Cloud Connectivity Monitoring of a Photovoltaic-Powered Water Purification Unit

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***Abstract*—Access to safe drinking water and reliable energy sources continues to be a major concern in rural and remote regions. This paper presents the design and implementation of a cloud-connected monitoring system for a photovoltaic-powered water purification unit, developed to provide a sustainable and efficient solution for water treatment in off-grid areas. The system operates using solar energy and incorporates a multi-stage purification process to remove physical, chemical, and biological contaminants, ensuring the production of safe drinking water. An embedded microcontroller is used to monitor important parameters such as solar panel output, battery condition, water flow rate, and water quality indicators. These parameters are continuously collected and transmitted to a cloud platform using IoT-based communication. The cloud system enables real-time monitoring, data storage, and performance analysis through user-friendly web or mobile interfaces. The integration of cloud monitoring enhances system reliability by allowing early detection of faults and supporting predictive maintenance. It also reduces the need for manual supervision, making the system suitable for remote and resource-limited environments. The proposed system is cost-effective, energy-efficient, and scalable for wider deployment.**

Overall, this work demonstrates how the combination of solar energy, water purification technologies, and cloud-based monitoring can improve access to clean water while supporting sustainable development goals related to health, clean energy, and environmental protection.

I. INTRODUCTION

Providing safe drinking water continues to be a serious challenge in many rural and remote areas, where access to electricity and proper purification systems is limited [1,9]. People in such regions often depend on untreated water sources, which can lead to serious health issues due to contamination.

This paper presents a solar-powered water purification system integrated with cloud-based monitoring. The system operates using photovoltaic energy and applies multiple purification stages to ensure water safety. In addition, IoT-enabled sensors monitor key parameters and send data to a cloud platform for real-time tracking and analysis [6].

The proposed system is designed to be portable, energy-efficient, and easy to use, making it suitable for off-grid locations and emergency conditions [2,3]. It offers a sustainable and reliable approach to improving access to clean drinking water.

II. LITERATURE REVIEW

Several studies have explored solar-powered water purification as a sustainable solution for clean water access [11]. Early works focused on portable systems that combine multiple filtration methods such as activated carbon, nanofiber membranes, solar distillation, and UV treatment to improve water quality [1,4]. These systems are lightweight, cost-effective, and suitable for rural and disaster-affected regions.

Many researchers have emphasized the use of renewable energy to reduce dependence on conventional electricity. Solar-powered purification units with battery backup and efficient energy

management have been developed to ensure continuous operation even in low sunlight conditions. Some designs also incorporate reverse osmosis technology with reduced power consumption, making them more suitable for off-grid applications [2,8].
Recent developments highlight the integration of microcontrollers and sensor-based monitoring systems. These systems measure parameters such as water quality and system performance, enabling automation and improving reliability. In addition, IoT-based approaches allow real-time data transmission and remote monitoring through web or mobile platforms [7,9].
Overall, existing studies demonstrate that solar-powered purification systems are effective, economical, and environmentally friendly. However, there is still a need for systems that combine efficient purification, reliable energy management, and advanced cloud-based monitoring in a single integrated solution [3,5].

III. SYSTEM ARCHITECTURE

The system is designed as an integrated setup combining solar power, water purification, and cloud monitoring [8,11]. It consists of three main sections: power supply, purification unit, and control system.
The power unit uses a solar panel with battery storage to provide continuous energy. Voltage converters are used to supply appropriate power levels for both the pump and electronic components [2,8].
The purification unit follows a multi-stage process, including sediment filtration, carbon filtering, reverse osmosis, and UV treatment, ensuring safe drinking water. A float switch is used to control water levels and protect the system [3,4].
The control unit is built around an ESP32 microcontroller, which collects data from sensors and automates system operation. The data is also sent to a cloud platform, enabling real-time monitoring through a web or mobile interface [6,7].

