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A Cost-Effective Approach to Sustainable Agriculture through Implementing Solar Energy in Iot- Enabled Fertigation Systems for Enhanced Crop Productivity

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Abstract

In contemporary agriculture, the utilization of fertigation systems has emerged as a highly effective method for enhancing the growth and yield of crops, when compared to traditional cultivation techniques. However, many farmers rely on generators and conventional electricity to operate water pumps, which incurs substantial operational, transportation, and maintenance costs. This project aims to investigate and assess the performance of a solar-powered system designed to optimize the efficiency of fertigation practices in relation to varying weather conditions. Furthermore, the system incorporates an Internet of Things (IoT) framework that facilitates real-time monitoring of data related to energy production and environmental conditions via the Blynk application. The primary objective of this research is to explore the correlations between solar energy output and key parameters, including temperature, humidity, and precipitation levels. Additionally, the harvested solar energy will be stored in a battery for subsequent use in the fertigation system, specifically for powering the water pump. By enabling users to identify optimal timing and weather conditions for energy production, this project offers a practical prototype, a software interface, and a comprehensive monitoring analysis for solar panel systems based on IoT technology.

Keywords: Fertigation, Solar Energy, IoT (Internet of Things), Weather condition

Introduction

The growing discourse surrounding renewable energy has gained unprecedented traction as the world grapples with escalating energy demands and the urgent need to combat climate change.

Renewable energy, particularly solar energy, has emerged as a pivotal solution in the quest for sustainable energy systems. Over the past few decades, the transition from fossil fuels to renewable energy sources has been marked by significant advancements in technology and policy frameworks aimed at fostering sustainable development (International Renewable Energy Agency [IRENA], 2023). Among the various forms of renewable energy, solar energy stands out due to its vast potential, accessibility, and decreasing cost of photovoltaic (PV) technology (Gonzalez et al., 2021).

Solar energy is often termed a 'modern renewable,' transitioning from a marginal contributor to a major player in the global energy landscape. Historically, solar energy accounted for a small fraction of global energy production; however, technological advancements have propelled it into a position of prominence. In 2022, solar energy contributed approximately 1.5% to global energy production, illustrating its increasing significance in the global energy mix (International Energy Agency [IEA], 2023). This shift has been driven by a combination of factors, including the urgent need for energy security, environmental sustainability, and economic viability.

The intersection of solar energy and agriculture represents a particularly promising avenue for sustainable development. Agriculture is inherently energy-intensive, relying heavily on fossil fuels for various processes, from irrigation to fertilization. Traditional farming practices often lead to substantial operational costs and environmental degradation. The integration of renewable energy sources, particularly solar energy, into agricultural practices offers an innovative solution to these challenges (Moussa et al., 2022; Alshammari et al., 2021).

One notable advancement in this field is fertigation, a sophisticated technique that combines fertilization and irrigation to enhance crop productivity. Fertigation allows for the precise application of fertilizers through irrigation systems, thereby improving nutrient management (Zhang et al., 2021). This method exemplifies the principles of precision agriculture, which emphasize the importance of real-time monitoring and adaptive management. By optimizing the timing, quantity, and concentration of fertilizer application, fertigation systems can significantly increase crop yields while minimizing environmental impacts (Smith et al., 2023; Liu & Wei, 2021).

The integration of solar-powered fertigation systems is a key development that enhances both energy efficiency and agricultural productivity. These systems leverage solar energy to power water pumps and other irrigation components, thereby reducing reliance on conventional electricity sources (Alshammari et al., 2021). By utilizing inexhaustible solar energy, farmers can achieve significant cost savings, reduce their carbon footprint, and improve the sustainability of their agricultural practices (Baba et al., 2020). The operational efficiency of solar-powered fertigation systems not only benefits individual farmers but also contributes to broader environmental goals by reducing greenhouse gas emissions associated with fossil fuel consumption (Chen et al., 2022).

Moreover, the rapid advancement of the Internet of Things (IoT) has further revolutionized agricultural practices. IoT technology enables seamless interconnectivity among devices, facilitating real-time data collection and analysis (Roberts & Adams, 2021). In the context of fertigation, IoT-enabled systems allow farmers to monitor environmental conditions, such as temperature and humidity, and make informed decisions regarding irrigation and fertilization. This data-driven approach enhances the efficacy of solar-powered fertigation systems by optimizing energy use and ensuring that crops receive the necessary nutrients at the right time (Kim & Park, 2020).

