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Single-Axis Solar-Powered Water Quality Monitoring with Internet of Things

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Abstract

This project focuses on the design and implementation of a single-axis solar-powered water quality monitoring system integrated with Internet of Things (IoT) technology to enable real-time data collection, transmission, and analysis of key water parameters. The aim of this project is to provide an efficient, reliable, and sustainable solution for monitoring water resources, particularly in remote or off-grid areas where traditional manual sampling methods are time-consuming, costly, and often result in delayed responses. The system incorporates a single-axis solar tracking mechanism designed to maximize energy generation by continuously adjusting the position of the solar panel toward the sun throughout the day. During testing at UTHM lake, the solar tracking system successfully produced an output power of 21.04 W, demonstrating its ability to supply continuous energy to power the IoT-based sensors. These sensors recorded key water quality parameters, including pH levels ranging from 6.29 to 6.39, turbidity measured at 42.5 NTU, and water temperature between 28.3°C and 32.3°C. The collected data was transmitted in real time to a cloud platform for storage, monitoring, and analysis, enabling timely detection of changes in water quality. The findings of this project demonstrate that the system can operate effectively under actual environmental conditions, offering a practical and environmentally friendly solution for continuous water quality monitoring and proactive water resource management.

1. Introduction

In recent years, combining solar energy with environmental monitoring has gained attention as a sustainable way to manage natural resources. One effective application is solar-powered water quality monitoring, especially in water sports areas like swimming and boating sites. Poor water quality caused by contaminants such as pathogens and pollutants can pose serious health risks, making it essential to monitor parameters like pH, dissolved oxygen (DO), temperature, and turbidity [1]. Traditional testing methods are often slow and inefficient but using Internet of Things (IoT) sensors powered by solar energy allows for real-time, automated monitoring [2]. A single-axis solar tracking system improves energy efficiency by adjusting the solar panel's position throughout the day, ensuring continuous power even in off-grid or remote areas environments [3].

Previous studies have highlighted the growing importance of IoT-based water quality monitoring systems because they provide real-time data and operate efficiently in remote or off-grid areas using solar energy. These systems can monitor important water parameters such as pH, temperature, dissolved oxygen, and turbidity without manual testing. For instance, Pires and Gomes [4] designed a system that uses LoRa technology to transmit data over long distances, which is especially useful in rural areas. Similarly, Bahri et al. [5] showed that integrating solar energy with IoT ensures continuous system operation and reduces carbon emissions, making it a more environmentally friendly option. In comparison, traditional systems rely on grid power or frequent battery replacements, which limit their efficiency and application in remote areas. These systems typically use more energy due to manual processes and offline data handling and support fewer sensors, making data collection slower and more labor-intensive [5].

Furthermore, they are prone to data loss during power outages, especially when backup power is unavailable [6]. Consequently, they contribute to a higher carbon footprint due to the limited use of renewable energy sources. In contrast, IoT-based systems are equipped with batteries to store energy and automated features that reduce the need for manual maintenance. They are often powered by solar photovoltaic (PV) panels, which offer a clean and cost-effective energy solution [6]. Moreover, Chen et al. [7] emphasized the importance of using strong, weather-resistant sensors to ensure long-term accuracy. Additionally, Rosita et al. [8] highlighted the use of cloud-based platforms with real-time dashboards, which allow users to respond quickly to changes in water quality. To address data security concerns, Huan et al. [9] proposed the integration of blockchain technology, while Parra et al. [10] applied machine learning to analyze historical data and predict future issues, supporting proactive maintenance. Overall, combining IoT, solar energy, and advanced technologies such as cloud computing, blockchain, and artificial intelligence provides a reliable, energy-efficient, and sustainable solution for modern water quality monitoring.

This project aims to design and implement such a system to provide a reliable, sustainable solution for water safety and environmental protection in water sports environments. By reducing dependence on grid electricity and lowering carbon emissions, this approach supports long-term environmental and economic sustainability goals [11]. The system will allow continuous real-time monitoring, enabling faster detection of water quality issues that may pose health risks to users. Additionally, it can serve as a model for future smart environmental monitoring systems in similar remote or recreational settings.

2. Methodology

In this project, the NodeMCU ESP32 is used for water quality monitoring. At the same time, an Arduino Uno controls the single-axis solar tracker using a worm gear motor for precise solar panel adjustment. Sensors measuring pH, temperature, and turbidity are connected to the ESP32 to monitor water quality. Additionally, voltage and humidity sensors are used to monitor the system's performance and environmental conditions. The Arduino Uno adjusts the position of the solar panel using the worm gear motor for optimal energy collection, ensuring continuous system operation. All collected data is displayed on a local LCD screen for real-time monitoring and transmitted to the Blynk IoT platform for remote monitoring and analysis through a smartphone or web dashboard.

