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Research Article

Monitoring and Control of a Remote Hybrid Powered Reverse Osmosis Unit for McCallum, NL

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Abstract: This study presents the design and implementation of a low-cost, fully offline Supervisory Control and Data Acquisition (SCADA) system for monitoring and controlling a Reverse Osmosis (RO) water treatment unit powered by a Hybrid Energy System (HES) in the remote community of McCallum, Newfoundland and Labrador. The HES comprising PV panels, a wind turbine, batteries, and a DC diesel generator was designed and validated in prior work. To address the lack of Internet and cellular connectivity, the proposed system combines Long-Range (LoRa) communication with a local Message Queuing Telemetry Transport (MQTT) broker to facilitate real-time monitoring and bidirectional control. Two ESP32 LoRa modules form the hardware backbone, enabling wireless data transmission and control across a 400-meter range. Sensor data is visualized through FUXA, an open-source, web-based SCADA platform hosted locally. The system also provides audible alerts for fault conditions. Seven operational scenarios were tested to evaluate system performance, confirming reliable data acquisition, robust wireless communication, and effective remote actuation. Lab tests showed average end-to-end latency of 200–300 ms, zero packet loss in line-of-sight conditions, and a field-unit power demand of ~21–22 Wh/day. The modular architecture supports scaling to multiple RO units or larger communities without requiring Internet connectivity. The proposed architecture offers a scalable, energy-efficient, and Internet-independent SCADA solution for critical infrastructure in disconnected and resource-limited environments.

***Keywords*:** Supervisory Control and Data Acquisition (SCADA), Long-Range (LoRa), Message Queuing Telemetry Transport (MQTT), Hybrid Energy System (HES), real time control, remote monitoring

1. Introduction

Access to clean and reliable water remains a persistent challenge in remote off-grid communities such as McCallum, Newfoundland and Labrador, where drinking water shortages, lead contamination resulting from naturally occurring lead in the soil, and geographic isolation limit the implementation of conventional solutions. This remote community also lacks access to an interconnected power grid and relies on a diesel generator.

In response to these water and energy challenges, our earlier work proposed a Reverse Osmosis (RO) water treatment unit for the community, to be powered by a reliable and clean Hybrid Energy System (HES). The proposed HES consisted of photovoltaic (PV) panels, wind turbines, batteries, and a DC diesel generator as a backup power source [1] . This configuration was subsequently validated through dynamic simulation studies in MATLAB/Simulink, which demonstrated

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the system's stability and reliability under the inherently variable conditions associated with wind and solar energy sources [2].

However, such systems' practical deployment and sustainable operation face significant challenges, particularly the lack of communication infrastructure, internet connectivity, and regular on-site supervision. These limitations hinder real-time monitoring and remote control—especially for critical components like diesel generators, which must operate reliably during renewable energy shortfalls. Several studies have explored the potential of Long-Range (LoRa) and Message Queuing Telemetry Transport (MQTT) for remote monitoring applications. For example, Huang et al. [3] developed a LoRa + MQTT prototype for marine water quality monitoring, showcasing LoRa data collection and local processing. However, their system lacked Supervisory Control, Data Acquisition (SCADA) dashboards and two-way control capabilities [4]. Similarly, Rhesri et al. [5] implemented a low-cost Internet of Things (IoT) platform using ESP32 and MQTT for three-phase energy monitoring in a university campus, demonstrating the effectiveness of open-source tools. Yet, the system depended on stable Wi-Fi connectivity and lacked LoRa or offline functionality, limiting its use in isolated locations. Pires and Gomes [6] deployed a LoRa + MQTT system for river water monitoring, visualized through Node-RED. While offering real-world deployment, the system did not include field actuation or SCADA-level integration.

While previous work has shown that LoRa and MQTT are effective for IoT-based monitoring, most systems rely on Internet/cloud services, lack SCADA integration, and support only one-way data flow [6]. FUXA, though promising as a web-based SCADA tool, has not yet been applied in fully offline, bidirectional control systems, with prior deployments still dependent on online connectivity or lacking field actuation capabilities [4]. This study addresses these gaps by developing a fully local system featuring LoRa communication, MQTT messaging on an offline broker, full SCADA integration via FUXA, and two-way diesel generator control in a remote community. The subsequent sections present the Materials & Methods, detailing the system layout and communication architecture; system design, describing the hardware components and software logic of the Field and Operation Units; and results, including real-world testing scenarios and performance evaluation metrics that validate the system's performance under different operating conditions.

2. Materials & methods

McCallum as a remote coastal community lacks centralized power infrastructure and has no access to reliable Internet or cellular networks. As shown in Figure 1, the RO system and HES are installed near the community's water well, while the operator station is located approximately 400 meters away across the harbor. This physical separation, combined with the absence of connectivity presents a substantial barrier to conventional monitoring and control making a robust, locally autonomous solution essential.

This paper developed a compact monitoring and control system specifically designed for isolated environments. The system integrates ESP32 modules with LoRa radios to create a long-range wireless link between the field and operator units. Unlike conventional SCADA platforms that rely on network infrastructure, this design operates entirely offline and consumes minimal power. Sensor data is transmitted over LoRa to a receiver LoRa located at the operator station. There, a locally hosted MQTT broker processes the incoming data and delivers it to the web-based SCADA system platform (FUXA) interface for visualization. In addition to monitoring, the system enables two-way control over the same LoRa link, allowing SCADA-issued commands to reach the field unit. Its modular, open-source, and fully local design offers a scalable, low-cost solution for managing critical infrastructure in disconnected settings. By avoiding reliance on cloud services or commercial networks, the architecture enhances resilience and meets the practical need for real-time control in remote, infrastructure-limited environments. For this study, the system was implemented and tested in a controlled laboratory environment using simulated HES and RO loads, rather than in the field at McCallum. This approach allowed controlled evaluation of functionality and communication performance, though long-term outdoor environmental effects were not assessed at this stage. The system is structured into two interacting units: the Field Unit and the Operation Unit. The overall architecture and related data flow are illustrated in Figure 2 and can be summarized as follows:

(i) **Monitoring path** – sensors (HES/ RO System) → ESP32 → LoRa Transmitter (TX role) → LoRa Receiver (RX role) → ESP32 → Mosquitto broker→ FUXA

(ii) **Control path** – FUXA GUI → Mosquitto broker → ESP32 → LoRa (TX role) → LoRa (RX role) → ESP32 → relay → diesel generator (Roles indicate direction per path; each board is a transceiver).

