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Conference Paper · April 2024

DOI: 10.1109/ICAEEE62219.2024.10561689

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Developed an IoT-based smart solar energy monitoring system for environmental sustainability

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***Abstract*—Currently, electricity demand is constantly increasing all over the world, and the demand for this electricity is much higher than the production. As a result, the whole world is facing a global problem. In this decade, many researchers have been concerned about it and have suggested many ways to generate electricity in several ways, but they are not all concerned about low-cost, user-friendly, reliable data loggers and monitoring systems. To resolve the issue, we proposed an intelligent and environment-friendly way to generate electricity in all areas of a developing country. Initially, heat is generated either through household cooking activities or by burning excess or unnecessary garbage. After that, the solar panels are charged from the generated heat, and the charge is stored in a battery from the solar panel. The data logger, which is based on the ESP32 microcontroller, records all monitoring parameters on the cloud and presents them in the Android application. All the processes are completed automatically without any human interaction, and burning unnecessary garbage establishes environmental sustainability. The data logger hardware prototype that has been created incorporates four sensors to measure temperature, humidity, voltage, and current, which show up on an Android application with real-time data on many metrics. Additionally, it provides maintenance professionals with crucial information about any problems related to battery charging. To complete the work, we have created the hardware implementation of photovoltaic systems that use the IoT for remote data collection to provide us sustainability, and this prototype's total cost is affordable.**

***Index Terms*—Smart Solar Systems, IoT, Remote monitoring, and Environment Sustainability**

I. Introduction

Recent concerns about climate change and the depletion of traditional energy resources have prompted a shift toward sustainable and eco-friendly alternatives. Power production is becoming more expensive, and growing societies struggle to store energy after that demand, which is increasing environmental contamination. Among these alternatives, solar energy has emerged as a promising solution due to its abundance, cleanliness, and renewable nature.

Smart energy systems have been the subject of a great deal of research, with articles covering a wide range of topics. Iba *et al.* [1] demonstrated that smart energy systems can solve major global energy-related issues sustainably. Their results showed that increasing the number of products from the same energy source decreases emissions per unit product and increases efficiencies. In [2], they have presented novel potential prospects for the implementation of environmentally friendly practices in energy generation and use. The authors' idea is based on Dincer's methodology, which outlines six essential components for the implementation of environmentally friendly energy systems. The advantages of these components include enhanced efficiency, improved cost-effectiveness, optimized resource use, advanced design and analytical capabilities, enhanced energy security, and a more favorable environmental impact. In their study [2], they introduced a new greenization factor and used it to assess the greenization potential of several conventional and innovative energy systems in different scenarios. In their study, Singh et al. [3] performed a comprehensive analysis of several methods used to measure sustainability. They collected data on the development of sustainability indices, including the strategies, scale, normalization, weighting, and aggregate techniques used.

As the globe seeks more efficient energy management, IoT technologies are poised to transform monitoring and control systems. The effort develops and implements a proposed system to promote environmental sustainability. IoT and solar energy combine to improve energy efficiency and promote environmentally friendly technology. This paper discusses the system's main components, functions, and advantages to help readers comprehend its potential contributions to smart and sustainable energy solutions. The primary contributions of this research are as follows: enhanced monitoring and control, data-driven decision-making, environmental impact reduction, scalability and interoperability, and technological innovation.

The remainder of this study is in Section III where we describe the system architecture and its component functions. Section IV discusses the system's installation and outcomes, offering empirical insights. The study results' ramifications and importance are also examined. Section V summarises major contributions and suggests further study in the dynamic IoT-renewable energy junction.

979-8-3503-8828-2/24/$31.00

II. RELATED STUDY

The intersection of IoT technologies with renewable energy systems, particularly in the context of solar energy monitoring, has been a focal point of research in recent years. Numerous studies have explored various facets of this convergence, examining the potential for enhanced efficiency, sustainability, and smart management. Existing literature reveals notable efforts in the development of IoT-based solutions for solar energy. The intersection of IoT technologies with renewable energy systems, particularly in the context of solar energy monitoring, has been a focal point of research in recent years. Numerous studies have explored various facets of this convergence, examining the potential for enhanced efficiency, sustainability, and smart management.

