connector. The sensor's humidity measurement component is resistive, providing a humidity measurement range of 20% to 90% with an accuracy of 5%. The device has a Negative Temperature Coefficient (NTC) temperature measurement component that can measure temperatures from 0°C to 50°C with an accuracy of 2% [18]. The sensor is powered by a voltage range of 3.3V to 5V. The DHT11 sensor transmits 40 bits of data during operation, which includes temperature and humidity information. We will gather data from the DHT11 sensor by linking it to pin D3 of the Arduino.

3.5. The solar panel (PV) voltage

The primary challenge when measuring the voltage at the terminals of a photovoltaic panel is that the voltage can exceed the 5V range that the Arduino circuit is designed to handle. One possible solution to this issue is employing an LV 25-800 voltage sensor designed for direct current and alternating current (DC/AC) voltage measurement. This sensor offers galvanic isolation, ensuring separation between the primary circuit (high voltage side) and the secondary circuit (electronic circuit side), enabling accurate voltage measurements even if they exceed 5V.

The LV 25-800 sensor generates a current proportional to the input voltage, increasing by 25mA for every 800V, with a precision of +/- 0.8% [19]. A direct current (DC) voltage inverting amplifier with a gain of 60 is introduced between the current-voltage converter and the Arduino to achieve precise voltage measurements. This setup modifies the current from 25mA per 800V to 150V per 800V and is then connected to the A2 analogue input channel of the Arduino. This circuit uses the TL084 operational amplifier (AOP) as a current-voltage inverting amplifier, the output curent $\mathrm{I_m}$ from the LV- 25-800 sensor is converted into a voltage as described by(2).

$$V_{s1} = -\mathrm{I_m}.R_1 = -\mathrm{I_m}.100 \quad (2)$$

Where V_{s1} represents the voltage at the output of the current-voltage converter, $\mathrm{I_m}$ is the current generated by the LV 25-800 sensor, and is R the value of the resistor in the circuit. The voltage of this specific channel can be determined using (3), which describes the conversion and amplification process illustrated in Figure 2.

$$V_s = -\left(\frac{\mathrm{R3}}{\mathrm{2.R2}}\right).\mathrm{V_{s1}} = 6000.\mathrm{I_m} \quad (3)$$

3.6. The solar panel (PV) output current

The solar panel (PV) module's output current is effectively measured using an ACS712 current sensor. Based on the Allegro ACS712 ELC chip, this particular sensor is adept at measuring both DC and AC currents of up to 5A. Its exceptional features include high sensitivity and precision, making it a reliable choice for accurate measurements. The sensor boasts an accuracy of ±1.5%, and its sensitivity is rated at 180mV/A [20]. The ACS712 current sensor provides an analogue voltage output to interface with the Arduino board. The sensor module is designed to operate at a 5V supply, which the Arduino itself conveniently provides. The output reference voltage of the sensor is set at 2.5V [1] to enable measurement and data acquisition; the output from the ACS712 current sensor is connected to the analogue input channel A1 of the Arduino. This analogue input allows the Arduino to read the voltage output from the sensor, which is then converted into corresponding current values using the sensitivity and calibration information provided by the sensor's datasheet. Overall, this setup facilitates measuring and monitoring the output current of the solar panel(PV) module, enabling accurate and reliable data collection for further analysis or control applications.

3.7. Solar Radiation Sensing

A pyranometer, illustrated in Figure 2, is utilised for measuring global solar radiation (E_g) on the surface of the PV panel. The electrical response from the pyranometer V_{mes} can be converted into solar radiation (E_g) using the (4) provided below.

$$E_g = \frac{1000}{101.5} V_{mes} (w/m^2) \tag{4}$$

For more accurate solar radiation measurements, a TL084 operational amplifier (AOP) with a gain of 30 can be incorporated between the pyranometer sensor and the Arduino's Analog-to-Digital Converter (ADC). This setup modifies the voltage applied to the input of the Arduino. Initially, the voltage conversion was 101.5mV per 1000w/m², but with the addition of the TL084, the voltage conversion becomes 3045mV per 1000w/m². The output from the TL084 is then connected to the analogue input channel of the Arduino. The applied voltage $v_s$can be calculated using equation (5).

$$v_s = v_e.\left(1 + \frac{R6+R7}{R2}\right) = 30.v_e \tag{5}$$

3.8. The Real-Time Clock (RTC) DS1307

The Real-Time Clock (RTC) DS1307 module comprises a crystal oscillator and a 3V battery [21]. The battery ensures that the RTC module remains powered even when the Arduino is turned off, thereby preserving the time data in memory. The module supports a power supply ranging from 1.8V to 5V and provides information such as seconds, minutes, and hours.