Figure 1. SCADA system with 400 m LoRa communication path in McCallum, NL, Canada [7]

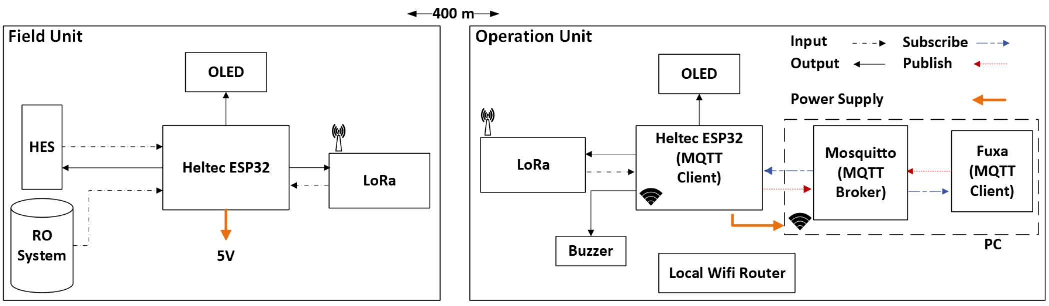

Figure 2. Proposed SCADA system block diagram in Field Unit and Operation Unit

2.1 *Field Unit*

The Field Unit is installed at the location of the RO and HES system and is responsible for acquiring all electrical and water-related measurements, as well as executing control commands.

2.1.1 *HES & RO system simulator*

Instead of a full-scale HES, this implementation utilizes a Solar/Wind Energy Training System (LabVolt) as to simulate the PV, wind, and battery sources. Furthermore, a DC power supply (TEAMA) simulates the DC diesel generator source. This platform with details mentioned in Table 1 and configuration shown in Figure 3 safely provides a stable 120 V AC output to power the load, which is represented by the simulated RO system.

Table 1. HES system details

Component	Specification
PV Module	85 W, Vmp: 17.9 V, Imp: 4.84 A
Wind Turbine Generator	400W,7 A, driven by a 90 V PMDC motor at 1800 rpm
Battery Bank	12 V, 110 Ah, sealed AGM lead-acid
Power Inverter	1 kW, 12 V DC to 120 V AC, 60 Hz
Solar Charge Controller	PWM, 12 V, 30 A max charging current,
DC Diesel Generator	DC Power Supply, 0–30 V, current-limited at ~5 A

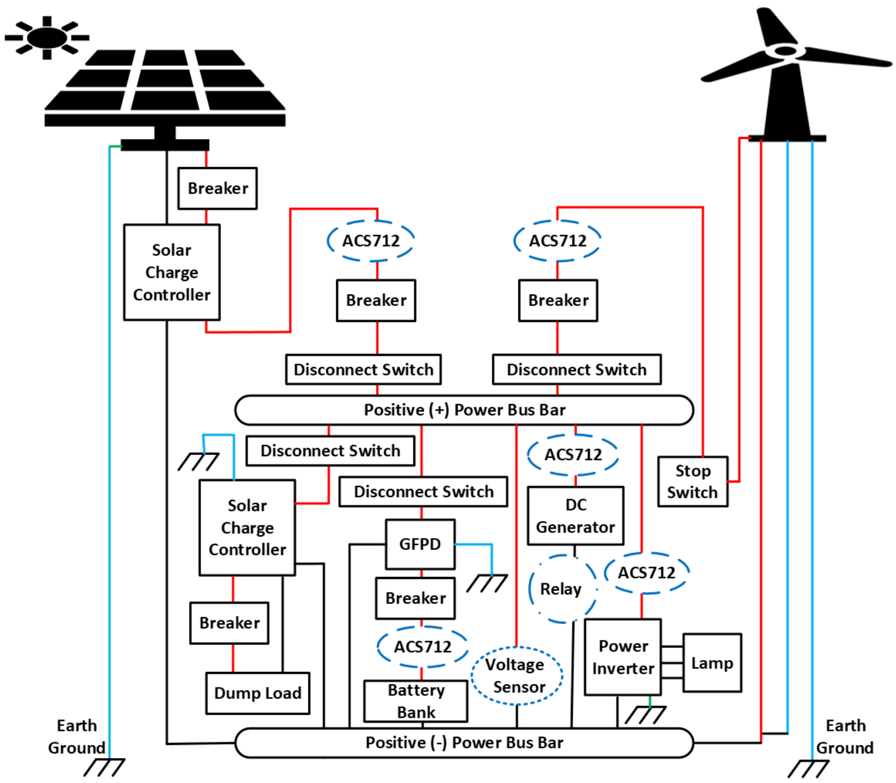

Figure 3. HES Architecture with sensing and relay control

2.1.2 *Sensor and actuation subsystem*

The Field Unit integrates analog and digital sensors and an actuation device interfaced with the Heltec ESP32 microcontroller to enable real-time monitoring and remote control of the hybrid-powered RO system. These components deliver essential measurements to the SCADA system and support control actions.

1. **Current measurement:**

Current sensing uses ACS712 Hall-effect sensors (±5 A), which provide a ratiometric analog voltage output with a typical sensitivity of 185 mV/A [8]. Five sensors monitor key current paths: PV, Wind turbine, battery charging/discharging, inverter, and the diesel generator line. To ensure compatibility with the ESP32's ADC, which operates at a maximum input voltage of 3.3 V, a voltage divider circuit as illustrated in Figure 4 is used on the sensor's analog output to safely scale the signal.

