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# Design of a SCADA-Based Control System for Hybrid Power Generation Integrating a Screw Turbine and Solar Panels

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**Abstract:** The increasing demand for sustainable electricity requires hybrid renewable energy systems capable of improving power supply reliability and operational supervision under variable energy-source conditions. **Purpose:** This study aims to design and implement a laboratory-scale hybrid renewable energy control system integrating an Archimedes screw turbine and a photovoltaic system with PLC-based control and SCADA monitoring. **Methodology:** An experimental design and implementation approach was employed by integrating renewable energy generation, battery storage, electrical measurement devices, an industrial PLC, HMI, and cloud-based SCADA platform. Electrical voltage, current, power, energy, battery condition, and load status were acquired during laboratory testing and evaluated based on the functionality of monitoring, data logging, trend visualization, alarm notification, battery protection, and load control. **Findings:** The developed system successfully integrated renewable energy generation and industrial automation into a unified supervisory platform. The PLC continuously acquired electrical parameters, executed battery protection and load-switching logic, and communicated with the HMI and SCADA system. Real-time monitoring, historical data recording, graphical trend visualization, alarm notification, and remote load control operated successfully during experimental testing. **Implications:** The proposed architecture provides a practical platform for renewable energy monitoring, industrial automation education, and further development of automatic energy management and predictive supervision systems. **Originality:** Unlike previous studies that primarily focus on photovoltaic performance, Archimedes screw turbine optimization, or SCADA architecture separately, this study integrates photovoltaic generation, an Archimedes screw turbine, battery storage, industrial PLC control, HMI visualization, and cloud-based SCADA monitoring within a single laboratory-scale hybrid renewable energy platform.

**Keywords:** Archimedes screw turbine; hybrid renewable energy system; photovoltaic; programmable logic controller; supervisory control and data acquisition.

## INTRODUCTION

Renewable energy systems have become an important solution for reducing dependence on fossil fuels and improving the sustainability of electricity generation. However, the output of individual renewable energy sources is generally affected by environmental conditions, such as solar irradiance, temperature, water flow, and seasonal variation. Therefore, a single renewable energy source may not always provide continuous and stable power generation. Hybrid renewable energy systems are developed to overcome this limitation by combining two or more renewable sources with storage and control strategies. Such systems can improve energy reliability, operational flexibility, and power supply continuity under variable source conditions (Khan et al., 2022). Recent studies also emphasize that hybrid renewable energy systems require appropriate architecture, battery integration, sizing, optimization, and control methods to maintain stable operation and improve energy utilization (Giedraitytė et al., 2025; León Gómez et al., 2023).

Solar photovoltaic technology is one of the most widely applied renewable energy technologies because it can directly convert solar radiation into electrical energy and can be implemented in different scales, from small stand-alone systems to larger power generation applications. The development of photovoltaic systems has continued to improve in terms of technology, efficiency, applications, and system integration. However, photovoltaic output remains dependent on solar irradiance, temperature, weather conditions, and installation characteristics (Ahmed et al., 2025). Photovoltaic technology can also be classified based on material generation, configuration, and application, making it suitable for integration with other renewable energy sources in hybrid systems (Herez et al., 2023). In addition, the efficiency and sustainability of photovoltaic systems are influenced by design factors, power conversion, environmental conditions, and energy storage integration (Iturralde Carrera et al., 2025).

Besides photovoltaic energy, low-head hydropower can be used as a complementary renewable source, especially in locations with available water flow. The Archimedes screw turbine is one of the micro-hydropower technologies that can operate under low-head and low-speed conditions. This characteristic makes it suitable for small-scale hydropower generation and laboratory-scale renewable energy studies. Recent research shows that the performance of an Archimedes screw turbine is influenced by hydraulic conditions, turbine geometry, rotational speed, flow rate, and operating parameters (Abbas et al., 2024). Other studies have investigated the effect of blade number, parameter scaling, and numerical analysis on Archimedes screw turbine performance, showing that this turbine remains an active research topic for micro-hydropower applications (Erinofiardi et al., 2022; Mohedano-Castillo et al., 2025; Simmons et al., 2023). A recent review also highlights the potential of Archimedes screw turbines for sustainable low-head hydropower applications (Sołowiej & Łapiński, 2025).

The integration of photovoltaic and micro-hydropower sources in a hybrid renewable energy system requires an effective monitoring and control system. Without proper supervision, the system may experience difficulties in observing source performance, battery condition, load status, and abnormal operating conditions. Supervisory Control and Data Acquisition systems are widely used in renewable energy applications because they support real-time data acquisition, visualization, control, historical data storage, and alarm management (Qays et al., 2022), showed that IoT-aided SCADA systems can be used to monitor renewable energy systems by collecting and transmitting operational data to a supervisory platform. (Omidi et al., 2023) also demonstrated that SCADA architecture can be implemented in hybrid power systems to support monitoring and control functions. In addition, IoT-based SCADA systems can improve accessibility through remote monitoring, while SCADA-based energy management can support coordinated operation between renewable sources, battery storage, and loads in microgrid applications (Aghenta & Iqbal, 2020).

Previous studies have discussed photovoltaic systems, Archimedes screw turbines, hybrid renewable energy systems, and SCADA-based monitoring separately. Many studies on Archimedes screw turbines focus on hydraulic performance, blade configuration, scaling, and numerical analysis, while photovoltaic studies commonly discuss technology development, efficiency, and applications. Meanwhile, SCADA-related studies generally focus on monitoring architecture, IoT platforms, and microgrid supervision. However, there is still a need for a practical laboratory-scale design that integrates photovoltaic and Archimedes screw turbine sources with battery storage, PLC-based control, HMI visualization, and SCADA monitoring in one hybrid renewable energy system. This gap is important because a laboratory-scale system can be used to evaluate control logic, monitoring functions, alarm response, and data visualization before larger-scale implementation.

