Intelligent IoT Platform for Performance Evaluation of Solar–Wind Hybrid System

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***Abstract*—The growing demand for clean and sustainable energy has accelerated the adoption of solar–wind hybrid systems. However, their performance is significantly influenced by varying environmental conditions. This paper presents an Intelligent IoT-based platform that integrates ESP32 microcontrollers, smart sensors, cloud communication, and data analytics to continuously monitor and evaluate the performance of solar–wind hybrid energy systems. The system acquires real-time data on voltage, current, temperature, and humidity from both solar panels and wind turbines, processes it at the edge, and transmits it to an IoT cloud platform for visualization, predictive maintenance, and energy forecasting. Experimental results demonstrate that the proposed system enhances operational reliability, minimizes downtime, and improves overall energy efficiency. The paper covers hardware design, firmware implementation, IoT connectivity, and performance analytics.**

***Index Terms*—Edge Computing, ESP32, Hybrid Renewable Energy, IoT Monitoring, Performance Evaluation, Predictive Maintenance, Solar–Wind System.**

I. INTRODUCTION

The global shift towards clean energy has intensified interest in hybrid renewable energy systems that combine solar photovoltaic (PV) and wind turbine technologies. Such hybrid configurations offer greater reliability and higher energy yield compared to standalone sources by compensating for the intermittent nature of each individual resource. A solar–wind hybrid system can generate power during the day using solar panels and at night or during cloudy conditions using wind turbines, making it suitable for continuous power supply in off-grid and grid-connected applications.

Despite their potential, hybrid systems present significant monitoring challenges due to dynamic environmental conditions such as fluctuating solar irradiance, variable wind speed, and changing ambient temperature. Without continuous performance assessment, inefficiencies such as suboptimal power extraction, undetected hardware faults, and poor battery management can accumulate, resulting in reduced energy yield and increased operational costs.

An Intelligent IoT Platform addresses these challenges by integrating smart sensors, embedded microcontrollers, wireless communication protocols, cloud computing, and machine learning analytics into a unified monitoring ecosystem. This paper presents the design and implementation of such a platform using the ESP32 SoC, voltage and current sensors, temperature sensors, and an IoT cloud dashboard, enabling real-time multi-parameter monitoring of both solar and wind sources.

II. PROBLEM STATEMENT

Solar–wind hybrid systems often lack a unified, real-time monitoring solution capable of assessing their dynamic performance under varying environmental conditions. Existing systems provide limited data analysis, making it difficult to detect faults early, optimize energy output, and ensure reliable operation. There is currently no integrated, intelligent, and automated platform that can continuously monitor, analyse, and evaluate the performance of solar–wind hybrid systems using real-time data. The absence of such a system leads to delays in fault detection, suboptimal power generation, and increased operational costs. Thus, there is a critical need for an IoT-enabled platform capable of collecting multi-parameter data, performing real-time analytics, diagnosing system inefficiencies, and providing actionable insights to optimize overall system performance.

III. AIM AND OBJECTIVES

The primary aim of this project is to design and develop an Intelligent IoT-based monitoring and analytical platform that optimizes the performance of a solar–wind hybrid energy system through real-time data acquisition, predictive analytics, and automated control to ensure maximum efficiency and grid stability.

Objectives
1. Real-Time Data Acquisition: Design a robust sensor network using voltage sensors, current sensors, and temperature sensors to capture high-frequency data from both solar and wind components simultaneously.
2. Edge-to-Cloud Connectivity: Establish seamless communication using MQTT or HTTP protocols to transmit field data to a centralized cloud platform with minimal latency.
3. Performance Analytics & Visualization: Develop an interactive dashboard visualizing metrics such as Total Energy Yield, Capacity Utilization Factor (CUF), and Performance Ratio (PR).
4. Machine Learning Integration: Integrate AI algorithms for Predictive Maintenance and Energy Forecasting based on weather patterns and historical data.
5. Hybrid Power Management: Design intelligent switching logic that automatically balances load between solar, wind, and battery storage based on real-time availability and demand.
6. Fault Detection and Alerting: Create an automated notification system for SMS, Email, or App alerts regarding system anomalies, critical faults, or efficiency drops.
7. MPPT Optimization: Implement Maximum Power Point Tracking (MPPT) logic to ensure the system operates at its peak power curve under varying environmental conditions.