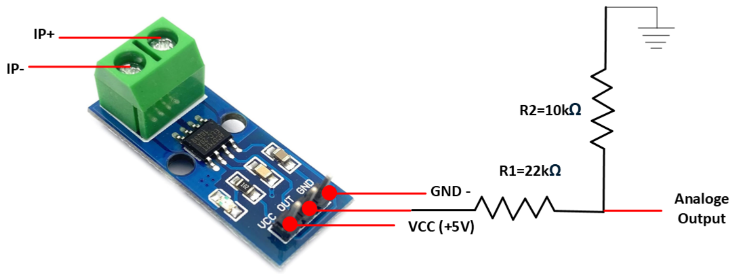

Figure 4. ACS712 current sensor module [8]

2. **Voltage measurement:**

The B25 voltage sensor as shown in Figure 5 is used to continuously measure the DC bus voltage. It employs a built-in resistive divider to scale input voltages up to 25 V DC down to a 0–5 V analog output, compatible with the ESP32 ADC input [9]. Since the DC bus voltage does not exceed 13 V, the module's output remains safely within the 3.3 V input range of the ESP32 ADC, and no additional external divider is used.

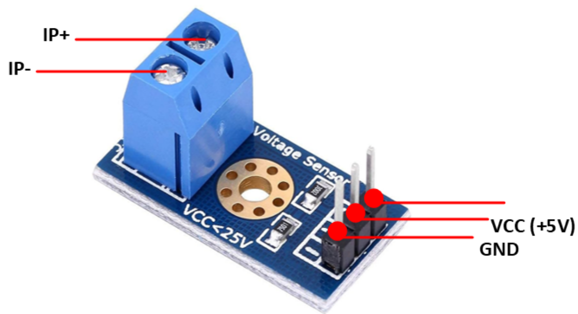

Figure 5. Voltage divider sensor module [9]

3. **Water level sensing:**

An ultrasonic sensor as illustrated in Figure 6 is mounted above the RO water tank and measures distance using a 40 kHz pulse. It supports a 2–400 cm range, with ±3 mm accuracy and a 15° beam angle, and TTL-compatible echo pulse output providing non-contact level measurement [10].

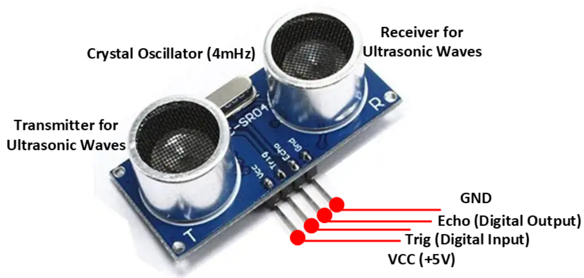

Figure 6. HC-SR04 ultrasonic distance sensor module [10]

4. **Relay-based actuation:**

Actuation is handled by an SRD-05VDC-SL-C electromagnetic relay as presented in Figure 7, directly triggered via a GPIO pin on the ESP32. It supports switching up to 10 A at 250 VAC or 28 VDC and includes SPDT contacts, opto-isolation, and flyback protection for safety and reliability [11].

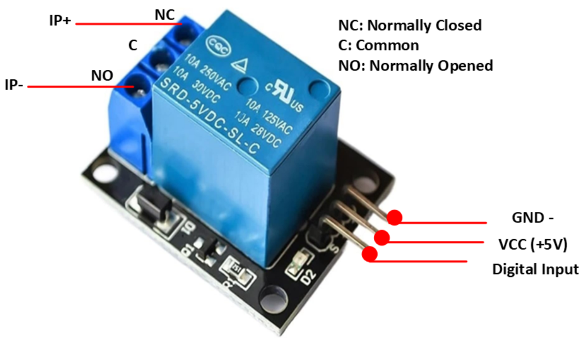

Figure 7. Electromechanical relay module [11]

2.1.3 *Main processing and communication module*

At the core of the Field Unit is a Heltec Wi-Fi LoRa 32 V3.2 development board, which manages sensor interfacing, wireless communication, local display, and actuator control. It features an ESP32-S3 dual-core processor (240 MHz) and an SX1262 LoRa transceiver, capable of 21 dBm transmission and 137 dBm sensitivity [12], ensuring reliable communication over 400 meters. In Figure 8 Wi-Fi LoRa module pin map is illustrated.

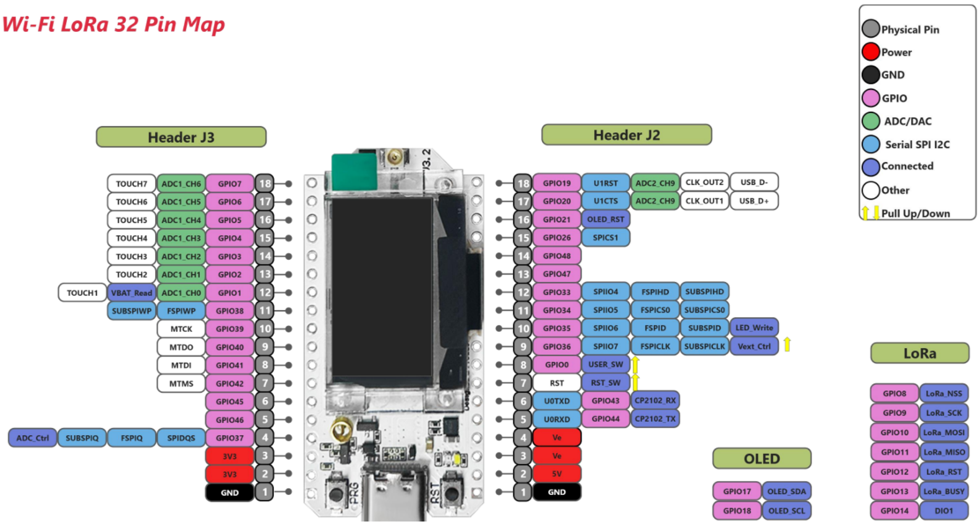

Figure 8. Wi-Fi LoRa 32 V3.2 pin map [12]

Sensor data from ACS712, B25, and HC-SR04 sensors is read via the board's 12-bit ADCs and processed in real time. Key parameters are visualized on the onboard 0.96-inch OLED. LoRa enables bidirectional data exchange: the board transmits telemetry to the Operation Unit and receives control commands to actuate the diesel-generator relay via GPIO. A regulated 5 V supply powers the board. The implemented code in the IDE follows the algorithmic logic detailed in Figure 9.