We need to follow these steps to establish a connection between our RTC and the Arduino. First, connect Arduino's power output pin (5V) to the module. Next, connect the serial data line (SDA) pin to A4 and the serial clock line (SCL) pin to A5 on the Arduino.

3.9. Bluetooth Shield HC-05

It is possible to employ a Bluetooth shield to transmit sensor data from an Arduino board to a mobile device [22]. The Bluetooth shield enables the establishment of the connection between the Arduino microcontroller and a mobile phone through Bluetooth technology. By establishing a connection between the sensors and the Arduino board and implementing suitable programming, it becomes feasible to retrieve data from the sensors and transmit it to the phone using wireless means [22]. Regarding telephony, it would be necessary to create a software application compatible with Bluetooth technology capable of receiving and deciphering the data transmitted by the Arduino device. In this manner, it becomes feasible to actively observe and exhibit real-time sensor data on a mobile device.

4. Results and discussion

App Inventor provides a user-friendly drag-and-drop interface, which enhances its usability for individuals with limited programming proficiency. Solar plant operators can readily develop tailored applications for monitoring and management needs. The inherent flexibility of App Inventor facilitates the development of intuitive and user-friendly interfaces, effectively presenting real-time data in a visually captivating manner. App Inventor allows the application to be connected to the solar panel monitoring system via Bluetooth or alternative wireless communication protocols. The application can access and collect up-to-date information from individual solar panels, encompassing voltage, current, temperature, and power production data.

Figure 3 illustrates two main procedures. Figure 3(a) is a flowchart illustrating the Arduino UNO procedure. The microcontroller's operation is summarised in this flowchart, from reading sensor values to writing them to a microSD card to sending them over Bluetooth to the user. The Android app's flowchart is shown in Figure 3(b). This flowchart depicts the operation of the photovoltaic (PV) system application, emphasizing the transfer of measurement data from the sensor circuit to the user's smartphone interface.

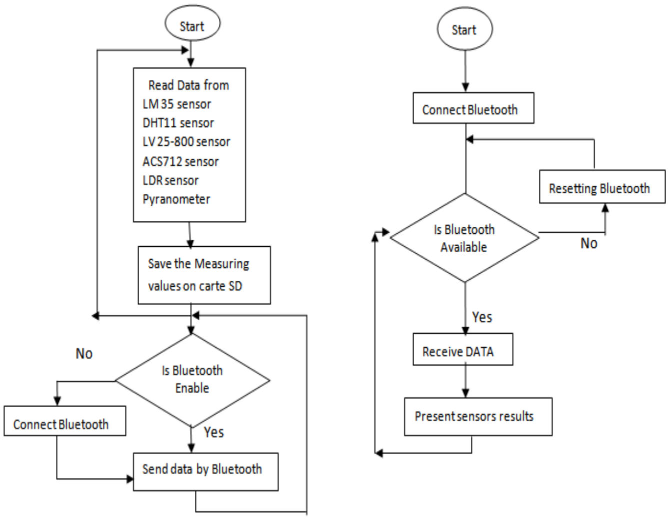
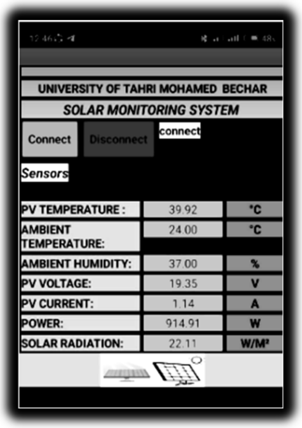


Fig.3. Flowchart of the system: (a) Sensors circuit, (b) Smartphone application flowchart

This data is then presented to users in real-time, enabling prompt responses to performance deviations, as seen in Figure 4. Saving sensor values on a microSD card offers significant advantages for regularly and precisely monitoring the solar system's performance in Figure 5. Storing data on the memory card facilitates valuable long-term analyses, extracting useful results and ultimatelyimproving the system's efficiency and sustainability over time. Furthermore, this data becomes crucial in promptly identifying any performance issues in the system, enabling