In Table I, we perform a comparison of the features of software, hardware, burning of garbage value (BGV), IoT, and real-time observing (RO) among many researchers that are used for solar energy systems. We have seen that most of the researchers have not worked on all of the features, but in our proposed systems, we have used all of them.

Related works:	software	hardware	BGV	IoT	RO
[4]	Yes	Yes	No	Yes	No
[5]	No	Yes	No	Yes	No
[6]	Yes	Yes	No	Yes	No
[7]	Yes	Yes	No	Yes	No
[8]	Yes	Yes	No	Yes	No
[9]	No	Yes	No	Yes	No
[10]	Yes	Yes	No	Yes	No
[11]	No	Yes	No	Yes	No
[12]	Yes	Yes	No	Yes	No
Our Research	Yes	Yes	Yes	Yes	Yes

TABLE I: Comparison between the recent work and our proposed work.

Jia *et al.* [13] provided an in-depth investigation of the uses of the IoT in energy from renewable sources, with a particular focus on the importance of sensor networks for monitoring in real time. Similarly, Maisagalla *et al.* [14] have shown that the total capacity of solar electricity has the potential to increase twofold every two years. According to Swanson's rule, the cost per watt of solar photovoltaic modules decreases by 50% for every tenfold increase in capacity [15]. They presented data demonstrating the rapid expansion of solar power production as a renewable energy source, which also proves its cost competitiveness compared to conventional thermal energy sources such as coal, crude oil, and natural gas.

Mainali and Silveira [16] have examined several approaches for sustainability assessment and presented a technique for evaluating the sustainability of intelligent energy systems. Certainly, evaluating the technological aspects is a crucial consideration when selecting among many alternatives for power provision. Tran and Daim conducted a comprehensive analysis of the techniques and instruments used in the evaluation of technology. Historically, the conventional method of doing a technology evaluation was a straightforward study of costs and benefits among the many accessible possibilities [17].

In [18], the authors introduced an innovative demand response approach for determining the appropriate size of a hybrid renewable energy system. This system comprises a wind solar system, a PV solar system, batteries, diesel engines, and loads. The demand response technique was designed to adjust tariffs, specifically for the production of renewable energy systems, to meet load needs by either increasing or decreasing them. The ideal dimensions of each HRES component have been fine-tuned by several methodologies, including particle swarm optimization, social mimicry optimization, and the algorithm for bats. The actual data on the electricity demand of a rural city located in the northern region of Saudi Arabia has been taken into account for the design of a hybrid renewable energy system.

The authors [19] conducted a feasibility study on the use of a hybrid renewable energy system to provide power to a university building located at Al Baha University, Saudi Arabia. The hybrid renewable energy system included photovoltaic panels, wind turbines, fuel cells, and battery storage systems. The building's AC loads included an air conditioning system, labs, lights, and several other pieces of equipment.

Through integrating IoT technologies, our proposed system offers real-time monitoring, data analytics, and remote control capabilities, enabling efficient utilization of solar energy resources. By addressing challenges such as energy management and environmental impact, the proposed system holds promise for enhancing the adoption and effectiveness of solar energy solutions, contributing significantly to the transition towards a more sustainable future.

III. PROPOSED IOT-BASED SOLUTION

Our daily lives require electricity, which has an impact on world progress. Electricity has been rising steadily on a worldwide scale, and the demand for this is very high. So in this regard, our attempts have helped in the settlement of this problem and revolutionized the power generation industry. We have completed the process of electricity consumption based on solar charging through the burning of unnecessary waste and gas stove heat in our house and easily monitoring and load-controlling it through apps, which is shown in Fig. 1.