The performance of solar panels is influenced by a range of environmental factors, including temperature, irradiance, and humidity levels. Research indicates that understanding these dynamics is crucial for maximizing solar energy output (Yadav & Singh, 2022). For instance, high temperatures can adversely affect the efficiency of PV systems, while optimal irradiance levels are essential for enhancing energy conversion (Sharma et al., 2021). Consequently, real-time monitoring of weather conditions and solar panel performance is vital for developing adaptive management strategies.

As climate change continues to intensify, the variability in weather patterns poses challenges to the predictability of solar energy generation (Ehsan & Kumar, 2021). This underscores the importance of integrating weather forecasting models with solar energy systems to enhance reliability and planning (Gonzalez et al., 2021). By developing systems that utilize both performance data and weather metrics, farmers can better anticipate energy production fluctuations and optimize their operations accordingly (Torres et al., 2020).

Integrating renewable energy technologies, such as solar power, with modern agricultural practices is not merely a response to environmental concerns but also a recognition of the economic benefits associated with sustainable energy practices. As the global economy increasingly shifts towards sustainability, investments in renewable energy and smart agricultural technologies will play a critical role in shaping the future of food production and energy security (United Nations, 2020; Tran et al., 2021). Furthermore, this research aligns with global sustainability goals, providing essential data that can inform policy and investment decisions in the renewable energy sector.

The transition to renewable energy sources, particularly solar energy, is crucial in achieving a sustainable future. By harnessing the power of the sun, the agricultural sector can not only enhance its productivity but also contribute to the mitigation of climate change. The dual benefits of economic viability and environmental sustainability make solar harvesting an essential component of modern agricultural practices (Alavi & Mirzaei, 2022; Vasilakos & Kranis, 2022).

The motivation for this project is further grounded in the broader goal of promoting sustainable energy practices. As the world grapples with the repercussions of climate change, the need for innovative solutions in renewable energy generation becomes paramount. This research aligns with global sustainability goals, providing critical data that can inform policy and investment decisions in the renewable energy sector (United Nations, 2020). Ultimately, this project aims to contribute to the body of knowledge that supports the transition to cleaner energy systems, ensuring a more sustainable future.

Methodology

Overview of the System

This project aims to investigate the performance of solar panels in relation to weather conditions. The core components of the system include:

i) ESP32 Microcontroller
ii) Current Sensor
iii) Voltage Sensor
iv) DHT11 Sensor

As illustrated in Figure 1, the system utilizes both a voltage sensor and a current sensor to measure key parameters such as voltage, current, and power output. The DHT11 sensor is employed to monitor temperature and humidity levels.

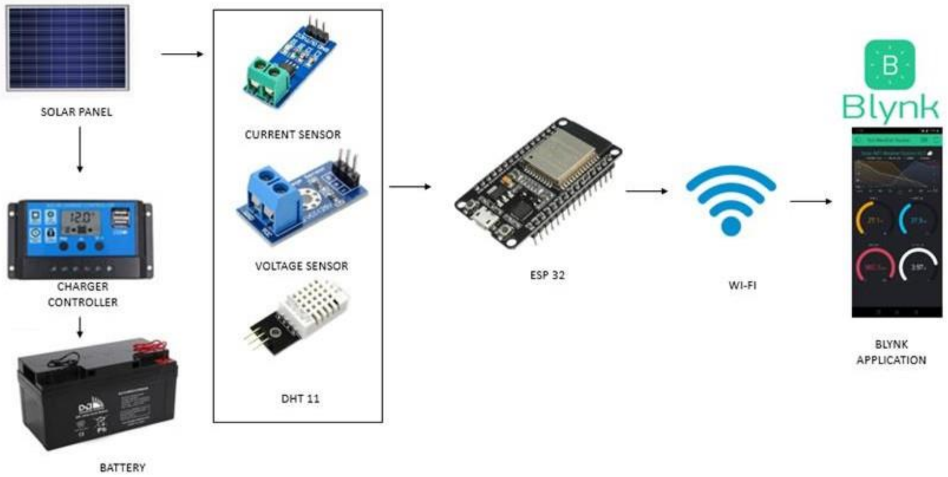


Figure 1 : Block Diagram of the system

The system is designed to continuously monitor the output of the solar panel array, as shown in Figure 2. This capability will enable users to identify variations in the output of the photovoltaic (PV) panels, which may arise from various environmental and meteorological factors. Additionally, the system will track changes in energy output due to the inherent unpredictability of solar energy generation. By enhancing the efficiency of solar energy utilization, this project aims to contribute to the long-term advancement of solar energy technology.