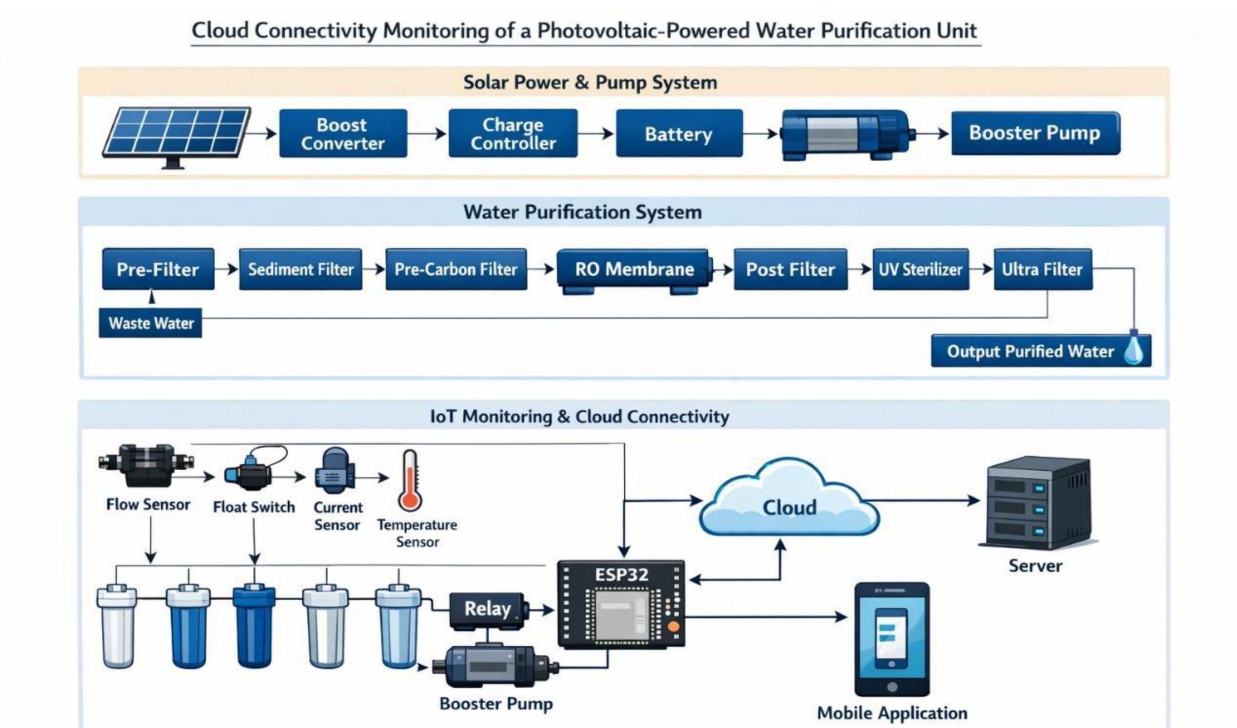

Fig.1. Block diagram of system architecture

IV. METHODOLOGY

A.Filtration Process
The system uses a multi-stage purification method [4]. Water first passes through sediment and carbon filters to remove particles and impurities. It is then pressurized through a reverse osmosis membrane to remove dissolved contaminants. Finally, UV treatment and post-filtration improve water quality and ensure safe drinking water [3,10].

B.Power Management

Solar energy is used to power the system [11]. A photovoltaic panel charges a battery through a charge controller [2]. A boost converter supplies power to the pump, while a buck converter provides stable voltage to the controller and sensors [8,9].

C. Control and Automation

The ESP32 microcontroller monitors sensor data and controls the pump based on water level [6]. A delay mechanism avoids frequent switching, and safety features automatically stop the system during abnormal conditions [7,10].

D. Cloud Monitoring

Sensor data is sent to a cloud platform for real-time monitoring. Users can view system performance through a web or mobile interface, enabling remote control and analysis.

V. DESIGN AND IMPLEMENTATION

A. Hardware Design and Interfacing

The hardware architecture is centered around the ESP32 microcontroller, which acts as the link between the purification system and the cloud platform. Special care is taken to protect the controller from high-current components such as the booster pump by ensuring proper electrical isolation.

The ESP32 is chosen due to its built-in Wi-Fi capability and efficient processing performance, allowing it to handle both sensor data acquisition and communication tasks. The system uses a dual power arrangement: a boost converter provides a stable 24 V supply for the pump, while a buck converter steps down the voltage to a safe level (3.3 V–5 V) for the controller and sensors. This separation ensures stable operation even during sudden load changes [6].