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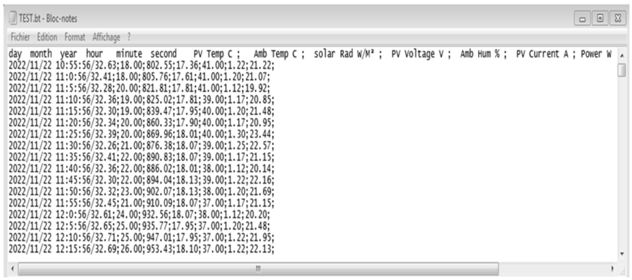
SOLAR MONITORING SYSTEM

PV TEMPERATURE :	39.92	°C
AMBIENT TEMPERATURE:	24.00	°C
AMBIENT HUMIDITY:	37.00	%
PV VOLTAGE:	19.35	V
PV CURRENT:	1.14	A
POWER:	914.91	W
SOLAR RADIATION:	22.11	W/M²

Fig.4. Android App



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day  month  year  hour   minute  second   PV Temp C ;   Amb Temp C ;  solar Rad W/M² ;  PV Voltage V ;  Amb Hum % ;  PV Current A ; Power W
2022/11/22 10:55:56/32.63;18.00;802.55;17.36;41.00;1.22;21.22;
2022/11/22 11:0:56/32.41;18.00;805.76;17.61;41.00;1.20;21.07;
2022/11/22 11:5:56/32.28;20.00;821.81;17.81;41.00;1.12;19.92;
2022/11/22 11:10:56/32.36;19.00;825.02;17.81;39.00;1.17;20.85;
2022/11/22 11:15:56/32.30;19.00;839.47;17.95;40.00;1.20;21.48;
2022/11/22 11:20:56/32.34;20.00;860.33;17.90;40.00;1.17;20.95;
2022/11/22 11:25:56/32.39;20.00;869.96;18.01;40.00;1.30;23.44;
2022/11/22 11:30:56/32.26;21.00;876.38;18.07;39.00;1.25;22.57;
2022/11/22 11:35:56/32.41;22.00;890.83;18.07;39.00;1.17;21.15;
2022/11/22 11:40:56/32.36;22.00;886.02;18.01;38.00;1.12;20.14;
2022/11/22 11:45:56/32.30;22.00;894.04;18.13;39.00;1.22;22.16;
2022/11/22 11:50:56/32.32;23.00;902.07;18.13;38.00;1.20;21.69;
2022/11/22 11:55:56/32.45;21.00;910.09;18.07;37.00;1.17;21.15;
2022/11/22 12:0:56/32.61;24.00;932.56;18.07;38.00;1.12;20.20;
2022/11/22 12:5:56/32.65;25.00;935.77;17.95;37.00;1.20;21.48;
2022/11/22 12:10:56/32.71;25.00;947.01;17.95;37.00;1.22;21.95;
2022/11/22 12:15:56/32.69;26.00;953.43;18.10;37.00;1.22;22.13;
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Fig.5. Saving sensor values on an SD card

quick interventions to maintain optimal performance. By leveraging this information, users can make informed decisions to tackle problems and ensure the solar system operates at its highest potential.

CONCLUSION

To summarise, the combination of Arduino and Bluetooth technology, specifically the HC-05 module, offers a revolutionary method for enhancing the effectiveness of solar panel systems. The setup's real-time monitoring capabilities enable users to make well-informed decisions, ensuring the most efficient harnessing and consumption of energy. The Arduino platform demonstrates adaptability by seamlessly integrating data collecting, processing, and transmission from solar panels to the user's device. This integration improves overall system performance and promotes sustainability by reducing energy waste. The HC-05 module enables users to monitor their solar panels remotely by providing Bluetooth connectivity, offering additional convenience. This corresponds to contemporary lifestyles and simplifies effective maintenance and troubleshooting procedures. Furthermore, the research establishes the foundation for forthcoming progress in renewable energy technologies. Users can utilise the real-time data collected to do predictive analysis, enabling them to foresee possible problems and further enhance the efficiency of their solar panel systems. The solar panel monitoring system discussed in this article represents a notable advancement in maximising efficiency. By utilising Arduino and Bluetooth technology, we can monitor solar panels and actively participate in worldwide initiatives aimed at building greener and more sustainable energy infrastructure.

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