2.1 Block Diagram

Fig. 1 illustrates the overall process and workflow necessary for the successful implementation of this project. The primary tasks involve identifying the problem statement and formulating clear objectives and scopes to serve as a guideline for the project. A well-defined objective and scope are essential to ensure the project's alignment and focus. This project combines several sensors—pH, temperature, turbidity, DHT, and voltage sensors—connected to a NodeMCU ESP32 microcontroller to monitor water quality. The sensor data is shown on an LCD screen and sent to the Blynk IoT platform for real-time remote monitoring. The system is powered by a single-axis solar tracking setup, which includes a solar panel, charge controller, sealed lead-acid battery, switch, and step-down module to provide stable power. The solar panel charges the battery, and the battery powers all components, ensuring continuous and reliable operation. An Arduino Uno with an LDR sensor detects sunlight intensity and controls a worm gear motor via a relay module to adjust the solar panel's angle for better energy capture. This setup allows the water quality monitoring system to run efficiently using sustainable solar energy.

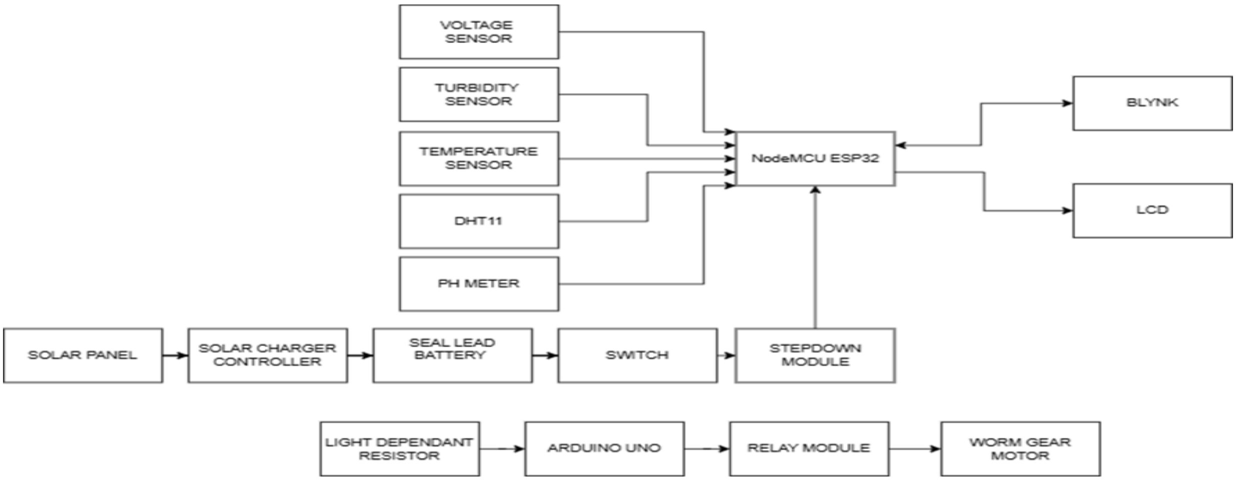

Fig. 1 *Block Diagram of Solar-Powered IoT based Water Quality Monitoring System*

2.2 Hardware Schematic Diagram

Fig. 2 illustrates the schematic diagram of the single-axis solar-powered water quality monitoring system, which combines solar energy with real-time water quality monitoring. The system uses IoT sensors, a NodeMCU ESP32, and a solar tracking mechanism controlled by an Arduino Uno. A Light Dependent Resistor (LDR) detects sunlight and, through a relay module, activates a worm gear motor to adjust the solar panel's angle for better energy capture. The solar panel charges a 12V 7AH sealed lead-acid battery via a solar charge controller, supplying power to the system. Sensor readings are shown on an LCD and sent to the Blynk IoT platform for real-time monitoring.