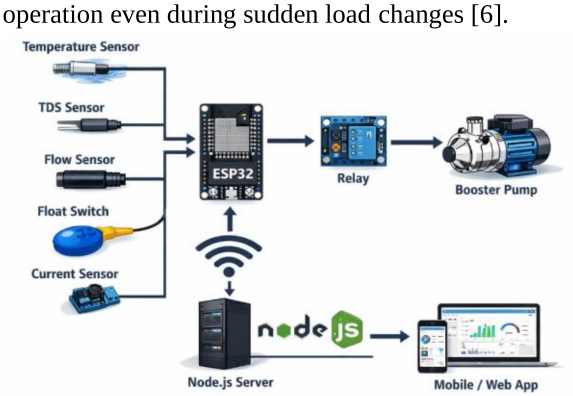

Fig.2.System block diagram

Different types of sensors are integrated into the system. Analog sensors, such as the TDS and current sensors, are connected to the ADC pins of the ESP32 with proper voltage scaling to maintain safe input levels. Digital sensors, including the temperature sensor, communicate using a single-wire protocol, while the flow sensor generates pulses that are counted to measure water flow accurately [2,11].

B. Physical System Architecture

The purification unit is designed using a multi-stage filtration process arranged in a modular flow sequence to improve efficiency.

Initially, raw water passes through sediment and carbon filters to remove larger particles and unwanted odors. The water is then pressurized and sent through a reverse osmosis membrane for fine purification. To maintain performance, a flushing mechanism is included to clean the membrane periodically.

After this stage, the treated water undergoes further purification through ultra-filtration and ultraviolet sterilization to eliminate remaining microorganisms. A final mineralization stage adjusts the water quality to make it suitable for drinking.

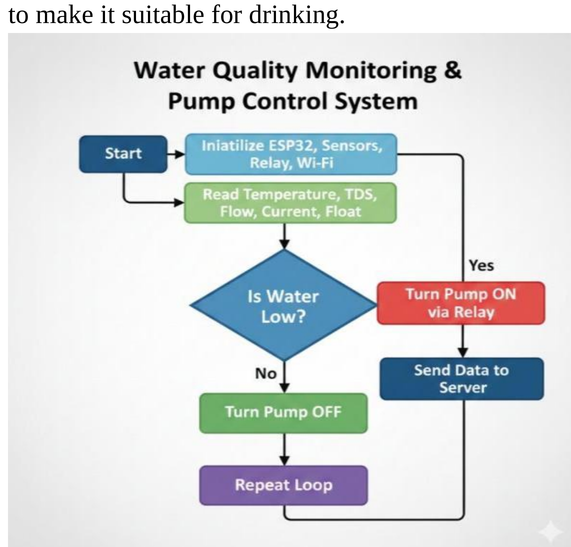

Fig.3.System flow chart

The purified water is stored in a dedicated tank equipped with a float switch. This switch communicates with the controller, enabling automatic control of the pump based on water levels, thereby preventing overflow and dry running.

C. Software Implementation and Firmware Logic

The software is developed using a structured approach based on a finite state machine, implemented in C++ within the Arduino development environment [5,11].

The controller begins by connecting to a wireless network and then continuously monitors system conditions. Based on the water level detected by the float switch, the pump is automatically turned on or off. To improve accuracy, sensor readings are processed using filtering techniques that reduce noise and fluctuations.

For remote monitoring, the system sends data to a cloud server at regular intervals. Sensor values are formatted and transmitted using HTTP requests. On the server side, a backend application processes this data and updates it in real time, allowing users to view system performance through a web or mobile interface. This setup ensures smooth communication between the hardware and the user without delays [7,11].

VI. TESTING AND RESULTS

A. Calibration and Sensor Validation

Prior to full system operation, all sensors were carefully calibrated to ensure reliable measurements. The temperature sensor was compared with a standard thermometer and showed only a small variation within ±0.5°C. The TDS sensor was calibrated using distilled water (0 ppm) and a standard solution (1000 ppm) to establish a linear relationship within the controller program.

Similarly, the current sensor was tested under different load conditions to accurately measure the current drawn by the pump. These calibration procedures ensured that the data transmitted to the cloud accurately reflects real system conditions [7].

B. Power Management and Solar Performance

The solar power system was evaluated under both daytime and night-time conditions. During peak sunlight hours, the photovoltaic panel generated enough energy to operate the pump while simultaneously charging the battery. The voltage output remained stable even with minor fluctuations in sunlight.

During night-time testing, the battery successfully powered the controller and sensors for over 18 hours without interruption.

The power conversion system operated efficiently with minimal energy loss. The transition between solar supply and battery backup was smooth, with no system resets or disruptions observed [2,8].