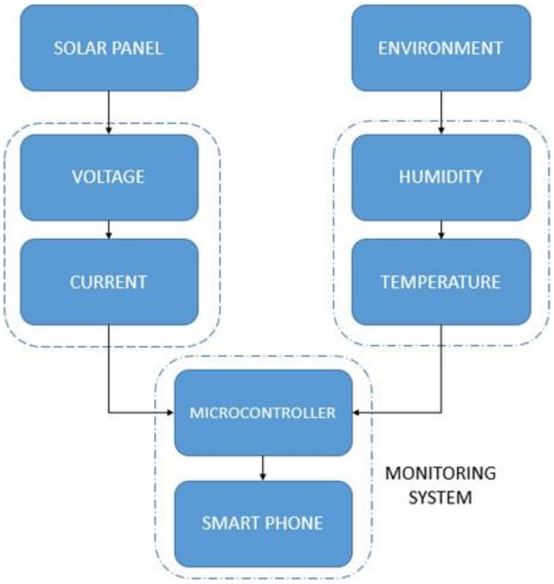


Figure 2 : Overview of the system

Flowchart for Overall System

Figure 3 presents the flowchart that outlines the operational sequence of the project. The process begins with the solar panel, which serves as the primary hardware component that converts sunlight into electrical energy. The ESP32 microcontroller establishes a connection with the Blynk application, facilitating real-time communication. Concurrently, the sensors collect data on various parameters, which are then displayed on the Blynk application interface, providing users with valuable insights into system performance.

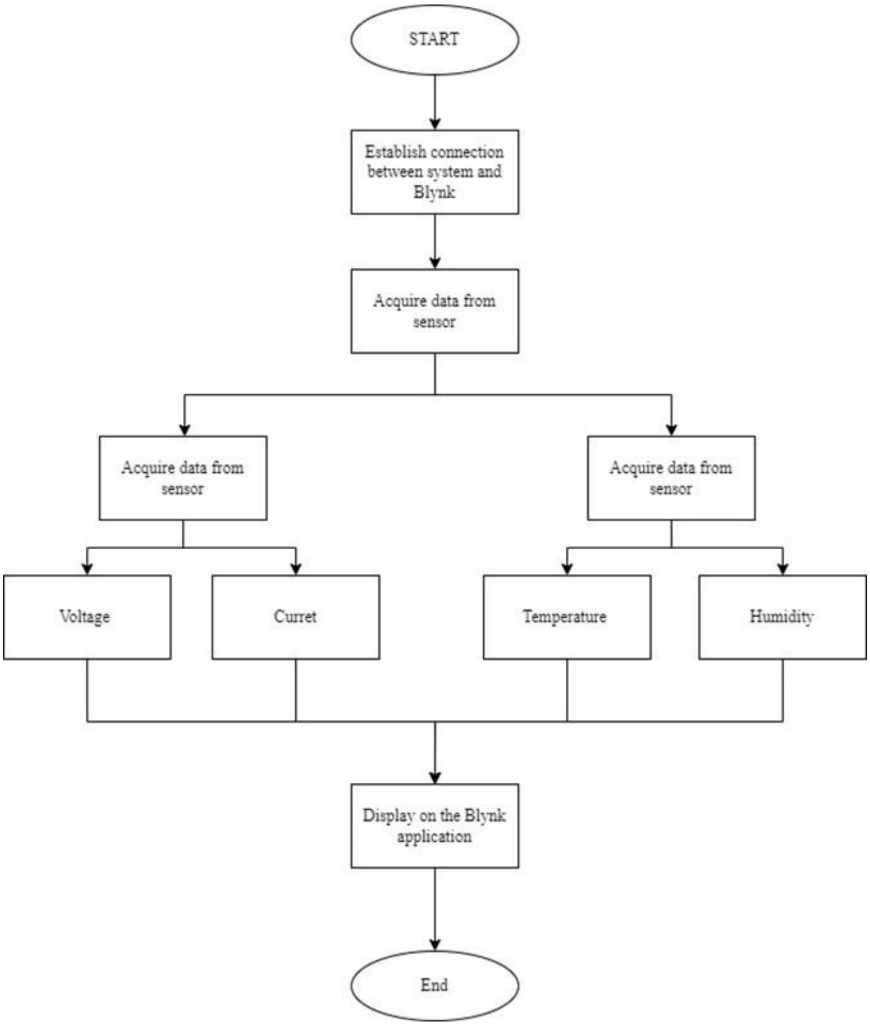


Figure 3 : Flowchart for Overall System.