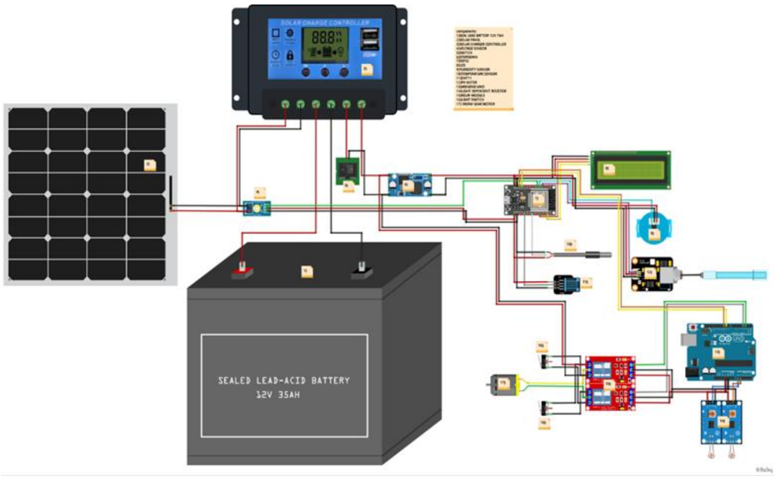

Fig. 2 *Single Axis Solar Powered Water Quality Monitoring System Schematic Diagram*

As shown in the Fig. 2, the entire hardware setup is designed using Fritzing software and connects all components from the solar panel to the water quality monitoring system. These components include the Solar Panel, Solar Charge Controller, Battery, Voltage Sensor, Switch, Step-Down Converter, ESP32, LCD, Turbidity Sensor, Temperature Sensor, DHT11, pH Meter, Arduino Uno, LDR, Relay Module, Limit Switch, and Worm Gear Motor. Each element is essential for ensuring reliable energy supply, effective solar tracking, and accurate collection of water quality data.

2.3 Battery Selection and System Runtime Analysis

The battery selection section is crucial in determining the appropriate power source for a system. This process ensures that the battery meets the energy and voltage requirements of all components while providing sufficient runtime and longevity. The battery must be selected based on its capacity, which is a key factor in ensuring the system operates for the desired duration. Battery capacity is typically expressed in amp-hours (Ah) or milliamp-hours (mAh) and indicates how much charge the battery can store and deliver over time. To calculate the required battery capacity, use Equation 1:

$$\text{Capacity(Wh)} = \text{V} \times \text{Ah} \tag{1}$$

where:

- V is the battery voltage in volts (V),
- Ah is the battery capacity in amp-hours (Ah).

This ensures the battery can meet the energy demands of the system and provides the necessary power over the desired period. System Runtime Analysis is a critical part of the battery selection process, as it helps determine how long the battery will last while powering the system before needing a recharge. This analysis considers the power consumption of the system and the capacity of the selected battery. To calculate the runtime, use Equation 2:

$$\text{Runtime (hours)} = \frac{\text{Battery Capacity(Wh)}}{P_{\text{Total}}} \tag{2}$$

where:

- Battery Capacity (Wh) is the total energy stored in the battery (calculated from the battery's voltage and amp-hour rating),
- P_{Total} is the total power consumption of the system in watts.

2.4 Blynk IoT Application

To enable notifications and data exchange over the internet, an IoT system requires a smartphone application that can connect to the NodeMCU ESP32 microcontroller. Blynk is an ideal IoT platform that allows users to remotely monitor and control the ESP32 device through the internet. It provides a user-friendly dashboard with clear visuals to display sensor readings, graphs, and real-time data, making the monitoring process simple and effective. Blynk supports two-way communication with the NodeMCU ESP32, enabling the device to both send and receive data. Compatible with both iOS and Android, it is widely accessible. As a versatile IoT solution, Blynk offers features such as device-cloud connectivity, data visualization, remote control, and system management—making it a powerful tool for IoT-based water quality monitoring systems. Fig. 3 shows the Blynk IoT application interface used to display water quality data such as pH, turbidity, and temperature in real time via a smartphone.

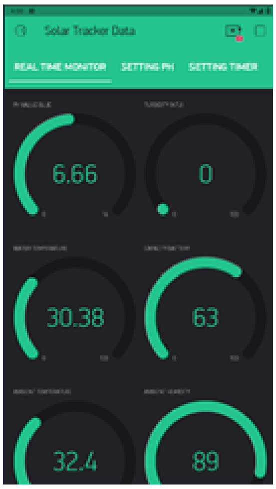

Fig. 3 *Blynk IoT application interface*

3. Results and Discussion

This segment presents the results and analysis from the study, focusing on the single-axis solar-powered water quality monitoring system integrated with the Internet of Things (IoT). The data collected and the subsequent calculations address key constraints and performance parameters of the system. These results provide a comprehensive basis for evaluating the effectiveness of the selected components and subsystems, and they guide further optimization efforts to enhance system reliability, efficiency, and accuracy.