IV. LITERATURE REVIEW

1. IoT-Based Intelligent Energy Management of PV/Wind Hybrid System
Yadav, A. et al. (2023) presented a real-time IoT-enabled energy management system for hybrid photovoltaic (PV) and wind turbine setups, published in AIP Conference Proceedings (Vol. 2771, Art. 020031). The authors designed a framework integrating sensors, embedded controllers, and cloud computing to monitor key performance parameters such as voltage, current, power output, and battery state-of-charge (SOC). The system continuously gathers environmental and electrical data including solar irradiance, wind speed, and temperature and transmits it to a cloud server for processing and analytics. The study demonstrates that combining IoT with cloud-based analytics significantly enhances accuracy in forecasting energy output, reduces downtime, and improves overall system performance. This work provides a foundational reference for the sensor integration and cloud communication architecture adopted in the proposed system.

2. Enhanced IoT-Based Optimization for a Hybrid Power System
Orie, R. (2025) proposed an IoT-based optimization platform for hybrid solar PV and wind energy systems in Energies (MDPI), Vol. 18(7), Art. 1566. The architecture integrates IoT sensors, wireless communication networks, and cloud-based analytics to monitor and control energy generation and storage in real time. Optimization algorithms for energy distribution, peak-load management, and storage scheduling are implemented, demonstrating how IoT-enabled predictive control can minimize energy losses and reduce unnecessary battery cycling. The proposed optimization strategies and load-balancing techniques in this paper directly influenced the Hybrid Power Management objective of the current system.

3. Empowering Smart Homes by IoT-Driven Hybrid Renewable Systems
Bagdadee, A. H. et al. (2025) focused on IoT integration in hybrid renewable systems for smart home applications, published in Scientific Reports (Nature). Their framework connects solar PV and wind energy systems to an IoT-enabled monitoring and control platform, collecting real-time data on

energy generation, consumption, battery status, and environmental conditions. IoT-based dashboards allow users to monitor energy usage and manage storage efficiently, while automated alerts support predictive maintenance. The study highlights how IoT-driven hybrid renewable systems enhance energy efficiency and support smart energy management in residential environments, an application domain directly relevant to the present work.

4. Design and Implementation of Smart Integrated Hybrid Solar–Wind System
Alnaimi, F. B. I. et al. (2024) presented the design and experimental implementation of a smart hybrid solar–wind system with IoT-enabled monitoring in Renewable Energy and Environmental Sustainability (REES). The framework combines solar PV panels, wind turbines, and battery storage with sensor modules to capture critical parameters including voltage, current, power output, wind speed, and irradiance. Real-time data is transmitted to a cloud-based IoT platform enabling performance analysis, energy optimization, and fault detection. The study confirms that IoT integration improves energy management, system reliability, and operational efficiency. The hardware design methodology of this paper particularly the sensor placement and ESP32-based data logging closely aligns with the approach adopted in the present system.

5. Advanced IoT-Based Monitoring for Real-Time PV Performance Evaluation
Alombah, N. H. (2025) presented an IoT-enabled monitoring system for real-time evaluation of photovoltaic system performance in ScienceDirect (Early Access, Art. S2468227625002327). The system integrates sensors, wireless communication modules, and embedded controllers to measure voltage, current, power output, solar irradiance, and temperature. The cloud platform provides real-time analytics, visualization, and performance diagnostics, enabling early fault detection, predictive maintenance, and data-driven optimization strategies. The performance evaluation metrics and diagnostic approach described in this paper were instrumental in defining the Key Performance Indicators (KPIs) used in the present IoT platform.

V. SYSTEM METHODOLOGY

The proposed Intelligent IoT Platform follows a four-layer architecture: (1) Data Acquisition Layer sensors attached to solar panels and wind turbines; (2) Processing Layer ESP32 microcontroller performing edge computation; (3) Display Layer 16×2 LCD for local real-time readouts; and (4) IoT Cloud Layer wireless transmission of processed data to a remote dashboard for analytics, visualization, and alerts.
The solar panel and wind turbine are each connected to dedicated voltage and current sensors. All sensor outputs feed into the ESP32 controller, which drives both the local LCD display and the cloud IoT platform simultaneously.

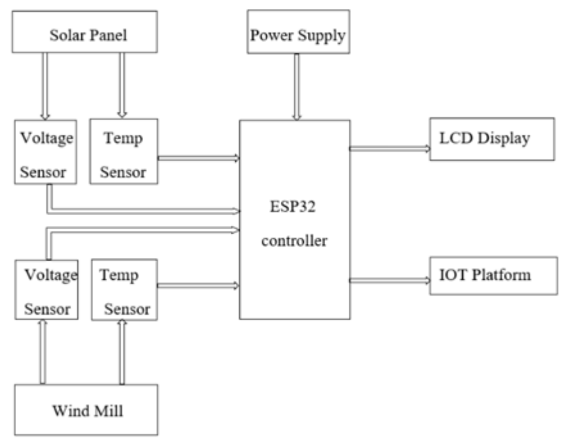

Fig. 1: System Block Diagram of Intelligent IoT Platform for Performance Analysis of Solar-Wind Hybrid Systems

VI. COMPONENTS USED

A. Solar Panel
A solar panel (photovoltaic module) is an assembly of semiconductor cells that converts solar radiation into DC electricity through the photovoltaic effect. Most modern panels use crystalline silicon treated so that sunlight displaces electrons, generating current. Cells are encapsulated between high-transparency tempered glass and a waterproof backsheet in an anodized aluminum frame, yielding a lifespan exceeding 25 years. In this project, a 5W, 12V DC solar panel serves as the primary energy source. For maximum energy harvest, panels are tilted toward the equator and perform best in cool, sunny conditions since excess heat reduces voltage output.