Initialization:
1.Include necessary libraries;
2.Initialize GPIO pins for sensor inputs and relay output;
3.Initialize OLED display;
4.Initialize LoRa module with defined frequency for North America (915 Hz)
Sensor Measurement and Display:
5. Read values from analog sensors;
6. Measure water level;
7. Display all sensor values on OLED screen for local monitoring;
Data Transmission and Control Handling:
8. Format sensor values into a JSON string;
9. Transmit JSON data via LoRa to Receiver Node;
10. Continuously check for incoming LoRa packet;
while LoRa receives control command packet do
    11. Parse JSON and extract relay control signal "ON" or "OFF";
    12. Set relay GPIO pin accordingly to control diesel generator;
end
13. Delay and return to Step 5;

Figure 9. Algorithm implemented in the IDE for the ESP32 module in the Field Unit

2.2 *Operation Unit*

The Operation Unit is located approximately 400 meters from the Field Unit and serves as the central interface for real-time monitoring, SCADA visualization, and remote supervisory control. This unit enables both local data access and the ability to issue control commands back to the Field Unit via the LoRa wireless link, without Internet.

2.2.1 *LoRa transceiver and display module*

A second Wi-Fi LoRa 32 V3.2 board is configured primarily for data reception, receiving and decoding telemetry from the Field Unit. Key values—voltage, current, and water level—are displayed on its onboard OLED screen, allowing the operator to visually monitor system status even without accessing the SCADA dashboard. The implemented code in the IDE follows the algorithmic logic detailed in Figure 10.

Initialization:
1.Include required libraries;
2.Connect to Wi-Fi using SSID and Password;
3.Connect to MQTT Broker using static IP address;
4.Initialize OLED display and LoRa module;
Main Loop – Data Reception and Forwarding:
5. Listen for LoRa packets from Sender Node;
6. Upon data reception, parse JSON sensor data;
7. Display parsed values on OLED screen;
8. Publish each value to MQTT topics for visualization in FUXA;
Water Level Safety Condition:
9. **if** water level < 50% **then**
10. Activate buzzer GPIO
    else
        11. Turn off buzzer;
    end
Command Handling from FUXA via MQTT:
12. Subscribe to MQTT DC Diesel Generator control topic;
13. **if** a new MQTT message is received **then**
        14. Parse "ON" or "OFF" command;
        15. Send command via LoRa to Sender Node;
        end
16. Go to step 5;

Figure 10. Algorithm implemented in the IDE for the ESP32 module in the Operation Unit

2.2.2 *Alarm handling*

To improve operational safety, a 5 V, 30 mA electronic buzzer [13] is connected to the ESP32 via a transistor switch circuit as in Figure 11. The buzzer is activated based on predefined conditions (water level falling below 50%) received via the LoRa communication link, providing immediate audible alerts. Since the ESP32's 3.3 V GPIO could not supply sufficient voltage or current to drive the buzzer directly, a transistor was used to switch the buzzer on using the 5 V power rail.

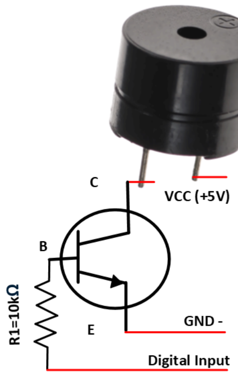

Figure 11. Active buzzer module [13]

2.2.3 *Local MQTT network: broker and client configuration*

MQTT is a lightweight publish–subscribe messaging protocol designed for low-bandwidth, low-power, and high-latency networks, making it ideal for IoT applications. It operates over TCP/IP and separates data producers (publishers) and consumers (subscribers) through an intermediary broker, which routes messages based on topic hierarchies [14]. The MQTT protocol offers three Quality of Service (QoS) levels, summarized in Table 2 [15].

Table 2. Three quality of service level offered by [15]

Level	Message delivery detail
QoS 0	at most once, no guarantee
QoS 1	at least once, may duplicate
QoS 2	exactly once, guaranteed

Its small protocol overhead (fixed 2-byte header) and ease of integration with low-cost microcontrollers have led to its widespread adoption in SCADA, smart grid, energy monitoring, and smart agriculture systems [16] . Open-source MQTT brokers like Mosquitto enable fast deployment on local devices, supporting efficient publish-subscribe communication in offline or constrained environments [15].

MQTT forms the core of local communication between the Field Unit and Operation Unit in this system. The ESP32 board is powered via USB from a local PC, that hosts the Mosquitto MQTT broker. A Wi-Fi router establishes a local network linking the ESP32, broker, and SCADA interface (FUXA). Sensor readings from the ESP32 (e.g., current, voltage, water level) are published to specific MQTT topics, which are organized hierarchically and labeled for easy parsing. The FUXA SCADA system, running as a client on the same PC, subscribes to these topics for real-time visualization. Operators can also send control commands by publishing to predefined control topics, which the ESP32 listens to and executes via the Relay module. The system employs QoS levels 0 and 1 to balance reliability and performance while ensuring that real-time constraints are met within the ESP32's resource limitations. This architecture provides robust, low-latency, bidirectional communication for monitoring and control validating the MQTT protocol's suitability for distributed SCADA environments.