3.1 Power Output Comparison: Single-Axis Solar Tracking vs Fixed Solar Panel System

The performance of the single-axis solar tracking system was tested over three days to compare its power output with a fixed solar panel. Both panels were placed side by side under the same environmental conditions to ensure accurate and fair results. During the test, solar energy data from both systems was collected and analyzed. The results clearly show that the single-axis tracker consistently generated more power than the fixed panel. This is because the tracker follows the sun's movement, allowing it to capture more sunlight throughout the day. The findings prove that solar tracking improves power generation efficiency, which is especially important for reliable and sustainable use in remote or off-grid areas. Fig. 4, Fig. 5 and Fig. 6 show the comparison of power output between a single axis solar tracker and a fixed solar panel for 3 days. This difference in performance is clearly shown in all the figures.

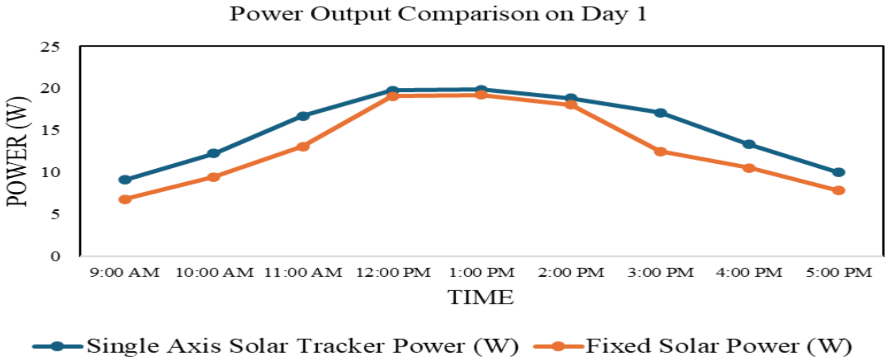

Fig. 4 *Graph Comparison of Power Output between Single Axis Solar Tracker and Fixed Solar on Day 1*

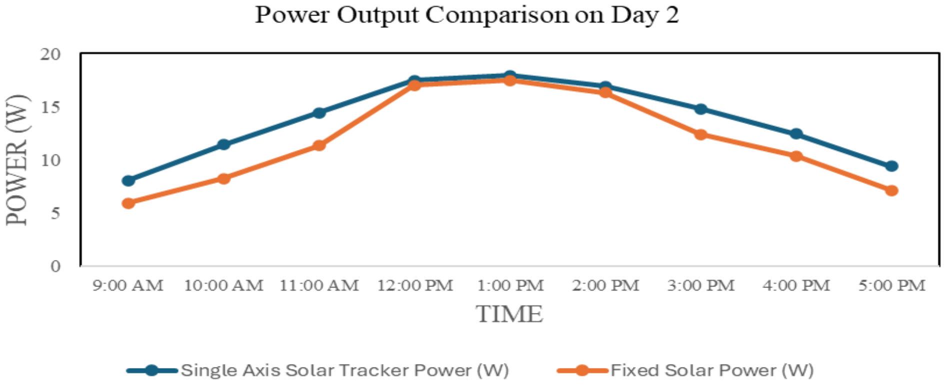

Fig. 5 *Graph Comparison Power Output between Single Axis Solar Tracker and Fixed Solar on Day 2*

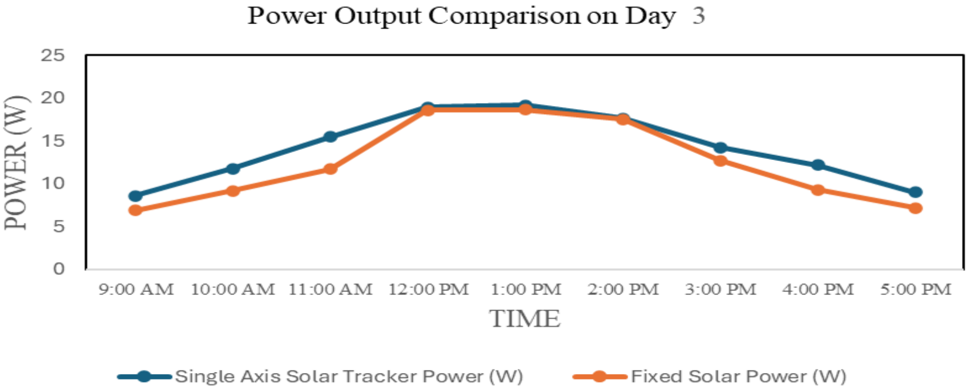

Fig. 6 *Graph Comparison Power Output between Single Axis Solar Tracker and Fixed Solar on Day 3*