Based on this background, this study aims to design a SCADA-based control system for a hybrid renewable power generation system integrating an Archimedes screw turbine and photovoltaic panels. The proposed system consists of renewable energy sources, charge controllers, battery storage, inverter, programmable logic controller, human-machine interface, sensors or monitoring devices, relays, and SCADA visualization. The system is designed to monitor voltage, current, power, battery condition, load status, historical data, real-time trends, and alarm conditions. The main contribution of this research is the development of a PLC–SCADA-based monitoring and control architecture for a laboratory-scale hybrid photovoltaic–microhydro system. Unlike studies that focus mainly on turbine optimization or photovoltaic performance analysis, this research emphasizes system integration, control logic, real-time monitoring, and supervisory visualization for hybrid renewable energy operation.

## RESEARCH METHOD

### System Architecture

The proposed system is designed as a laboratory-scale hybrid renewable power generation system integrating photovoltaic energy and micro-hydropower based on an Archimedes screw turbine. The main objective of the system architecture is to combine two renewable energy sources with battery storage, power conversion, PLC-based control, HMI visualization, and SCADA monitoring. The hybrid configuration is selected to improve energy availability because photovoltaic output depends on solar irradiance, while the screw turbine output depends on water flow conditions. Therefore, the two sources are integrated into a common energy storage system to support load supply and system monitoring.

The system consists of two main generation units. The first unit is a photovoltaic panel connected to a solar charge controller. The photovoltaic panel converts solar radiation into electrical energy, while the solar charge controller regulates the charging process before the energy is stored in the battery. The second unit is an Archimedes screw turbine coupled with a generator. In this laboratory prototype, water flow is produced by a pump in a closed-loop circulation system to simulate real water flow conditions. The water flow rotates the screw turbine, and the mechanical rotation is converted into electrical energy by the generator. The electrical output from the turbine generator is then connected to a protection device and charge controller before being supplied to the battery.

Both renewable energy sources are connected to a 12 V battery storage system through their respective charge controller circuits. The battery functions as the main energy buffer that stores energy from the photovoltaic panel and the Archimedes screw turbine. From the battery, the energy is distributed to the control panel, inverter, monitoring devices, PLC system, HMI, and electrical loads. The inverter is used when AC output is required, while DC monitoring devices are used to observe voltage, current, and power parameters from the sources, battery, and load side. This architecture allows the system to operate as a small-scale hybrid renewable energy system with centralized storage and supervised load control.

The control and monitoring section is built around a programmable logic controller as the main control unit. The PLC receives input signals from measurement devices and system status indicators, processes the control logic, and controls relay outputs for load operation and protection functions. The PLC is also connected to the HMI to provide local visualization and operator interaction. The HMI displays the main operating parameters, source status, battery status, load condition, and alarm information. In addition to local monitoring, the system is connected to a SCADA platform to support real-time monitoring, historical data recording, trend visualization, alarm display, and remote supervision.

The overall architecture follows the principle of hybrid renewable energy systems, where multiple renewable sources, storage, control, and monitoring units are integrated to improve system reliability and operational flexibility (Khan et al., 2022; León Gómez et al., 2023). The use of SCADA in this architecture supports real-time observation and supervisory control, which is important for renewable energy systems with variable source conditions (Omidi et al., 2023; Qays et al., 2022). In this study, the system architecture is not focused on optimizing the mechanical design of the turbine or maximizing photovoltaic conversion efficiency. Instead, the main focus is the integration of renewable energy sources with PLC-based control and SCADA monitoring to evaluate the operation of a hybrid photovoltaic–microhydro system in a laboratory environment.

Figure 1 shows the general architecture of the proposed hybrid renewable energy system. The architecture illustrates the energy flow from the photovoltaic panel and Archimedes screw turbine to the battery storage, and then from the battery to the inverter, control panel, and load. It also shows the data and control flow from the measurement devices to the PLC, HMI, and SCADA interface. Through this architecture, the system can monitor renewable source parameters, battery condition, load status, real-time trends, historical data, and alarm conditions in an integrated supervisory platform.