Our research workflow is divided into two sections: the hardware and software sections. In the first section, we collect heat from household cooking, the home's gas stove, or from burning unnecessary garbage; after that, we send it to the solar panels for charging, and the charge is stored in a battery and battery-to-load supply operations. It connected hardware and software through a controlling system, as shown in Fig. 1.

Here, we used an ESP32 Arduino and four solar panels that are connected in series with a battery, and several loads are connected to the battery. Diodes are used to balance the battery's charging voltage and the solar panel's voltage. The TP4056 module showed the battery charging status through a connection with Arduino and sent the battery status to the server through cloud storage. In the software section, our app shows a real-time view and control of charge status, automation, and detailed load, which is easy for the user to manipulate.

Our emergency warning system is triggered when the charge crosses a particular limit, making the charging time simply comprehensible for the user. Controlling the load current can be done in two ways: manually using a relay switch and automatically using the app throw. The architecture is assembled using a variety of PVC boards and wires, and all connections are made using the breadboard.

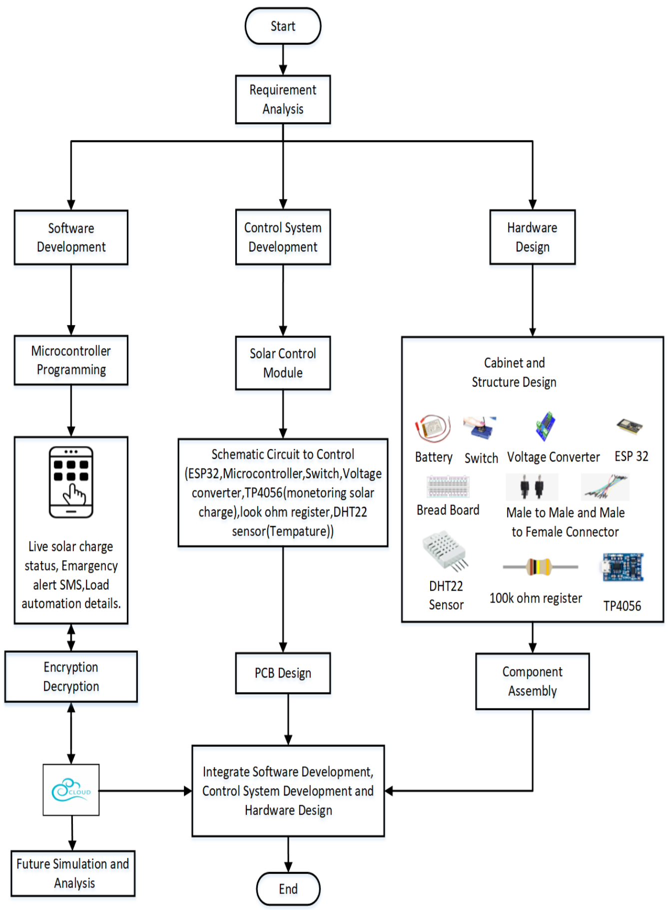

Fig. 1: Proposed development model for the efficient IoT solution for smart solar systems.

A. Hardware Design

The hardware prototype design for our proposed system, which endeavours to support environmental sustainability, is depicted in Fig. 2. Solar panels to capture solar irradiance, a DHT22 sensor for measuring temperature, and a TP4056 module for energy production are integrated into the system, which also includes a microcontroller for data transmission and processing. The gathered data is transmitted to a cloud server via wireless communication protocols, including Wi-Fi, to facilitate its storage and analysis. The hardware is designed with scalability, compactness, and low power consumption in mind to accommodate a variety of solar panel installations. This IoT-enabled solution promotes the effective utilization of solar energy through real-time monitoring and analytics, thereby making a significant contribution to environmental conservation initiatives. In Fig. 3, we have shown our real experimental prototype setup.