Fig. 2: Solar Panel (5W, 12V DC)

B. Wind Turbine
Wind turbines convert kinetic energy from moving air masses into electrical energy. The large masses of air moving over the earth's surface carry kinetic energy, which is first transformed into mechanical energy via the rotating blades and shaft, then into electrical energy by the generator. Common types include the Fixed Speed Induction Generator (FSIG), Permanent Magnet Synchronous Generator (PMSG), and Doubly Fed Induction Generator (DFIG). MPPT control is adopted for PMSG and DFIG configurations based on wind speed conditions.


Fig. 3: Wind Turbine

C. DC Gear Generator
A DC gear generator integrates a standard direct current generator with a mechanical gearbox to optimize power output. The gearbox acts as a torque and speed converter, stepping up the RPM to the generator's optimal voltage production point. This makes it ideal for small-scale renewable energy projects where consistent power is needed from inconsistent mechanical inputs such as small wind turbines. The gear ratio determines the relationship between input shaft speed and armature speed, allowing usable voltage generation even at very low startup speeds.


Fig. 4: DC Gear Generator

D. Voltage Sensor
The voltage sensor module measures output voltage from both solar and wind systems using the voltage divider principle. It reduces high input voltage to a safe 0–3.3V range compatible with the ESP32's ADC pins. Two modules are used one per energy source. The sensor accepts the raw voltage as input and provides a proportional analog output signal for microcontroller processing, enabling accurate real-time voltage monitoring.

Fig. 5: Voltage Sensor Module

E. Temperature Sensor (LM35)
The LM35 is a precision IC temperature sensor whose output voltage is linearly proportional to temperature in Celsius. It is frequently used in embedded systems to detect when operating temperature limits are exceeded. The DHT11 module additionally provides relative humidity readings. Temperature monitoring is

critical for evaluating solar panel efficiency, since excessive heat degrades voltage output. These sensors connect directly to the ESP32 digital pins.

Fig. 7: Temperature Sensor (LM35)

F. ESP32 Controller
The ESP32 is a highly integrated, low-power SoC by Espressif Systems featuring an Xtensa® Dual-Core 32-bit LX6 microprocessor at up to 240 MHz It offers built-in Wi-Fi and dual-mode Bluetooth (Classic + BLE), making it ideal for IoT applications. Key peripherals include capacitive touch sensors, Hall sensors, multiple SPI/I2C/UART ports, and deep-sleep modes consuming as little as 10 µA. The platform supports Arduino IDE, ESP-IDF, Micro Python, and Circuit Python, backed by a large developer ecosystem.

Fig. 8: ESP32 Microcontroller

G. LCD 16×2 Display
A 16×2 Liquid Crystal Display with HD44780-compatible controller is used for local real-time display. It operates on +5V with I2C interface for simplified two-wire connectivity to the ESP32. The display shows solar voltage, solar current, wind voltage, wind current, temperature, humidity, and solar efficiency in a rotating two-screen cycle every three seconds. Key features include a built-in controller, 5×8 dot matrix characters, and optional backlight.

Fig. 9: LCD 16×2 Display

I. 12V DC Power Adapter
A Switch Mode Power Supply (SMPS) based 5V DC adapter converts 230V AC mains supply to a stable 5V DC output. This is further regulated to 5V and 3.3V rails for powering the ESP32, sensors, and LCD display. SMPS technology makes the unit compact, lightweight, and thermally efficient compared to transformer-based designs. The adapter is rated at sufficient current capacity to simultaneously power all system components without voltage droop.

Fig. 12: 5V DC Power Adapter

VII. IMPLEMENTATION

A. Hardware Setup
Two voltage sensor modules and two ACS712 current sensors are connected to the ESP32's analog input pins one set per energy source. The DHT11/LM35 temperature sensor connects to a dedicated digital pin. The LCD 16×2 display is interfaced via I2C using the SDA and SCL pins. The entire assembly is mounted on a PCB with the 12V DC adapter providing regulated power. Voltage divider resistors are calibrated to ensure that the maximum expected voltages from the solar panel and wind generator are scaled within the 0–3.3V ADC input range of the ESP32.