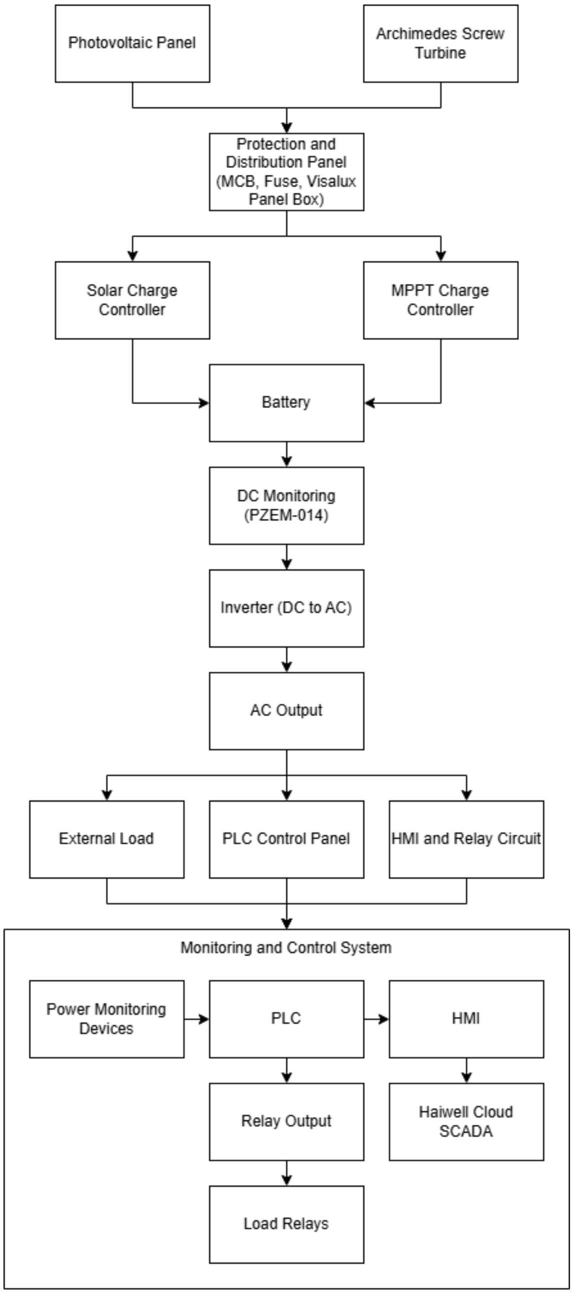



**Figure 1.** Proposed Hybrid Renewable Energy System Architecture

## Hardware Design

The proposed hybrid renewable energy system consists of renewable energy generation units, energy storage devices, power conversion equipment, industrial automation components, protection devices, and monitoring instruments. The hardware configuration was designed to establish a laboratory-scale platform capable of performing renewable energy generation, energy storage, supervisory monitoring, and automatic control under a PLC-SCADA architecture.

The renewable energy subsystem comprises two independent DC power sources: an Archimedes screw turbine generator and a photovoltaic (PV) module. The Archimedes screw turbine has a diameter of 10 cm and a total length of 120 cm with a single-flight stainless-steel screw. To simulate actual low-head hydropower conditions, water is circulated continuously using a water pump through a closed-loop hydraulic system. The flowing water rotates the Archimedes screw turbine, which converts hydraulic energy into mechanical rotational energy. This mechanical rotation is subsequently converted into electrical energy by a DC generator coupled directly to the turbine shaft. This laboratory-scale configuration enables continuous testing while maintaining operating conditions similar to a real low-head micro hydropower system.

The photovoltaic subsystem employs a 100 W polycrystalline solar panel as the second renewable energy source. Electrical power generated by the PV module is regulated using a Tesla CSP-30A Solar Charge Controller combined with an MPPT Solar Charge Controller, allowing maximum power extraction while protecting the battery against overcharging and excessive discharge.

Electrical energy generated from both renewable sources is stored in a 12 V 18 Ah Kayaba KYB12-18A Valve Regulated Lead Acid (VRLA) battery. The battery functions as the primary energy storage unit, ensuring continuous power delivery despite fluctuations in solar irradiation or water flow conditions. The stored DC energy is subsequently converted into AC electricity using a Taffware NBQ1000W inverter, which provides a continuous output capacity of 500 W to supply the experimental loads.

The monitoring subsystem continuously measures electrical parameters during system operation. A PZEM-014 DC power meter is employed to acquire DC voltage, current, power, and energy consumption, while a Wired Power Monitor P06S-100 provides additional electrical measurements for system verification. These monitoring devices transmit real-time electrical data to the PLC for processing and visualization through the SCADA platform.

Industrial automation is implemented using a Haiwell AT16S0R Programmable Logic Controller (PLC) as the primary controller. The PLC acquires electrical measurement data, executes the programmed control algorithm, manages relay switching, and communicates with the Human Machine Interface (HMI) and Haiwell Cloud SCADA platform. Local visualization is provided through a Haiwell B7H-W Human Machine Interface, enabling operators to monitor system conditions and perform supervisory control.

The electrical switching system consists of six Sankomec MK2P-I electromagnetic relays and three INS International MK3P-I relays, allowing the PLC to control multiple load channels automatically. Three FORT AD22-22DS indicator lamps are installed on the control panel to provide visual indications of the operating status of the system.

Electrical protection is provided by Schneider Domae C10 Miniature Circuit Breakers (MCB), Newpallas DZ47-63 MCB, and multiple fuse holders installed throughout the distribution panel. A Switching Power Supply S-120-24 supplies a stable 24 VDC source required for PLC operation, relay coils, HMI, and auxiliary control circuits.