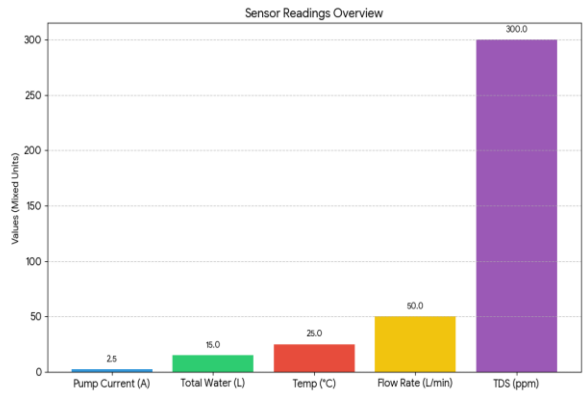

Fig.4.Sensor readings overview

C. Automation and Safety Testing

The system's automated control was tested under different fault conditions to verify reliability. In the overflow test, the tank was filled completely, and the float switch correctly signaled the controller to stop the pump.

In the dry-run test, the water supply was reduced, causing a drop in current consumption. The system detected this abnormal condition and automatically switched to a safe standby mode, preventing damage to the pump. These tests confirm that the automation logic improves system safety and reduces the need for manual monitoring [10].

D. Purification Performance and Data Handling

The purification process was evaluated by comparing water quality before and after treatment. The system achieved a TDS reduction of approximately 85–90%, indicating effective filtration. The water flow rate remained stable, and the UV unit operated continuously during purification [4,5].

On the monitoring side, the cloud platform maintained consistent performance during extended testing, successfully receiving and displaying real-time data from the system. This confirms the reliability of both the purification process and the data communication framework.

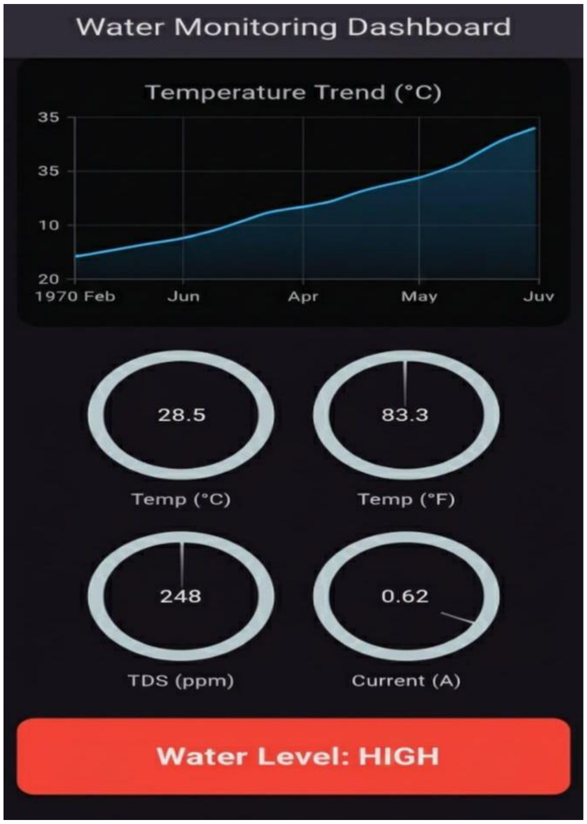

Fig.5.Application frontend

Fig.6.Application logo

VII. CONCLUSION AND FUTURE SCOPE

This work demonstrates the effectiveness of integrating cloud connectivity with a solar-powered water purification system to address the challenge of safe drinking water in off-grid areas. By combining photovoltaic energy with IoT-based monitoring, the system enables reliable purification while reducing the need for continuous manual supervision. Real-time tracking of water quality and system performance improves efficiency and ensures consistent output. The proposed approach highlights how renewable energy and smart technologies can work together to deliver a practical, cost-effective, and environmentally sustainable solution for clean water access.

FUTURE SCOPE:

The system can be further enhanced by incorporating advanced technologies to improve automation and reliability. Artificial intelligence can be used to predict maintenance requirements and optimize system performance based on data trends. Hybrid energy solutions, such as battery storage or additional renewable sources, can ensure uninterrupted operation during low sunlight conditions. Improved sensing techniques can enable detection of a wider range of contaminants, while low-power communication technologies can extend connectivity in remote regions. These advancements can transform the system into a fully autonomous and scalable solution capable of serving larger communities with minimal human intervention.

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