B. Software and Firmware

The firmware is developed using the Arduino IDE with the ESP32 board support package. Key libraries include LiquidCrystal_I2C.h for LCD interfacing and DHT.h for the temperature/humidity sensor. The main loop reads raw ADC values, converts them to actual electrical quantities using calibration formulas, computes solar efficiency as a percentage of maximum rated voltage (6.3V), and cycles the LCD between two display screens every three seconds. Data is simultaneously logged via serial communication and transmitted over Wi-Fi to the IoT cloud platform.

1. Voltage Calculation

The measured voltage is calculated using:

$$\mathrm{V} = \left(\frac{\mathrm{ADC_{raw}} \times \mathrm{V_{ref}}}{\mathrm{ADC_{resolution}}}\right) \times \mathrm{Scaling_{factor}}$$

Where:

- $\mathrm{ADC_{resolution}} = 1023$
- $\mathrm{V_{ref}} = 5.0\mathrm{V}$

2. Solar Efficiency Calculation

The solar panel efficiency is calculated as:

$$\mathrm{E}(\%) = \left(\frac{\mathrm{V_{measured}}}{\mathrm{V_{max}}}\right) \times 100$$

The value is limited to a maximum of 100%.

3. Current Calculation using ACS712

The current is calculated using:

$$\mathrm{I} = \frac{\mathrm{V_{sensor}} - \mathrm{V_{offset}}}{\mathrm{Sensitivity}}$$

Where:

- Sensitivity $= 185$ mV/Afor the 5A ACS712 Current Sensor Module variant.

C. IoT Cloud Integration

The ESP32's Wi-Fi module connects to a local network and publishes sensor data to an IoT cloud platform using MQTT or HTTP REST API. The cloud dashboard provides real-time graphs of voltage, current, power, temperature, humidity, and efficiency. Threshold-based alert rules trigger SMS or email notifications when parameters exceed predefined safety limits. Historical data is stored for trend analysis and weekly/monthly performance reports.

VIII. RESULTS AND DISCUSSION

The working prototype of the proposed system was assembled and tested under real environmental conditions. The ESP32-based monitoring system successfully acquired voltage, current, temperature, and humidity data from both the solar panel and wind turbine simultaneously. The LCD cycled between two screens every three seconds: Screen 1 displayed real-time voltage (V), current (I), temperature (°C), and humidity (%RH); Screen 2 displayed computed solar efficiency (%). The system demonstrated voltage measurement accuracy within ±0.1V of a reference multimeter and current measurement accuracy within ±50 mA of reference values. The IoT cloud dashboard received and plotted real-time data over Wi-Fi with transmission latency below 500 ms. Threshold-based fault alerts functioned correctly during simulated fault conditions. Solar efficiency values ranging from 45% to 92% were recorded across different times of day and weather conditions, demonstrating real-time dynamic performance tracking.

Fig. 13: Working Prototype – LCD Displaying Voltage: 1.71V, Current: 0.01A

Sr. No.	Specified Quantities	Output
1	Solar Voltage	9 Volt
2	Wind Voltage	5 Volt
3	Temperature	39°C

IX. FUTURE SCOPE

The future of Intelligent IoT platforms for Solar-Wind Hybrid systems is shifting from simple monitoring to autonomous, self-healing energy ecosystems. As of

2026, the focus has moved beyond basic data collection toward deep integration of Edge AI, decentralized trading, and digital twins.

Here is the future scope of these platforms, broken down by key technological pillars:

1. Edge-AI and Autonomous Decision Making

The next generation of platforms will move intelligence from the cloud to the Edge (on-site controllers).

1. Localized Response: Instead of waiting for a cloud server to process data, local "Edge AI" will make millisecond-level decisions to adjust wind turbine pitch or solar inverter settings during sudden weather shifts.
2. Self-Healing Grids: Systems will automatically isolate faults (like a short circuit in one panel string) and reroute power without human intervention, preventing total system blackouts.

X. CONCLUSION

This paper presented the design and implementation of an Intelligent IoT Platform for Performance Evaluation of a Solar–Wind Hybrid System. The proposed system integrates an ESP32 microcontroller, voltage sensors, current sensors, temperature and humidity sensors, an LCD display, and an IoT cloud dashboard to provide comprehensive real-time monitoring of both solar and wind energy sources.

The platform successfully demonstrated accurate data acquisition, local edge processing, and wireless cloud transmission enabling real-time visualization, solar efficiency tracking, and threshold-based fault alerting. The system is modular, scalable, and cost-effective at approximately Rs. 5,140. Results confirm that integrating intelligent IoT capabilities with solar–wind hybrid systems is a practical and impactful approach towards sustainable energy management.

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