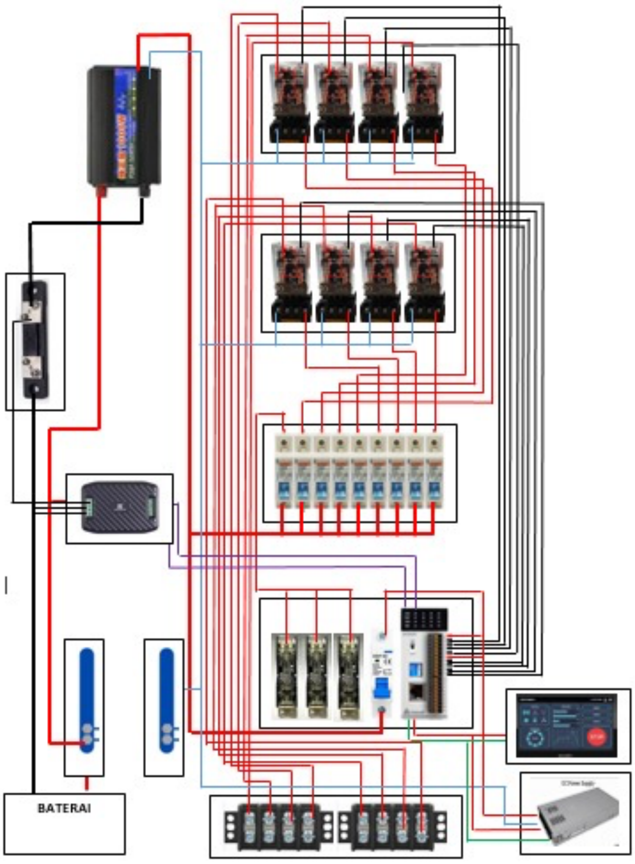
The electrical power flow begins with the photovoltaic panel and the Archimedes screw turbine generator. The generated electrical energy passes through the protection panel before entering the charging subsystem consisting of the solar charge controller and MPPT controller. The regulated energy is then stored in the VRLA battery, which supplies the inverter to provide AC power for the laboratory loads. Simultaneously, electrical parameters are continuously measured by the monitoring devices and transmitted to the PLC. The PLC processes the acquired data, executes the control logic, updates the HMI and SCADA displays, stores historical operating data, activates alarm notifications when abnormal conditions occur, and controls the relay outputs according to the programmed operating strategy.

Figure 2 illustrates the hardware configuration of the proposed hybrid renewable energy system, while Table 1 summarizes the specifications of all hardware components used in this research.

**Table 1.** Hardware Specification

| Component | Specification | Function |
|---|---|---|
| Photovoltaic Panel | Polycrystalline, 100 W | Solar energy source |
| Archimedes Screw Turbine | Stainless steel, Ø10 cm × 120 cm | Low-head hydropower source |
| Generator | DC Generator | Converts mechanical energy into electrical energy |
| Solar Charge Controller | Tesla CSP-30A | Battery charging regulation |
| MPPT Controller | MPPT Type | Maximum power point tracking |
| Battery | Kayaba KYB12-18A, 12 V 18 Ah VRLA | Energy storage |
| Inverter | Taffware NBQ1000W, 500 W | DC to AC conversion |
| PLC | Haiwell AT16S0R | Main controller |

| Component | Specification | Function |
|---|---|---|
| HMI | Haiwell B7H-W | Local monitoring and operation |
| DC Power Meter | PZEM-014 | Voltage, current, power, energy measurement |
| Power Monitor | P06S-100 | Electrical parameter monitoring |
| Relay | Sankomec MK2P-I (6 units) | Load switching |
| | INS MK3P-I (3 units) | Auxiliary switching |
| Indicator Lamp | FORT AD22-22DS (3 units) | System status indication |
| MCB | Schneider Domae C10 | Overcurrent protection |
| | Newpallas DZ47-63 | Circuit protection |
| Switching Power Supply | S-120-24 | 24 VDC supply for PLC and control system |



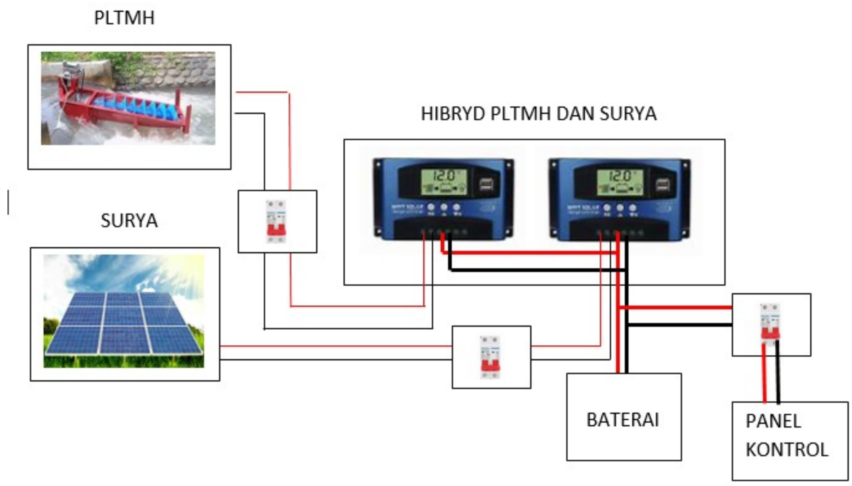



**Figure 2.** Hardware Configuration

## RESULT

### Communication System

The communication system is designed to connect the measurement devices, PLC, HMI, and SCADA platform into an integrated monitoring and control network. In this system, the photovoltaic panel, Archimedes screw turbine generator, battery, inverter, and load are monitored through electrical measurement devices installed in the control panel. The measured parameters include voltage, current, power, source status, battery condition, and load condition. These data are used to observe the operating condition of the hybrid renewable energy system and to support control decisions executed by the PLC.

The programmable logic controller functions as the main communication and control unit in the system. The PLC receives input signals from measurement devices and system status indicators, processes the control logic, and controls relay outputs according to the programmed conditions. The PLC also transfers operating data to the HMI so that the operator can observe the system condition locally. Through this communication arrangement, the operator can monitor source performance, battery voltage, load status, and alarm conditions from the HMI without manually checking each component in the control panel.