This project incorporates IoT technology through the Blynk application, allowing users to monitor and analyze solar panel voltage, current, and environmental parameters, such as temperature and humidity, remotely via a smartphone, as depicted in Figure 4. Initially, the solar panel captures sunlight and converts it into electricity. The voltage and current sensors are employed to measure the voltage, current, and power output generated by the solar panel. Meanwhile, the DHT11 sensor functions as a weather station, collecting data to determine optimal conditions for solar energy generation.

The ESP32 microcontroller serves as the core hardware component, equipped with Wi-Fi capabilities to facilitate seamless communication between the IoT system and mobile devices. Using the Blynk application, real-time data on energy production and weather conditions is transmitted directly to users' smartphones.

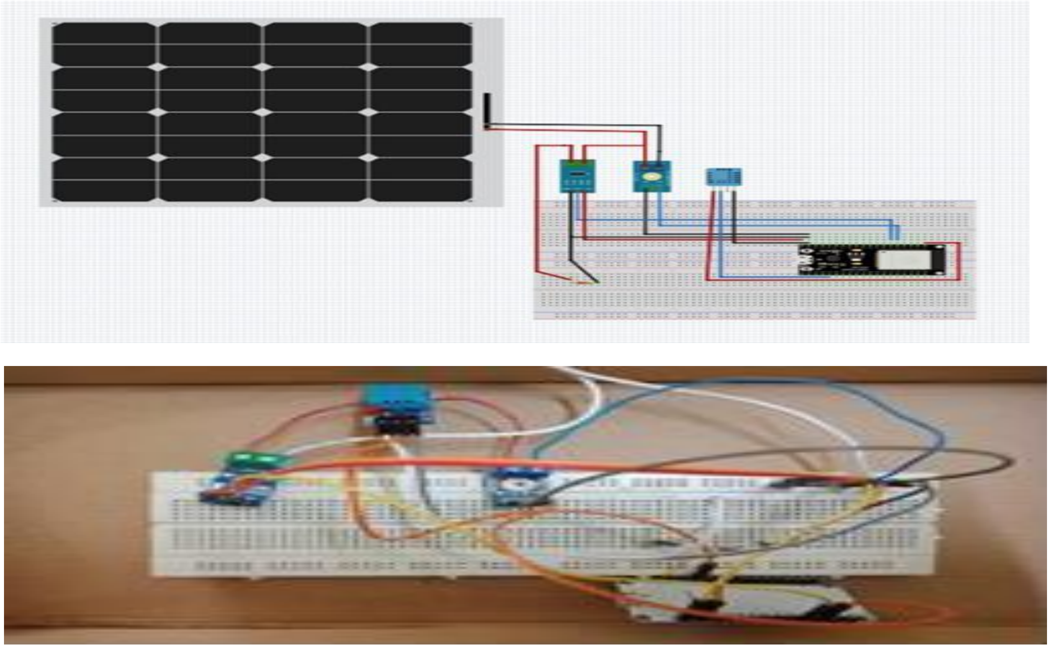


Figure 4 : Hardware connection

Figure 5(a) and 5(b) illustrate the complete hardware setup and prototype configuration for this project. The solar panel is strategically positioned to face the sun, with an inclination angle of approximately 45 degrees. The support structure for the solar panel is constructed from PVC pipes and fittings, providing stability and durability. The solar energy harnessed by the system is utilized to power the fertigation system, thereby eliminating the need for traditional electricity sources. This approach underscores the suitability of solar energy as a renewable power supply for agricultural applications.

(a) (b)

Figure 5 : The prototype setup for (a) Solar panel (b) Fertigation system

Results and Discussion

This section presents an analysis of data collected over the course of one month, focusing on solar voltage, current, and power output from the solar panel. Additionally, it will explore the relationship between weather conditions and solar energy harvest, with a specific examination of two scenarios: sunny days and rainy days.