2.2.4 *SCADA interface and control (FUXA)*

FUXA is a modern, open-source SCADA platform that offers a fully web-based interface for process monitoring and control. Built using Node.js and Angular, it enables rapid development of industrial dashboards and supports widely used communication protocols such as MQTT, Modbus, and OPC-UA. Its modular architecture and browser-accessible tools make it especially effective for lightweight and localized applications, particularly in IoT-based remote monitoring scenarios. FUXA simplifies the SCADA deployment process with its configuration tools and cross-platform compatibility, allowing seamless integration with devices over MQTT and other standard protocols [17].

In this system, FUXA subscribes to MQTT topics published by the ESP32 and visualizes data using charts, gauges, and status indicators. Operators can issue control commands through the GUI to start or stop the diesel generator; these commands are published to MQTT and transmitted over LoRa to the Field Unit, where the ESP32 activates the relay output. To host FUXA and Mosquitto reliably, the operator unit requires only a standard laptop or desktop with modest specifications (e.g., dual-core processor, 4–8 GB RAM). Installation: download from the official GitHub repository [18], install dependencies with Node.js (npm install), launch via npm start, and access locally at localhost:1881.

3. Results and discussion

In this part different scenarios are considered in Table 3 to check and measure responses of the deployed system shown in Figure 12.

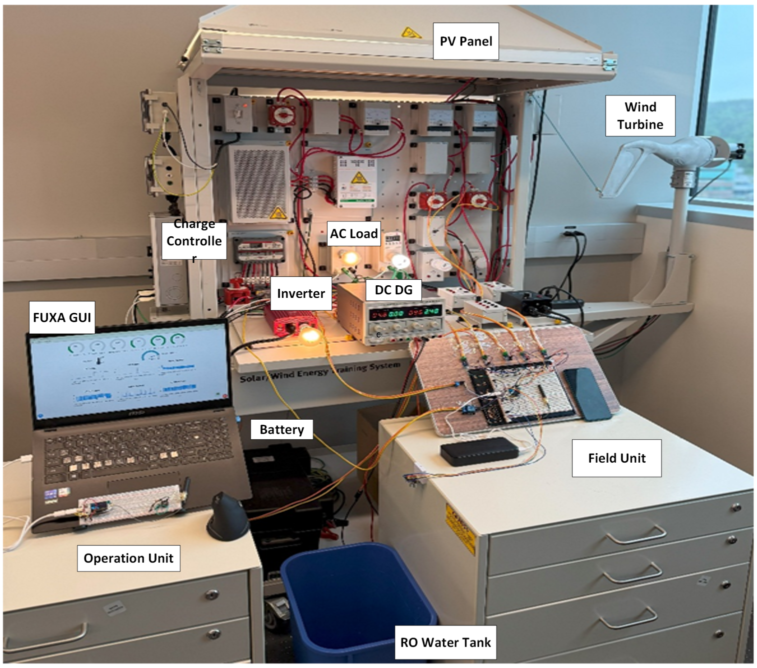

Figure 12. A photo of the experimental test setup in the lab

Table 3. Different scenarios for testing SCADA system

Scenario	1	2	3	4	5	6	7
PV	On	Off	On	Off	On	Off	Off
WT	Off	On	On	On	Off	Off	Off
DC DG	Off	Off	Off	Off	Off	Off	On
Inverter	Off	Off	On	On	On	On	On

In scenario 1 only the PV system is active. The wind turbine, diesel generator, and inverter are turned off, and no load is connected. Measured data show a negative battery current, indicating charging. This suggests that the excess energy from the PV output was directed to battery storage. The Graphical User Interface (GUI) is shown in Figure 13.

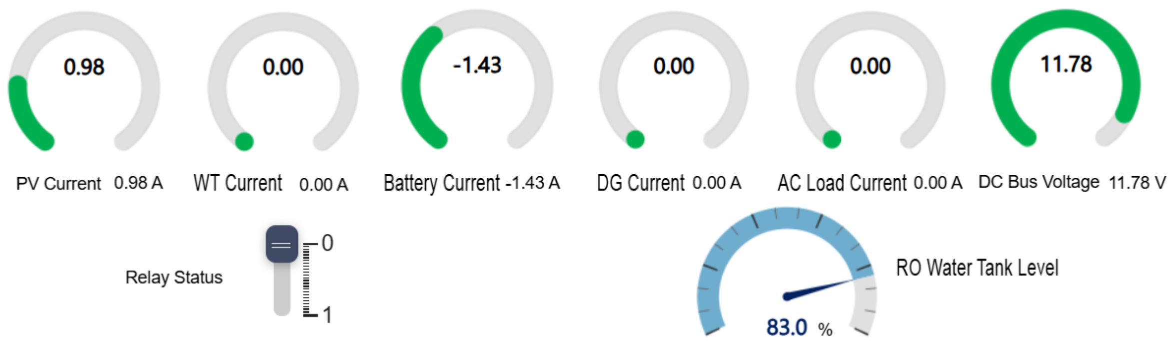

Figure 13. GUI of scenario 1

In scenario 2, the wind turbine supplies 3.80 A while the PV and diesel generator are off. Since there is no AC load, the battery is charging, indicated by the negative current (–3.60 A). The system maintains a stable DC bus voltage of 11.70 V as illustrated in Figure 14.