The HMI acts as the local supervisory interface of the system. It displays the main parameters of the photovoltaic source, screw turbine source, battery, and load. The HMI also provides access to real-time monitoring, historical data, trend display, load control, and alarm information. A previous study on a screw-turbine microhydro power plant also demonstrated that SCADA can be used to monitor DC voltage, current, power, and energy in real time while supporting load control through PLC and HMI integration (Saroinsong et al., 2023). This allows the operator to interact with the system directly from the control panel. Local monitoring through the HMI is important because it provides immediate information about system operation during laboratory testing and troubleshooting.

In addition to local monitoring, the system is connected to a SCADA platform to support supervisory monitoring and data visualization. The SCADA system receives operating data from the PLC and displays them in several monitoring pages, including Home, Real-Time Monitoring, Historical Data, Real-Time Trend, Load Control, and Alarm. The Home page provides an overview of the hybrid renewable energy system. The Real-Time Monitoring page displays live electrical parameters, while the Historical Data page records previous operating data for evaluation. The Real-Time Trend page visualizes changes in voltage, current, and power over time. The Load Control page displays the load condition, and the Alarm page shows warning information when abnormal conditions occur.

The communication system follows the concept of SCADA-based renewable energy monitoring, where field data are collected from the plant and transmitted to a supervisory interface for visualization, control, and analysis. (Qays et al., 2022) reported that IoT-aided SCADA systems can be used to monitor renewable energy systems by collecting and transmitting operational data to a supervisory platform. (Omidi et al., 2023) also demonstrated that SCADA architecture can support monitoring and control functions in a hybrid power system. Although the platform used in this study is based on Haiwell PLC, HMI, and SCADA, the communication concept remains similar, namely integrating field measurement, controller processing, operator interface, and supervisory monitoring.

The communication flow in the proposed system can be divided into data flow and control flow. The data flow begins from the renewable energy sources, battery, and load, where electrical parameters are measured by monitoring devices. These data are then displayed on the HMI and SCADA interface for observation and analysis. The control flow begins from the PLC program, which processes the operating conditions and activates relay outputs for load control and protection functions. When the battery voltage reaches a low-voltage condition, the PLC disconnects the load to protect the battery. When the battery voltage returns to a safe level, the PLC reconnects the load according to the programmed logic.

This communication structure improves the observability and controllability of the laboratory-scale hybrid renewable energy system. By integrating PLC control, HMI visualization, and SCADA monitoring, the system can provide real-time information, historical records, trend analysis, and alarm notification. These functions are important for evaluating the performance of the hybrid photovoltaic–microhydro system and for identifying abnormal operating conditions during testing. Therefore, the communication system supports the main objective of this study, which is to develop an integrated PLC–SCADA-based monitoring and control architecture for a hybrid renewable power generation system. The overall communication architecture of the proposed system is illustrated in Figure 3.

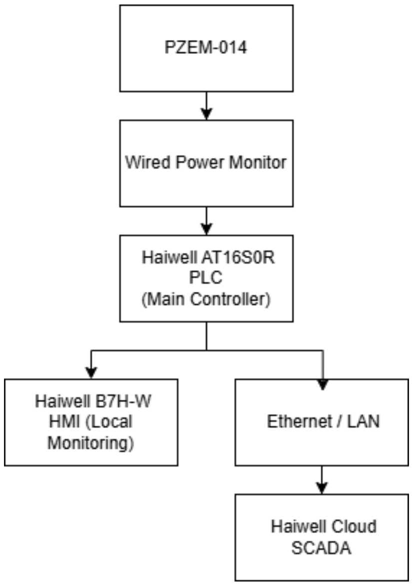



**Figure 3.** Communication System Architecture

**Software Design**

The software design is developed to support control, monitoring, visualization, data recording, and alarm functions in the hybrid renewable energy system. The software structure consists of two main parts: PLC control logic and HMI/SCADA visualization. The PLC program is responsible for processing input data, executing control logic, activating relay outputs, and determining load operation based on system conditions. The HMI and SCADA interface are used to display real-time parameters, historical data, real-time trends, load control status, and alarm information. This separation allows the PLC to perform control execution, while the HMI and SCADA system provide supervisory monitoring and operator interaction.

The PLC program is developed based on the operational requirements of the hybrid photovoltaic–microhydro system. The program begins with system initialization, including input and output configuration, communication setup, relay status, monitoring variables, and alarm parameters. After initialization, the PLC reads the electrical parameters from the photovoltaic source, Archimedes screw turbine generator, battery, and load. These parameters include voltage, current, power, source status, battery condition, and load condition. The measured data are then processed by the PLC and displayed on the HMI and SCADA pages.

The main control logic is focused on battery supervision, load control, and protection response. The battery voltage is used as the main reference for determining safe operation. When the battery voltage is below the upper charging limit, the photovoltaic panel and screw turbine generator are allowed to supply energy to the battery through their respective charge controllers. When the battery voltage reaches the upper charging threshold, the charging process is supervised to prevent overcharging conditions. In this design, the charge controllers regulate the charging process, while the PLC monitors the system condition and displays the charging status through the HMI and SCADA interface.

Load control is designed to protect the battery from excessive discharge. When the battery voltage falls below the low-voltage threshold, the PLC activates the protection logic and disconnects the load through the relay output. This condition is also displayed as an alarm on the HMI and SCADA interface. When the battery voltage increases above the recovery threshold, the PLC allows the load to be reconnected according to the programmed logic. In this study, the low-voltage threshold is set at 11.5 V, while the load reconnection threshold is set at 12.5 V. The upper charging threshold is set at 14.4 V to indicate the battery charging limit. These threshold values are used to support safe operation of the 12 V battery system during laboratory testing.