Analysis of Solar Voltage Data

Voltage is a critical parameter in solar energy systems, particularly for panels intended to charge 12V batteries. Typically, solar panels designed for this purpose have rated voltages between 16V and 17V. In this project, a polycrystalline solar panel with an efficiency of 18% is utilized, producing a maximum voltage of 18V, making it compatible with 12V systems. The relationship between voltage and current is crucial; lower voltage levels result in higher current (amperage). During peak performance, the rated terminal voltage of a 12V solar panel is generally between 17V and 18V. However, when utilizing a regulator for battery charging, this voltage typically drops to around 13V to 15V.

The initial investigation into solar electricity generation in the region was conducted from November 8 to December 8, 2021. Data from this study is illustrated in Figure 6, which displays the maximum, minimum, and average voltage produced daily. Notably, on November 24, 2021, the maximum recorded voltage reached approximately 13V, while the minimum voltage fell to 4V. The results indicate that at noon, when solar irradiance is at its peak, the voltage generated was about 13V. Conversely, the lowest voltage of approximately 7V was observed at 7 a.m., reflecting the conditions at sunrise. This data underscores the importance of considering voltage fluctuations in solar energy systems and emphasizes the need for effective regulation to optimize battery charging efficiency.

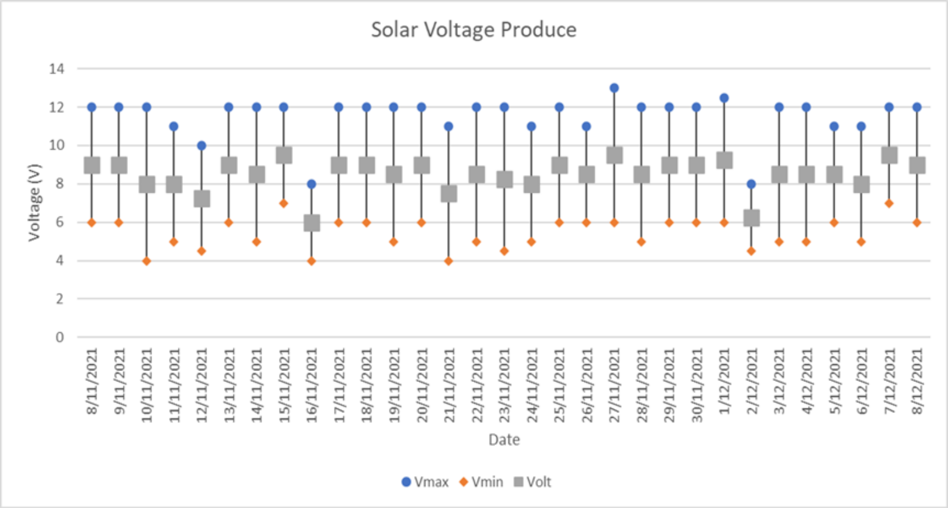


Figure 6 : Solar voltage produce in one month

Analysis of Solar Current and Power Data

The wattage (W) of a solar panel reflects its power output, with higher wattage indicating greater capacity. Current (A) and voltage (V) are critical: lower voltage correlates with higher current, resulting in faster charging of connected batteries. For instance, a solar panel rated at 30W with a maximum current of 1.67A will produce its rated power under ideal conditions.

Analyzing data from November 8 to December 8, 2021 in Figure 7, reveals a daily power output range from 4.4W to 12W, with a potential daily harvest of approximately 225 watt-hours, translating to 0.225 kilowatt-hours per panel. This indicates significant variability in solar energy generation, influenced by environmental factors, suggesting that efficiency optimization strategies could enhance overall energy capture in this region.

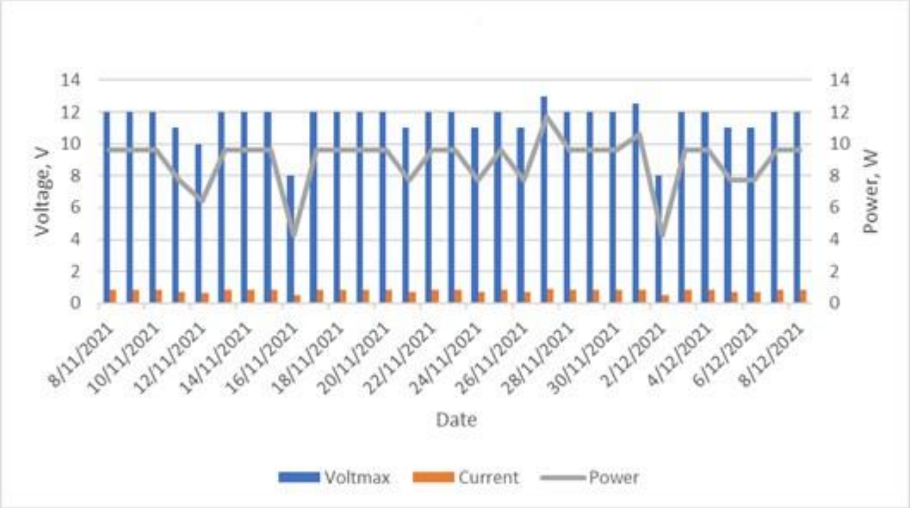


Figure 7 : The value of voltage, current and power of the solar panel.