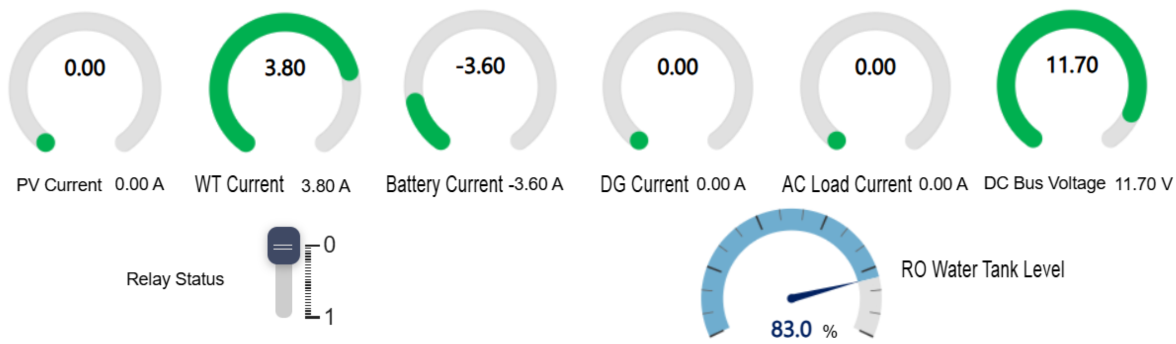

Figure 14. GUI of scenario 2

In scenario 3, with PV and WT generating and the inverter supplying a light load, the battery is correctly charging (–4.68 A), and the DC bus voltage is stable at 12.52 V, confirming normal system operation in Figure 15.

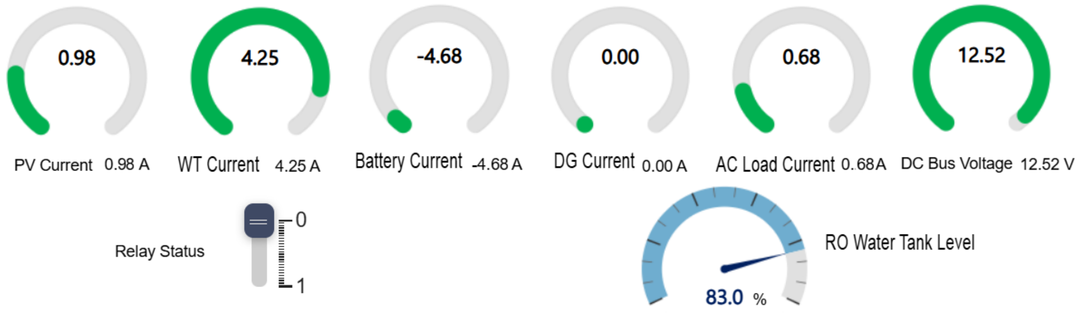

Figure 15. GUI of scenario 3

In scenario 4 and as seen in Figure 16, only the wind turbine is generating power (WT Current = 4.36 A), while the PV and diesel generator are off. The inverter is active, supplying an AC load (AC Load Current = 0.59 A). Since wind generation exceeds the load demand, the excess power is used to charge the battery, as indicated by the negative battery current (–3.99 A). The DC bus voltage is stable at 11.70 V, confirming proper system operation under a renewable-only supply.

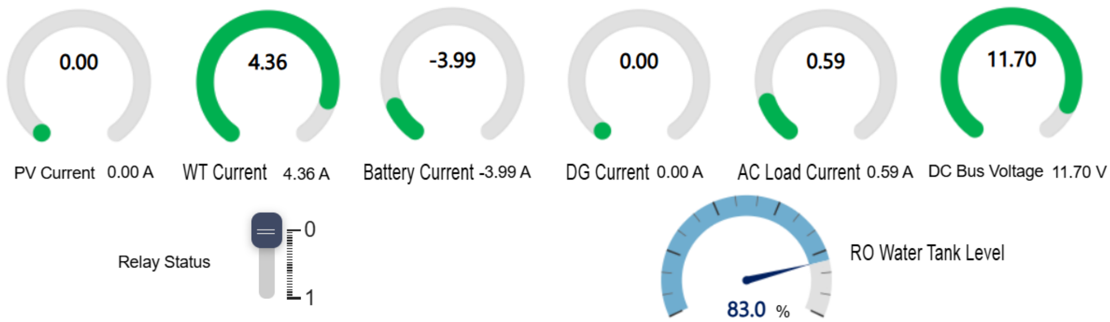

Figure 16. GUI of scenario 4

In scenario 5, the PV system generates power, while the wind turbine and diesel generator are off. The inverter is on, supplying an AC load (AC = 0.84 A). Measured values show PV output of 1.0 A and load draw of 0.84 A. The battery current (+0.20 A) suggests it was supplying the small deficit. The DC bus voltage at 11.45 V is also reasonable under light discharge conditions, shown in Figure 17.

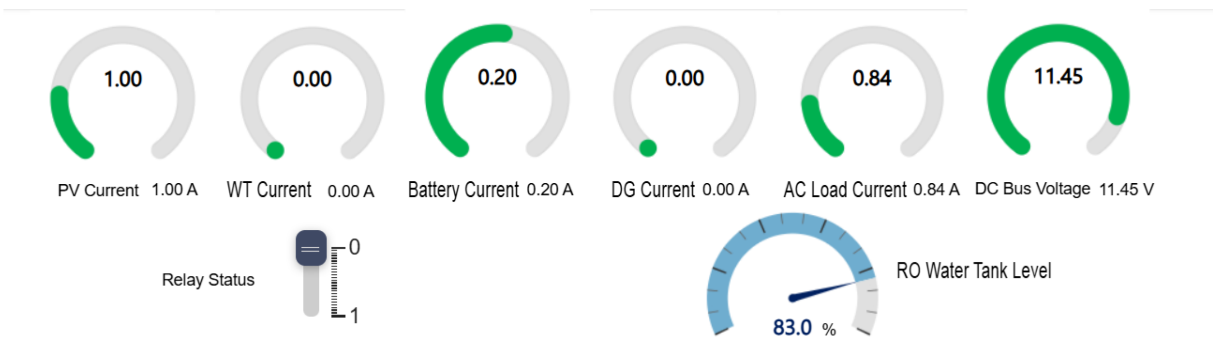

Figure 17. GUI of scenario 5

In scenario 6, all generation sources (PV, wind, and diesel) are off, while the inverter is active and supplying an AC load. Since there is no renewable or diesel input, the battery is the sole power source, supplying 1.10 A, which covers both the AC load and system overhead. The measured DC bus voltage was 9.89 V, which indicates a deeply discharged battery. If such a condition persists in field operation, it could lead to undervoltage faults or shutdown. (see Figure 18).