**Table 2**. Battery Voltage Thresholds and System Responses

| No. | Condition | Voltage Value | System Response |
|---|---|---|---|
| 1 | Fully charged battery / upper charging limit | ≥ 14.4 V | The system displays the upper charging-limit status. |
| 2 | Normal battery condition | 12.5–14.4 V | The load can operate normally. |
| 3 | Low battery condition | < 11.5 V | The load is disconnected and the alarm is activated. |

| No. | Condition | Voltage Value | System Response |
|---|---|---|---|
| 4 | Battery recovery condition | > 12.5 V | The load can be reactivated. |

The HMI design consists of several display pages that represent the main functions of the system. The Home page provides a general overview of the hybrid renewable energy system and shows the connection between the photovoltaic source, screw turbine source, battery, inverter, PLC, and load. The Real-Time Monitoring page displays live values of voltage, current, power, battery condition, and load status. The Historical Data page records previous operating data so that the system performance can be evaluated after testing. The Real-Time Trend page shows the changes in electrical parameters over time. The Load Control page displays the load status and control condition, while the Alarm page provides warning information when abnormal or unsafe operating conditions occur.

The SCADA interface is designed to support remote and supervisory monitoring of the system. The SCADA pages display the same main operating parameters as the HMI, but with additional visualization for data observation and analysis. Real-time monitoring allows the operator to observe the current system condition, while historical data and trend display help identify changes in source output, battery voltage, and load behavior during operation. The alarm display helps the operator detect abnormal conditions such as low battery voltage or unsafe operating states. These functions are important for evaluating the performance of the hybrid renewable energy system and for improving the observability of the laboratory-scale prototype.

The software design follows the concept of SCADA-based renewable energy monitoring, where field data are collected, processed, displayed, and recorded through a supervisory system. (Qays et al., 2022) emphasized that SCADA-based monitoring can support real-time observation of renewable energy systems. (Omidi et al., 2023)showed that SCADA architecture can be used in hybrid power systems to support monitoring and control functions. (Kermani et al., 2021) also demonstrated that SCADA-based energy management can support coordinated operation between renewable sources, battery storage, and loads in microgrid applications. Therefore, the software design in this study is developed to integrate PLC control logic, HMI visualization, SCADA monitoring, historical data recording, trend analysis, and alarm management in one hybrid renewable energy control system.

Overall, the software design supports the main objective of this research by enabling automatic supervision and control of a laboratory-scale hybrid photovoltaic–microhydro system. The PLC executes the control logic based on battery voltage and load condition, while the HMI and SCADA system provide visual monitoring and data recording. Through this software structure, the system can be used to observe renewable source output, battery condition, load operation, historical performance, real-time trends, and alarm events during experimental testing.

**Experimental Results**

The proposed hybrid renewable energy monitoring and control system was implemented and tested on a laboratory-scale prototype integrating an Archimedes screw turbine, a photovoltaic module, a battery storage system, and an industrial PLC-SCADA platform. The experiments were conducted to verify the functionality of the monitoring system, communication network, supervisory control, historical data recording, and alarm notification developed in this study.

During the experimental process, water was continuously circulated using a closed-loop hydraulic system to rotate the Archimedes screw turbine, while the photovoltaic module generated additional electrical energy under available solar irradiation. The generated electrical energy was regulated through the charging subsystem, stored in the battery, and supplied to the inverter for powering the laboratory loads. Simultaneously, electrical parameters were continuously acquired by the monitoring devices and transmitted to the Haiwell PLC for real-time processing and visualization.

The experimental evaluation focused on verifying five major functions of the proposed system:

1. Real-time electrical parameter monitoring.
2. Historical data recording.
3. Trend visualization.
4. Alarm notification.
5. Remote load control.

The experimental results demonstrate that all developed functions operated successfully throughout the testing period. Electrical parameters were continuously updated on the SCADA interface, historical operating data were automatically stored, trend graphs were generated in real time, abnormal operating conditions activated the corresponding alarm indicators, and electrical loads could be controlled through the supervisory interface.

## Real Time Monitoring

The primary function of the proposed SCADA system is to monitor electrical parameters in real time. Figure 4 illustrates the monitoring interface displaying the instantaneous values of DC voltage, current, power, and accumulated energy obtained from the electrical monitoring devices.

During the experiment, the SCADA interface continuously displayed the measured electrical parameters without noticeable communication interruption. The monitored voltage remained approximately 9.9 V, while the measured current was approximately 8.1 A with an output power close to 8 W during one of the experimental conditions. The displayed values were updated automatically as new measurement data were received from the PLC, demonstrating the capability of the proposed system to provide continuous supervision of hybrid renewable energy operation.

Furthermore, the monitoring page also provides High Alarm and Low Alarm indicators, allowing operators to identify abnormal operating conditions immediately. The alarm indicators remain inactive during normal operating conditions and are automatically activated whenever the predefined threshold values are exceeded.