Daily Performance Analysis

Solar panels can harness both direct and indirect sunlight to generate electricity, allowing them to remain functional even under cloudy or rainy conditions. On sunny days, the panels are most effective when exposed directly to sunlight. Conversely, solar panels do not operate at night, as they are inactive after 7 PM due to the lack of sunlight, which is necessary to trigger the photovoltaic effect for electricity generation.

Performance on Rainy Days

Figure 8 displays the performance of solar panels during rainy conditions on December 2, 2021, from 7 AM to 10 PM. The graph indicates that during peak hours around noon, the voltage produced by the solar panel was approximately 6V, with a temperature of 25°C, indicating rainy weather (humidity at 94%). The increased humidity during rain typically ranges between 24°C and 28°C. The voltage output varied from 4.5V to 8V. During heavy rainfall, solar panels generate only about 10% to 30% of their optimal capacity, while on cloudy days or during light rain, they can achieve 30% to 50% of their maximum output.

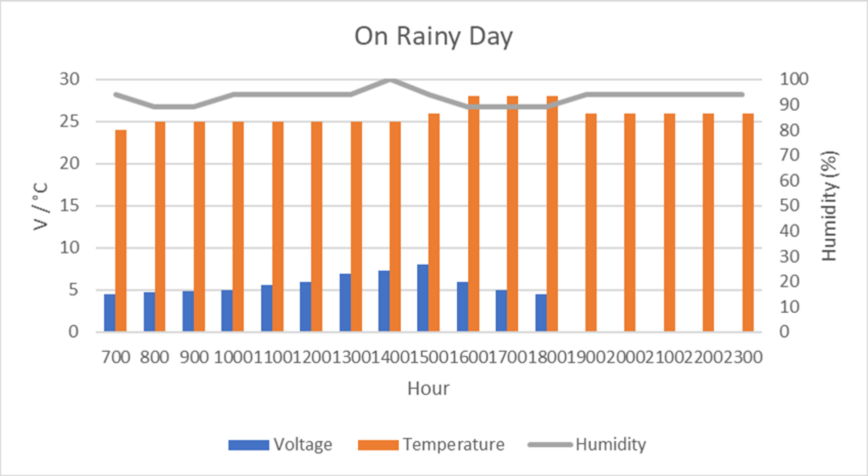


Figure 8 : The value of voltage, temperature, and humidity during a Rainy day.

Performance on Sunny Days

Figure 9 illustrates the solar panel performance on sunny days, specifically on December 7, 2021, from 7 AM to 10 PM. During peak hours at noon, the solar panel produced a voltage of 12 V, with a temperature of 33°C, signifying a hot day with a humidity level of 62%. As the temperature ranged from 26°C to 35°C, the humidity decreased, leading to a voltage output varying between 7 V and 12 V. This demonstrates the efficiency of solar panels in optimal weather conditions, highlighting their capacity to generate significant power when exposed to direct sunlight.

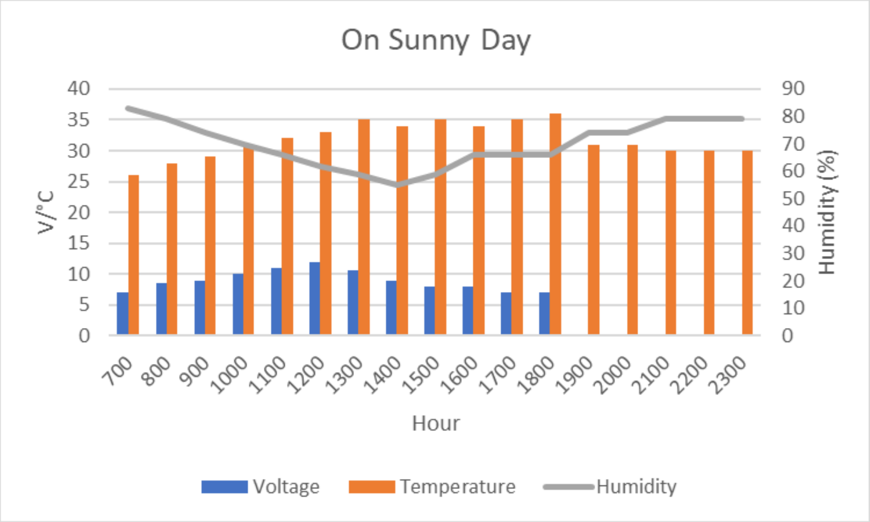


Figure 9 : The value of voltage, temperature, and humidity during a sunny day.