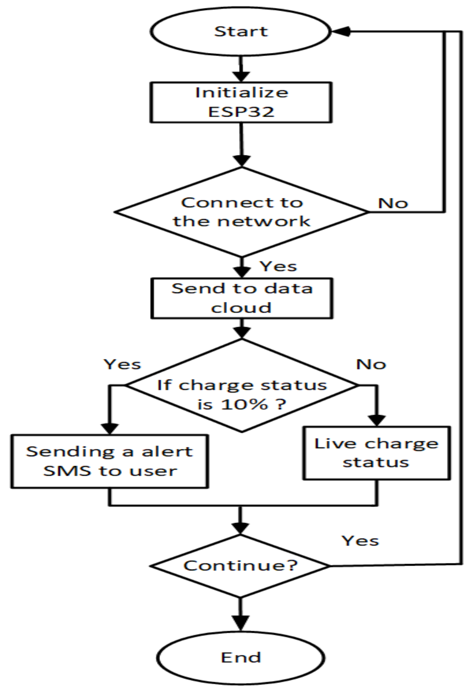

Fig. 2: Proposed hardware execution model for the smart solar system with sustainability.

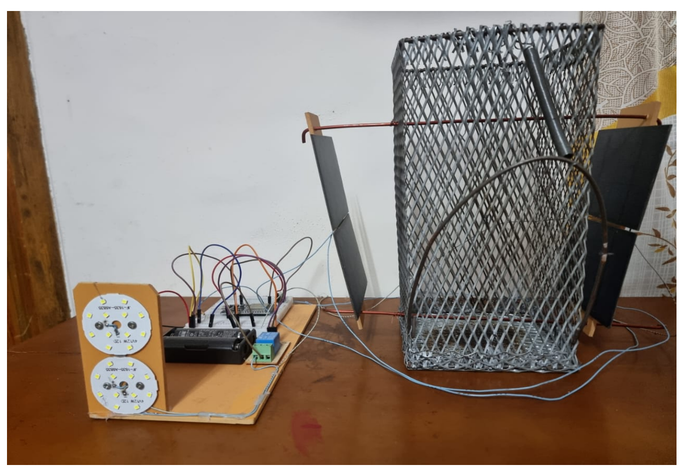

Fig. 3: Proposed real hardware experiment model for the smart solar system with sustainability.

B. Control System Development

Our proposed system's integration of a mobile application and an ESP32 microcontroller is the focus of the Control System Development section. By functioning as the user interface, the mobile application permits real-time monitoring and control of the system parameters. For the convenience of the user, it presents graphical depictions of energy generation, consumption, and environmental data. The ESP32 microcontroller functions as the primary processing unit, converting electrical energy generated by the solar energy system in our residence from the combustion of waste and gas stove heat into a digital value. This value is subsequently transmitted to the mobile application through Wi-Fi. Utilizing this integration, users can oversee energy production from a distance, monitor the effects on the environment, and optimize the efficiency of the system to promote greater environmental sustainability. The synchronization of the microcontroller and mobile application guarantees effective administration and communication of the intelligent solar energy monitoring system. Fig. 4 illustrates the control development model flowchart for the proposed system.

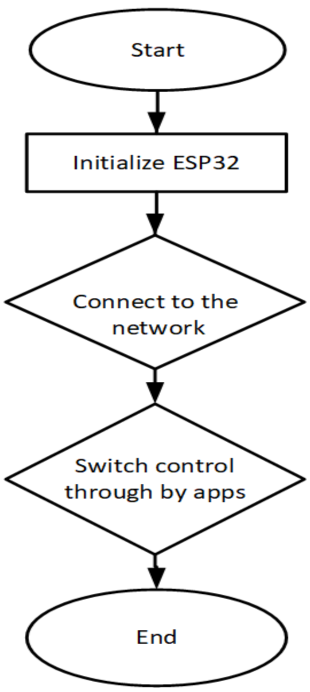

Fig. 4: Proposed control development model for the smart solar system with sustainability.