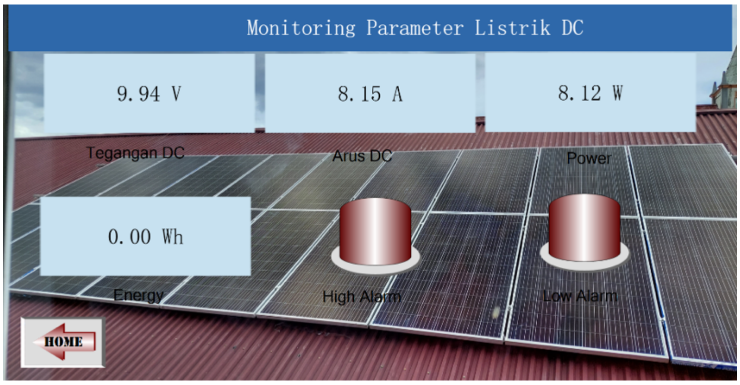



**Figure 4.** Real-Time Monitoring Interface

## Historical Data Interface

The Haiwell Cloud SCADA platform automatically records the measured electrical parameters during system operation. Figure 5 presents the historical data interface developed in this research.

The historical database stores the timestamp together with the corresponding voltage, current, power, and energy values acquired from the PLC. The recorded information enables operators to review previous operating conditions, analyze system performance, and evaluate long-term operation of the hybrid renewable energy system.

The automatic data logging capability eliminates manual recording procedures and improves data availability for future maintenance and performance analysis.

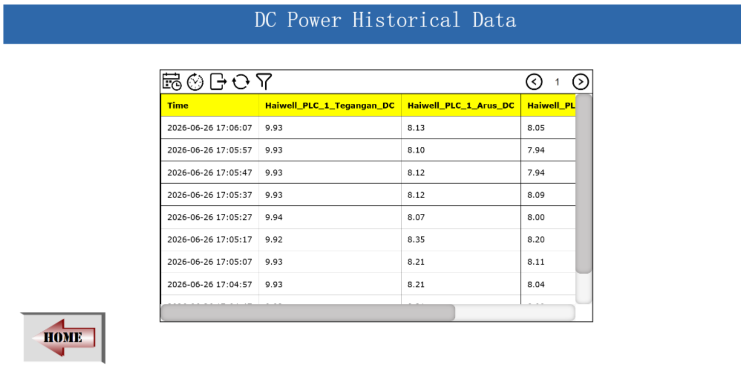



**Figure 5.** Historical Data Interface

## Real Time Trend Visualization

Trend visualization is an important feature of supervisory control systems because it allows operators to observe variations in electrical parameters over time.

Figure 6 presents the trend interface developed using Haiwell Cloud SCADA. The trend graph continuously plots the measured voltage, current, power, and energy values according to the acquisition time.

The experimental results show that the trend display updates automatically whenever new measurement data are received from the PLC. Consequently, operators can easily observe changes in system performance, detect fluctuations in electrical parameters, and evaluate the stability of the hybrid renewable energy system.

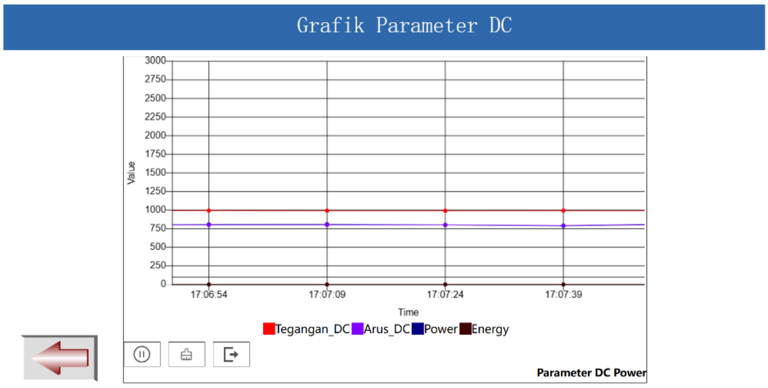



**Figure 6.** Real-Time Trend Interface

### Load Control Visualization

The proposed SCADA system also provides supervisory load control through six independent relay outputs controlled by the PLC.

Figure 7 illustrates the developed load control interface. Each load can be activated or deactivated independently through the SCADA application. The ON/OFF status of every load is displayed using graphical indicators that are synchronized with the actual relay condition.

The experimental results confirmed that all relay outputs responded correctly to the control commands issued from the SCADA interface. The synchronization between the graphical display and the actual relay status demonstrates the effectiveness of the communication between the PLC and the supervisory control system.

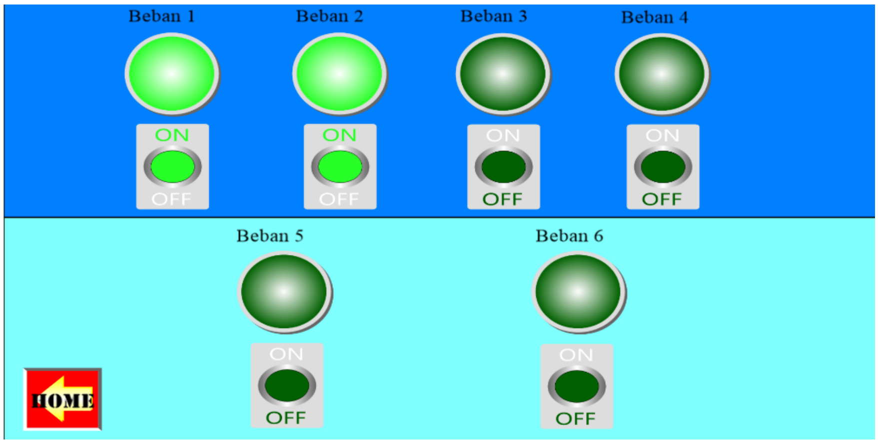



**Figure 7.** Load Control Interface

### SCADA Home Interface

Figure 8 shows the main interface of the developed Haiwell Cloud SCADA system. The Home Page serves as the central navigation interface connecting all monitoring modules, including real-time monitoring, historical data, trend visualization, alarm management, and load control. The graphical layout enables operators to access each supervisory function through a single interface, thereby improving operational convenience.