Display on the Blynk Application

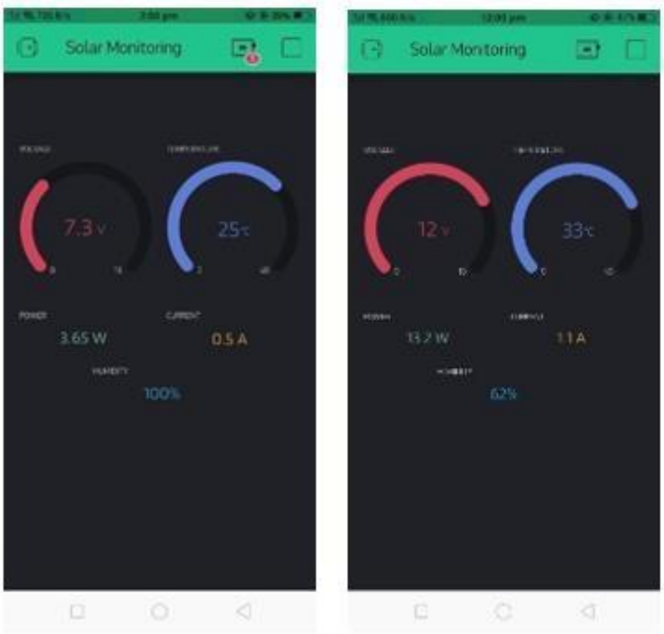
The Blynk application is integral to this project, serving as a platform for real-time data display and collection from the sensors. The primary advantage of using IoT for solar monitoring is that it enables users to verify the operational status of the solar system and to analyze data across different timeframes, comparing performance from previous days, months, and even years. As illustrated in Figure 10, the application shows data during nighttime when the solar panels are inactive due to the absence of sunlight. Consequently, the voltage, current, and power readings are all displayed as zero. However, the temperature remains at 28°C with humidity recorded at 87%.

Figure 10 : Blynk application display during the night

In Figure 11(a), presents data captured during a rainy day at 2:00 PM. The voltage reading shows 7.3 V, indicative of light rain, with minimal sunlight present. At this time, the current is 0.5 A, and the power output is 3.65 W. The temperature is recorded at 25°C, with humidity at around 100%, a result of heavy rain earlier that day, which led to a cooler environment and increased humidity levels.

In contrast, Figure 11(b) shows readings from a sunny day during peak solar hours. The panel produced a voltage of 12V, a current of 1.1A, and a power output of 13.2W. The temperature during this time was higher, at 33°C, with humidity reduced to 67%. The higher voltage and power output during sunny conditions are attributed to optimal sunlight availability, which directly enhances energy generation efficiency.

This analysis highlights the substantial impact of weather on solar panel performance. During cloudy and rainy conditions, power output is significantly diminished due to reduced sunlight, while sunny days enable the panel to operate at or near its optimal capacity. Additionally, the relationship between temperature, humidity, and power output indicates that while high temperatures can enhance energy generation, extreme humidity may lead to performance drops. Understanding these dynamics is essential for optimizing solar energy systems and managing expectations based on local weather patterns.



(a) (b)

Figure 11 : Blynk application display during (a) runny day (b) sunny day

Battery Charging Performance Analysis

Figure 12 illustrates the voltage output of the solar panel alongside temperature readings from 7 AM to 11 PM. The data reveals that the voltage steadily increases from 7 AM until noon, reaching its peak, before gradually declining from 1 PM until 7 PM. After 7 PM, the solar panel ceases to charge the battery. The charging duration indicates that the panel can effectively charge the battery for approximately 11 hours under optimal conditions.