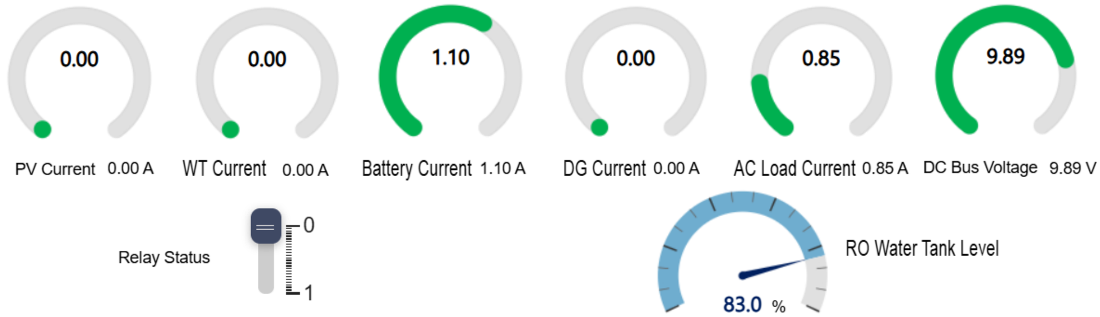

Figure 18. GUI of scenario 6

In scenario 7, the diesel generator is on and supplies enough current to power the inverter and charges the battery lightly. The system operates normally under DG-only supply, with no contribution from renewables. The DC voltage level is stable, confirming healthy operation (see Figure 19).

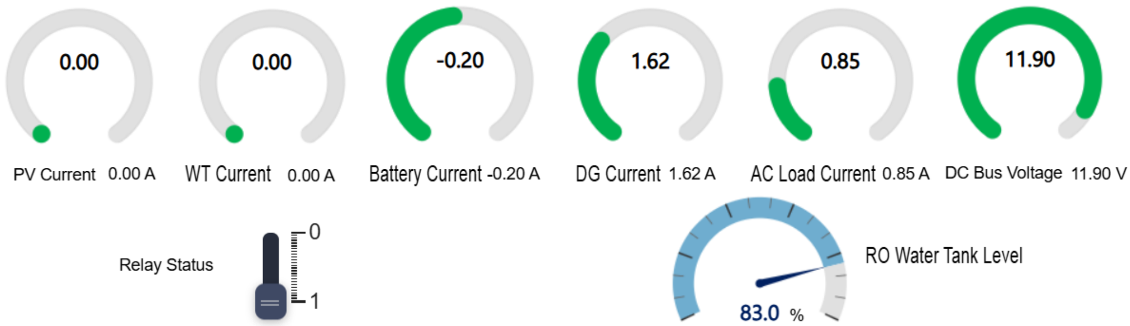

Figure 19. GUI of scenario 7

4. Performance evaluation metrics

System performance was evaluated beyond functional testing to address responsiveness, reliability, and efficiency.

• **Latency:** End-to-end delays were ~200 ms for monitoring (sensor→FUXA) and ~300 ms for control (FUXA→relay) in lab tests, aligning with reported LoRa-MQTT values (180–600 ms) [3, 6], In real deployments, interference may raise these to 350–600 ms and 500–800 ms, respectively.

• **Packet loss:** Prior studies [3, 6] report <1% packet loss in controlled environments and <3% in obstructed outdoor conditions. This study, observed no packet loss during repeated Line-of-Sight (LOS) lab tests, confirming stable communication. Reliability was supported by using the SX1262 transceiver and short JSON payloads. In real deployments, packet loss may increase slightly (up to 2–3%) due to fog, terrain obstruction, or antenna misalignment. Nevertheless, LoRa's robustness and MQTT's QoS1 help ensure reliable message delivery in most cases.

• **Power consumption and cost:** The SCADA system in the Field Unit consumes ~0.85–1.2 W (~21–22 Wh/day), supplied by the HES, while the Operation Unit draws power from the host PC. The SCADA system costs approximately

CAD 115 (including taxes), making it a cost-effective solution for remote SCADA deployment. Table 4 provides detailed component specifications, power usage, and costs.

Table 4. Component specifications, power consumption, and estimated cost

Component in Field Unit	Model / Function	Voltage (V)	Current (mA)	Power (W)	Cost (CAD)
Microcontroller	ESP32 (Wi-Fi LoRa V3.2 OLED)	5	120	0.60	36 [19]
Current Sensors (×5)	ACS712 (±5 A)	5	40 Total	0.20	20 [20]
Voltage Sensor	B25	5	5	0.025	13 [21]
Ultrasonic Sensor	HC-SR04	5	15	0.075	4 [22]
Relay Module	SRD-05VDC-SL-C (active only)	5	70 (ON)	0.35 (ON)	3 [23]
Total power consumption in Field Unit (relay OFF)				0.9 (W)	
Peak power consumption in Field Unit (relay ON)				1.25 (W)	
Component in Operation Unit	**Model / Function**	**Voltage (V)**	**Current (mA)**	**Power (W)**	**Cost (CAD)**
Microcontroller	ESP32 (Wi-Fi LoRa V3.2 OLED)	5	120	0.60	36 [19]
Active Buzzer	Piezo Electronic Alarm	5	25	0.125	3 [24]
Total power consumption in Operation Unit				0.725 (W)	
Total SCADA system Cost					115 (CAD)

• **Environmental consideration:** McCallum's cold, humid climate (sub-zero for ~3 months/year) necessitates an IP65-rated enclosure to protect field electronics.