The integration of multiple monitoring functions within one supervisory platform simplifies system operation and enhances user interaction.


**Figure 8.** Home Page of the Proposed SCADA System

**Overall System Performance**

The experimental results demonstrate that the proposed PLC-SCADA system successfully integrates renewable energy generation, industrial automation, and supervisory monitoring into a unified laboratory-scale platform. Throughout the testing process, the PLC continuously acquired electrical measurement data, executed the programmed control logic, and communicated with both the local HMI and Haiwell Cloud SCADA without communication failure.

The developed SCADA system successfully performed real-time monitoring, historical data logging, trend visualization, alarm notification, and supervisory load control. These functions enable operators to observe the operating condition of the hybrid renewable energy system continuously while improving operational reliability and facilitating future maintenance activities.

Overall, the experimental implementation verifies that the proposed architecture is suitable for laboratory-scale hybrid renewable energy applications and provides an effective platform for monitoring and controlling integrated photovoltaic and Archimedes screw micro hydropower generation systems.

## DISCUSSION

The experimental results demonstrate that the proposed PLC–SCADA system successfully integrates photovoltaic generation, an Archimedes screw turbine, battery storage, and supervisory load control in a laboratory-scale hybrid renewable energy system. The system was able to perform real-time monitoring, historical data recording, trend visualization, alarm notification, and remote load control. These results indicate that the developed architecture improves system observability and allows operators to monitor renewable sources, battery conditions, and load status through a centralized interface.

The successful operation of the system is supported by the integration of energy storage and PLC-based control. The battery acts as an energy buffer between variable renewable sources and electrical loads, while the PLC uses battery voltage as a reference for protection and load control. The load is disconnected when the battery voltage falls below 11.5 V and can be reactivated when the voltage exceeds 12.5 V. The different disconnection and reconnection thresholds reduce frequent relay switching caused by voltage fluctuations near a single limit and provide more stable system operation.

The findings are consistent with previous studies showing that SCADA systems can support real-time renewable energy monitoring, data acquisition, and supervisory control (Kermani et al., 2021; Omidi et al., 2023; Qays et al., 2022) also emphasized the importance of coordinated monitoring between renewable sources, energy storage, and loads. However, unlike previous Archimedes screw turbine studies that mainly focused on hydraulic performance, blade configuration, scaling, or CFD analysis (Abbas et al., 2024; Erinofiardi et al., 2022; Mohedano-Castillo et al., 2025; Simmons et al., 2023), this study focuses on system-level integration. The main novelty is the integration of an Archimedes screw turbine, photovoltaic module, battery storage, industrial PLC, HMI, cloud-based SCADA, alarm management, historical data, and multi-channel load control within a single laboratory-scale platform.

The results indicate that the effectiveness of hybrid renewable energy systems depends not only on combining multiple energy sources but also on monitoring and controlling the interaction between generation, storage, and loads. The developed SCADA system converts electrical measurements into useful operational information through real-time displays, trends, historical records, and alarm indicators. This architecture can therefore support research and education in renewable energy, industrial automation, instrumentation, and supervisory control.

Nevertheless, this study mainly validates the functionality of the monitoring and control architecture and does not yet evaluate overall energy efficiency, battery state of charge, communication latency, measurement uncertainty, or long-term reliability. In addition, the Archimedes screw turbine is operated using a pump-driven closed-loop water system; therefore, the turbine output should not be directly interpreted as net hydropower generation without considering pump energy consumption. Future studies should validate electrical measurements using calibrated instruments, evaluate the contribution of each renewable source, and calculate the complete energy balance of the system.

Based on these findings, further development should focus on automatic energy management, source prioritization, battery state-of-charge estimation, and load shedding based on load priority. Longer experimental testing is also required to evaluate communication reliability, relay switching frequency, and battery performance. The historical data generated by the SCADA system may further support predictive maintenance, anomaly detection, and artificial intelligence-based energy management. Thus, the proposed PLC–SCADA architecture provides an initial platform for developing more intelligent and autonomous hybrid renewable energy systems.

## CONCLUSIONS

This study presented the design and implementation of a laboratory-scale hybrid renewable energy monitoring and control system integrating an Archimedes screw turbine and a photovoltaic power generation unit using a PLC-SCADA architecture. The proposed system successfully combined renewable energy generation, battery energy storage, industrial automation, and cloud-based supervisory monitoring into a unified platform. Experimental implementation verified that the Haiwell AT16S0R PLC effectively performed real-time data acquisition, supervisory control, and communication with both the local Human Machine Interface (HMI) and the Haiwell Cloud SCADA platform. The developed system successfully provided real-time monitoring of electrical parameters, historical data logging, trend visualization, alarm notification, and remote load control, demonstrating reliable operation throughout the experimental testing.

The proposed architecture provides an effective laboratory-scale platform for research and educational applications in hybrid renewable energy systems while illustrating the integration of industrial automation with sustainable power generation technologies. The modular hardware configuration and cloud-based monitoring capabilities also provide flexibility for future expansion. Future work may include implementing automatic energy management algorithms, intelligent source prioritization, Internet of Things (IoT)-based optimization, predictive maintenance, and artificial intelligence techniques to further improve the efficiency, reliability, and autonomous operation of hybrid renewable energy systems.

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