This project utilizes a 12V, 30W solar panel in conjunction with a 12V, 30AH battery. The charging efficiency may vary due to temperature fluctuations, which directly impact the voltage supply necessary for battery charging. Higher temperatures can enhance the solar panel's performance by increasing voltage output, while cooler temperatures may reduce efficiency.

The ability of the solar panel to supply sufficient power for the fertigation system is crucial. Given that the battery has a capacity of 30AH, a fully charged battery can support the system's operational needs during periods without sunlight. This analysis emphasizes the importance of monitoring environmental conditions to optimize battery charging and ensure reliable power supply for agricultural applications.

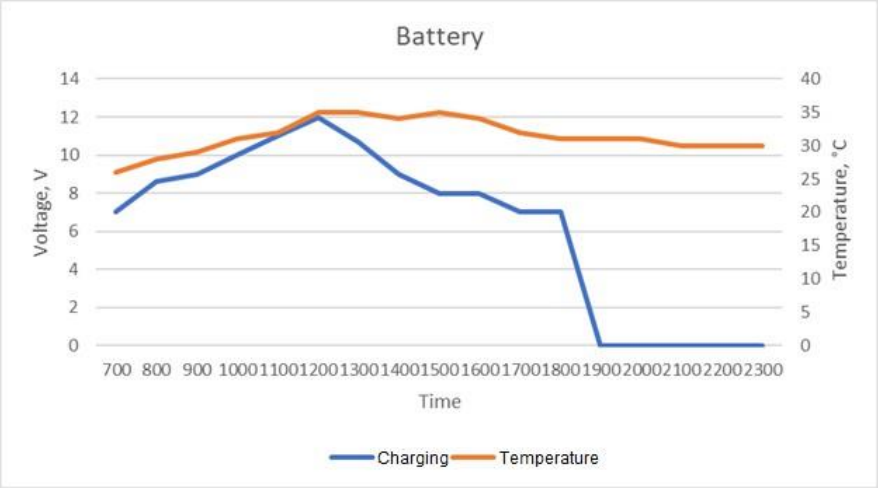


Figure 13 : Battery charging data

Future Works

For future improvements, one key suggestion is to add advanced sensors to the solar-powered fertigation system. By incorporating sensors like irradiance sensors, dust sensors, and light- dependent resistors (LDR), the system could better monitor environmental conditions. This real-time data would help optimize the timing and efficiency of fertigation, ensuring that crops receive the right nutrients based on current needs, which could lead to healthier plants and higher yields.

Another important enhancement would be to implement a solar tracking system. This system would adjust the solar panels' angle throughout the day to follow the sun's movement. By maximizing sunlight capture, the panels could generate more energy for the fertigation system. This additional energy would improve efficiency and provide a more reliable power source, benefiting farmers with better crop production.

Lastly, upgrading from the ESP32 microcontroller to a more powerful option like the Raspberry Pi could enhance the system's performance. The Raspberry Pi would support cloud data storage and allow for more detailed data analysis. With better monitoring and management capabilities, farmers could make smarter decisions about irrigation and fertilization. Focusing on these three improvements, adding sensors, implementing solar tracking, and upgrading the microcontroller, could greatly increase the system's effectiveness and support sustainable farming practices.

Conclusion

In conclusion, this project successfully achieved its goal of investigating a solar-powered fertigation system while analyzing the criteria necessary for its sustainability and cost-effectiveness. By integrating electrical and electronic components, with the ESP32 serving as the control center, the system has enabled effective circuit operation and streamlined processes.

The primary objective of this research was to develop an energy-efficient fertigation system that operates entirely on renewable solar energy, significantly minimizing the reliance on human intervention. The investigation encompassed two critical components: a Solar Monitoring System and a Weather Station System. Together, these systems empower users to monitor solar energy production in real-time through the Blynk application, providing an accessible interface for users to optimize their agricultural practices from the comfort of their homes.

This project not only promotes environmentally friendly practices but also contributes to a sustainable and safe environment by maximizing solar energy harvest based on real-time weather conditions. Furthermore, the cost-effective approach embedded within the solar-powered fertigation system makes it particularly advantageous for farmers. By reducing operational costs associated with conventional energy sources and enhancing the efficiency of water and fertilizer use, this system offers a compelling economic incentive for adoption.

Importantly, the solar-powered fertigation system is designed to be user-friendly, successfully meeting all outlined objectives and paving the way for future advancements in agricultural technology. As the agricultural sector increasingly embraces renewable energy solutions, this project exemplifies how innovative approaches can lead to both environmental sustainability and financial viability.

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