C. Software development

The software development phase encompassed the utilization of Arduino microcontroller programming to execute the proposed techniques. The Arduino IDE has been utilized to compose and transfer all pertinent programs onto the microcontroller board. All programs have been implemented using the embedded C programming language. Fig. 5 depicts the software development model utilized in the proposed IoT-based solution. An Android application with a user-friendly interface has been developed to allow users to monitor and control the system in real-time. Once user authentication is confirmed, access to the applications is granted. On the app's home page, we have shown battery life in percent, load control, an emergency message when the load goes too high or is damaged, every load detail, and automation control systems. In addition, we added a setting system for a home automation system that makes it easy to control the solar charge systems with a percentage value. If the battery falls below the specified minimum, the program will alert the microcontroller right away and send a feedback message about when to recharge it.

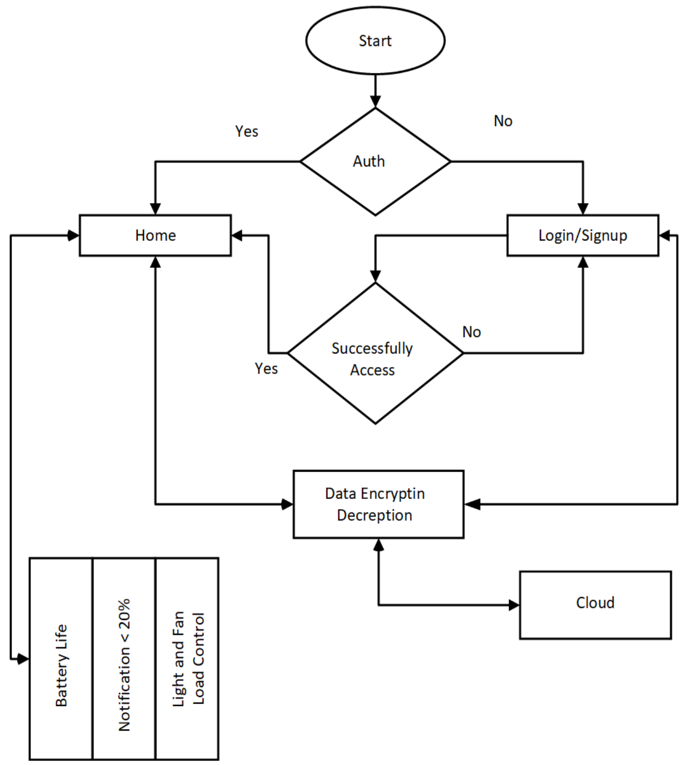

Fig. 5: Proposed Android application development model for the smart solar system with sustainability.

IV. EXPERIMENTAL RESULT AND ANALYSIS

We designed and implemented an IoT-based smart solar energy monitoring and controlling system to assess its effectiveness in promoting environmental sustainability. In our system, we have included the burning of unnecessary waste and gas stove heat in our house to measure solar panel output, environmental conditions, and energy consumption that ensure sustainability.

Day	E_Charge(%)	E_Load(%)	Service Time(Hours)
[1]	100	99	12
[2]	100	98.5	11.5
[3]	100	98	11
[4]	100	98.5	11.5
[5]	98	97.5	10.5
[6]	97	96.5	10
[7]	96	95	10.5

TABLE II: Comparison between estimated charge and load concerning time.

We have experimented for ten weeks, and in this paper, we included the last seven days' experimental data-sheet in

Day	Multimeter(Current)	Smart Solar System Apps
[1]	12.71	12.75
[2]	12.65	12.68
[3]	13.62	13.60
[4]	14.48	14.55
[5]	13.38	13.45
[6]	13.25	13.33
[7]	12.22	12.28
[8]	12.12	12.08

TABLE III: Comparison between multimeter and smart solar apps result.