3.2 Battery Charging by Single Axis Solar Tracker

Fig.7 shows the graph for the battery charging performance of the single-axis solar tracker from 9:00 AM to 5:00 PM. At the start of the day, the battery level was 74%. As the tracker followed the sun and adjusted its position throughout the day, it generated steady power, which helped increase the battery charge. By 1:00 PM, the battery had reached 86% as the tracker operated efficiently. The battery kept charging in the afternoon, reaching 90% by 3:00 PM. Even as sunlight gradually reduced towards the evening, the tracker maintained enough power generation to continue charging the battery. By 5:00 PM, the battery level reached 93%, showing the system's ability to operate effectively throughout the day. This gradual and consistent battery charging performance is clearly shown in Fig. 7.

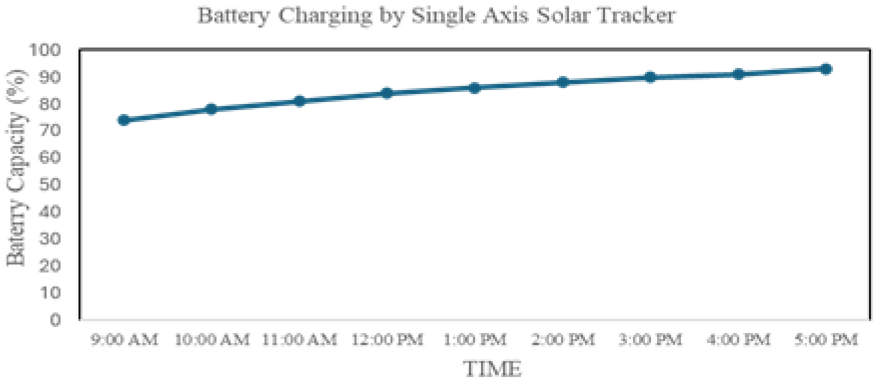

Fig. 7 *Graph Showing Battery Capacity Over Time*

3.3 Water Quality Monitoring Testing at UTHM Lake

Water quality monitoring was conducted at UTHM Lake from 11:00 AM to 5:00 PM, with data recorded every 2 hours. The purpose was to test the system's ability to measure and transmit real-time data using sensors powered by a single-axis solar tracker. Parameters such as temperature, pH, and turbidity were recorded, and all data were transmitted live through the Blynk application. All the recorded values are shown in Table 1. Table 1 summarizes the water quality parameters measured at UTHM Lake. The pH values ranged from 6.29 to 6.39, slightly acidic to neutral and still within the acceptable range for recreational use. Turbidity remained constant at 42.50 NTU—higher than drinking water standards but acceptable for water sports if no harmful substances exist. The water temperature varied between 28.3°C and 32.3°C, which is comfortable and safe for recreational activities. During testing, the ambient temperature was between 30.0°C and 32.0°C, with humidity levels ranging from 84% to 90%, typical for tropical weather. Participants are advised to stay hydrated and wear appropriate clothing when engaging in outdoor activities.

Table 1 *Water Quality Parameters Measured at UTHM Lake*

Time	pH Value	Turbidity (NTU)	Water Temprature (°C)	Ambient Humidity	Ambiant Temprature (°C)
11:00 AM	6.29	42.50	29.50	88.00	31.20
1:00 PM	6.39	42.50	32.30	84.00	32.00
3:00 PM	6.33	42.50	31.20	85.00	31.80
5:00 PM	6.36	42.50	28.30	90.00	30.00

4. Conclusion

This study shows that the single-axis solar-powered system is effective for powering water quality monitoring devices and performs better than fixed solar panels. By following the sun, the tracker captures more energy throughout the day, leading to higher power output and efficient battery charging. Over three days of testing, it consistently produced more energy and charged the battery from 74% to 93%, proving its reliability in off-grid conditions. The system successfully powered sensors to collect real-time data on temperature, pH, and turbidity, all transmitted through a solar-powered setup. The system is suitable for outdoor and remote use, where electricity may not be available. In conclusion, combining a single-axis solar tracker with water quality monitoring provides a reliable and sustainable solution for real-time data collection in remote areas.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception, design, data analysis and manuscript preparation****: Ahmad Syakir Iman Mohd;* ***manuscript verification:*** *Khairul Anuar Mohamad. All authors reviewed the results and approved the final version of the manuscript*

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