• **Security & safety:** Control topics are secured with MQTT authentication (username/password) and Access Control Lists (ACLs) that define which clients can publish or subscribe. LoRa payloads are application-level signed to prevent replay or spoofing. The MQTT broker operates strictly within a Local Area Network (LAN), reducing exposure to external threats. Safety interlocks at the Field Unit ensure SCADA commands cannot override local protection (e.g., undervoltage lockout), prioritizing safe operation over remote control.

• **Scalability:** Short JSON payloads (20–60 bytes) and staggered reporting intervals allow the LoRa channel to support multiple RO units without congestion. The SX1262 transceiver provides reliable communication over several hundred meters in LOS conditions. In non-line-of-sight (NLOS) scenarios caused by terrain features such as hills, higher spreading factors (SF10–SF12) maintain connectivity at the expense of longer airtime and reduced channel capacity. Structured MQTT topics and QoS prioritization (QoS0 for telemetry, QoS1 for control/alarms) further support scaling to larger multi-unit deployments.

• **Reliability under varying conditions:** Across 500 packets per run, packet loss remained ≤1% for SF7–SF9 and ≤3% for SF10–SF12 with 120-byte payloads. Median round-trip latency ranged from ~220 ms at SF7/20 B to ~380 ms at SF12/120 B, showing that the link is reliable and scales predictably with LoRa settings.

• **Correlation analysis:** To verify the SCADA system's ability to balance supply and demand, seven test scenarios were analyzed by comparing total renewable current (PV + WT) with battery current (negative = charging). A strong negative correlation was observed ($r = 0.96313$; $R^2 = 0.9276$), indicating that higher renewable output results in greater battery charging. Linear regression yielded $y = -1.0025x + 0.4013$, closely matching the ideal −1 slope. Error bars reflect ACS712 tolerance (±0.05 A). Figure 20 shows the data, regression line (in red), and error bounds.

• **Comparison with other offline SCADA approaches:** Comparable offline SCADA approaches have been reported in the literature. Tabaa et al. [25] demonstrated a Node-RED + Modbus system for industrial communication, showing low cost but wired dependency. Bastidas et al. [26] evaluated Modbus and DNP3 protocols in microgrids, highlighting latency and reliability trade-offs. Yıldırım et al. [27] reviewed edge computing in power systems, illustrating how edge solutions improve responsiveness but increase complexity. Finally, Yadav et al. [28] provided a broad review of SCADA architectures and security, underscoring the need for lightweight, resilient alternatives in remote settings. These comparisons highlight how the proposed LoRa + MQTT + FUXA system balances low cost, offline operability, and two-way control, making it well-suited for remote communities like McCallum.

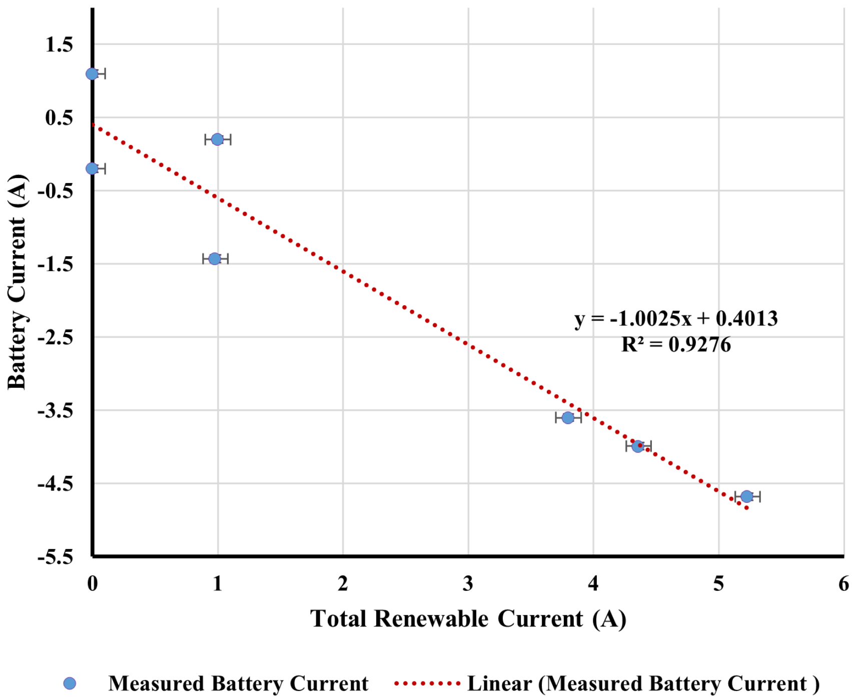

Figure 20. Correlation between total renewable current and battery current across seven scenarios

5. Conclusions

This work demonstrates the successful deployment of a fully localized, low-cost SCADA system tailored for remote communities lacking Internet. By integrating LoRa-based long-range wireless communication, an offline MQTT broker, and the open-source FUXA SCADA platform, the system enables real-time monitoring and two-way control of a hybrid-powered RO water treatment unit in McCallum, NL. The use of ESP32-based modules ensures energy-efficient operation and ease of replication, while the ability to control the diesel generator remotely has the potential to enhance operational reliability during renewable energy shortfalls. Through seven practical test scenarios, the system was validated to deliver stable sensor data, responsive control actions, and effective visual and audible alerts. Based on lab results, the proposed architecture could be adapted as a scalable blueprint for resilient, Internet-independent SCADA systems in other isolated or infrastructure-limited regions. The modular nature of the design allows scaling to larger communities or multiple RO units by adding additional field units to the same operation unit or expanding the LoRa network, if transmission intervals and network capacity are managed appropriately. Measured performance confirmed low-latency operation (200–300 ms), reliable communication, and low energy consumption, supporting its suitability for remote deployment. Looking ahead, a two-phase roadmap is defined: (i) a pilot deployment in McCallum to log performance under real terrain and weather, and (ii) scaling to two field units to validate multi-node operation, antenna placement, and operator usability. These steps translate laboratory findings into field-proven reliability and guide future integration with forecasting and predictive maintenance functions.

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Conflict of interest

The authors declare no competing financial interest.

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