Table II that we got from the microcontroller. In addition, we can easily view and control all of the real-time data by using a mobile application. In the end, the collected data enabled us to optimize energy harvesting strategies, contributing to enhanced overall system performance. Also, we used the formula for calculating solar energy as follows: $Energy = PanelArea * HeatIntensity * PanelEfficiency * Time$, which accounts for the solar panel size, efficiency, and heat input. The table presents daily averages of solar estimated charge percentage (E_Charge), estimated load percentage (E_Load), and service time (Hours) over the few days. In addition, we depict that Day 01 shows 100% of E_Charge, then 99% of E_Load, and lastly, Hours shows 12. On Day two, it shows 100, 98.5, and 11.5 accordingly, and finally, the result is graphically represented in Fig. 6.

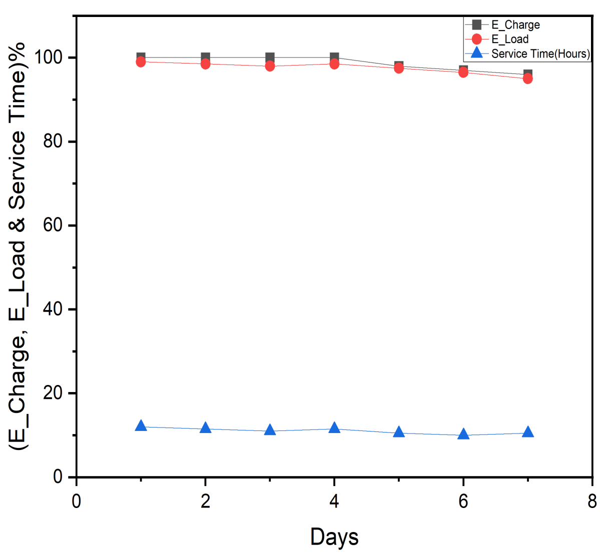

Fig. 6: Comparison between estimated charge and load to time.

Also in Table III, we compare the electronics multimeter and our proposed energy-gathering systems. We show the last seven days' data here and conclude that maximum case performance is, on average, the same. Day 01 shows a 12.71 multimeter voltage value, and similarly, our proposed systems show a 12.75 voltage value. The last seven days' data is

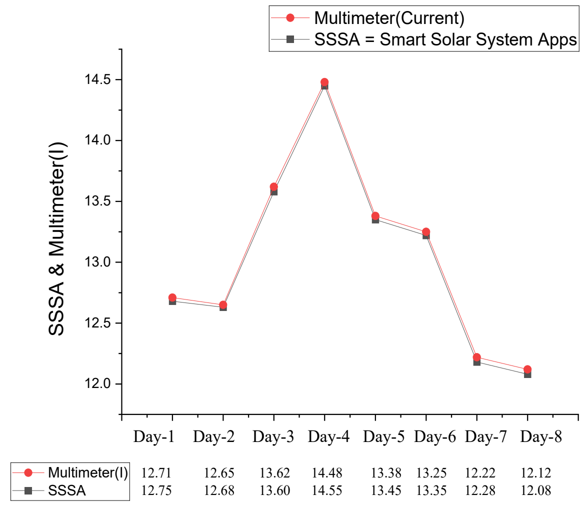

Fig. 7: Comparison between multimeter and smart solar apps result.

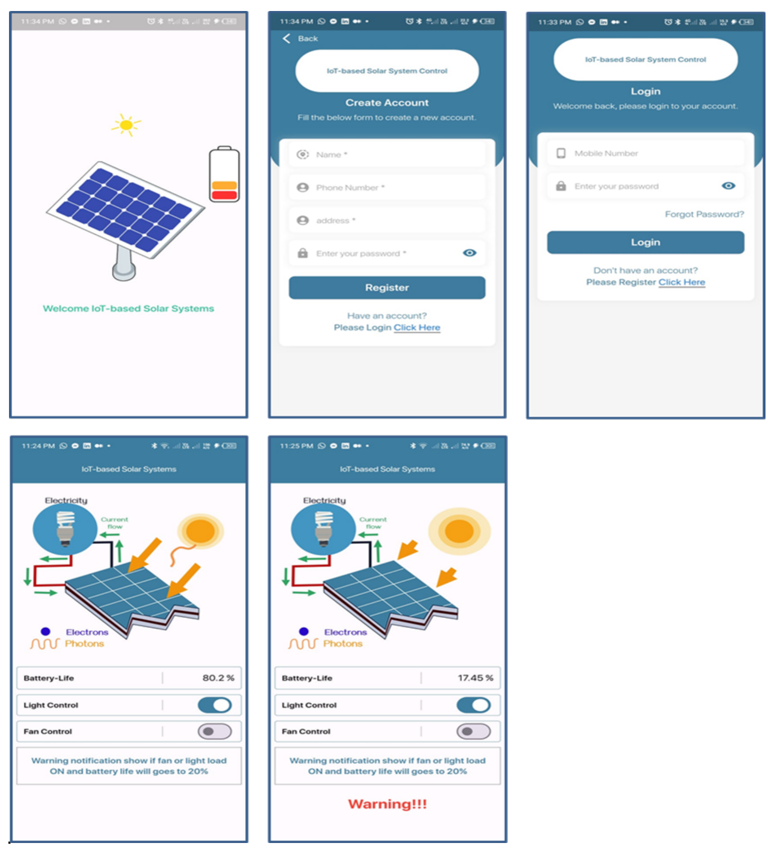

Fig. 8: Application view of our proposed system

depicted in Fig. 7 for more visualization and comparison.

Also, we deployed a mobile app integrated with our proposed system to display real-time data flow and control load description, which is shown in Fig. 8. The mobile app facilitated seamless user interaction, enabling efficient monitoring and control of solar energy systems. Real-time data visualization enhanced user engagement and understanding of energy usage patterns, promoting sustainable practices. Finally, we conclude that our proposed systems demonstrated the effectiveness of our IoT-based system for enhancing environmental sustainability through efficient solar energy monitoring.

V. CONCLUSIONS

The development of an IoT-based smart solar energy monitoring system marks a significant stride towards achieving environmental sustainability goals. Through the integration of advanced technologies, including IoT, this research has demonstrated the potential to efficiently monitor solar energy generation, consumption, and distribution in real-time. The system's ability to provide accurate data and actionable insights empowers stakeholders to optimize energy usage, reduce waste, and mitigate environmental impact.

By using this effort, unnecessary waste and garbage generate power by burning, a process that is highly significant for the environment. Moreover, the scalability and adaptability of the IoT framework pave the way for widespread implementation across various methods, from residential to industrial. As society increasingly recognizes the importance of renewable energy sources, this innovative solution holds promise for fostering a more sustainable future, where clean energy initiatives are central to global efforts to combat climate change and promote environmental stewardship. Our efforts will open up novel possibilities for solar power. In the future, work could focus on enhancing system scalability, integrating predictive analytics for energy forecasting, and exploring potential applications in smart grid infrastructures.

VI. RESEARCH QUESTION WITH ANSWER

Q1. How does the implementation of an IoT-based smart solar energy monitoring system contribute to environmental sustainability?

Answer: Implementing an IoT-based smart solar energy monitoring system facilitates real-time tracking and optimization of solar power generation, thereby reducing reliance on non-renewable energy sources and minimizing carbon emissions.

Q2. What are the key technological components required to develop such a system effectively?

Answer: Key components include sensors for data collection, IoT platforms for connectivity, and analytics tools for processing and interpretation of data.

Q3. What are the challenges and limitations associated with deploying IoT in solar energy monitoring, and how can they be addressed?

Answer: Challenges include connectivity issues, data security concerns, and interoperability of devices. These can be addressed through robust network infrastructure, encryption protocols, and standardized communication protocols.

Q4. What are the potential applications and scalability of the system in different environmental settings?

Answer: The system's adaptability allows its deployment in various environmental contexts, including residential, commercial, and industrial settings, fostering widespread sustainability initiatives.

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